SEISMIC RESPONSE CONTROL OF REINFORCED CONCRETE (RC) BUILDINGS USING FLUID VISCOUS DAMPERS

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CERTIFICATION

This is to certify that the thesis titled:

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DEDICATION

I would like to dedicate my work to my parents and teachers, without whom this could not have been possible.

ABSTRACT

Effective seismic response control is crucial for protecting reinforced concrete (RC) buildings against the destructive forces of earthquakes. This research project focuses on investigating the efficiency of fluid viscous dampers (FVDs) in enhancing the seismic performance of RC buildings. This study is vital to meet the increased seismic demands making buildings vulnerable to major seismic events. The study also explores the implementation of dampers in the phenomenon of seismic pounding.

The research methodology involved designing an RC building according to relevant design codes and guidelines, followed by conducting time history analysis using various earthquake records of varying intensities. The initial analysis served as a baseline, simulating the building's response without any seismic control measures. Subsequently, FVDs were strategically incorporated into the building's lateral force-resisting system, and the model was re-analyzed under the same earthquake excitations. Comparative analysis of the two scenarios revealed significant enhancements in the seismic performance of the building when FVDs were implemented. The inclusion of FVDs effectively dissipated seismic energy, resulting in reduced acceleration, base shear, displacement, and inter-story drift demands caused by seismic loads. The effectiveness of FVDs is also demonstrated through modelling a building case undergoing seismic pounding. These findings highlight the vital role of FVDs in mitigating structural damage and improving occupant safety during seismic events.

This study contributes valuable insights to the field of earthquake engineering, particularly regarding the effectiveness of FVDs as seismic response control devices. The outcomes emphasize the importance of considering passive control systems like FVDs in the design and retrofitting of RC buildings, especially in regions prone to seismic activities.

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CHAPTER 1: INTRODUCTION

1.1 General

Earthquakes are natural geological phenomena that occur when there is a sudden release of energy in the Earth's crust, resulting in shaking and ground motion. They are primarily caused by movement of the tectonic plates, these are large sections of the Earth's lithosphere that float on the semi-fluid asthenosphere below. The Earth's lithosphere is divided into several plates, and the boundaries where these plates interact are known as fault lines. The most common type of earthquake occurs when two plates become locked due to friction and then suddenly slip past each other, releasing accumulated energy in the form of seismic waves.

The intensity and potential danger of an earthquake are measured using the Richter scale or the moment magnitude scale (Mw), which quantifies the energy released by the earthquake. Earthquakes can vary in magnitude from minor tremors that are barely noticeable to catastrophic events with magnitudes exceeding 9.0, capable of causing widespread devastation.

For example: The 1906 San Francisco earthquake in the United States, with an estimated magnitude of 7.9 [1] caused widespread destruction, resulting in fires that ravaged the city and claimed numerous lives.

These tragic occurrences emphasize the importance of understanding earthquakes, implementing effective early warning systems, and implementing stringent building codes and infrastructure designs to minimize the loss of life and property in earthquake-prone regions.

1.2 The Impact of Earthquakes

Earthquakes are among the most destructive natural disasters, the dangers and effects associated with them stem primarily from their ability to trigger various secondary hazards. These include ground shaking, which can lead to the collapse of buildings and infrastructure, landslides, liquefaction and tsunamis. Throughout history, numerous tragic occurrences resulting from earthquakes have left indelible marks on human society.

1.2.1 Seismic Damages to Buildings

Earthquakes can cause significant damage to buildings, leading to injuries, fatalities, and economic losses. The extent of damage depends on various factors, including the magnitude of the earthquake, the distance from the epicenter, the type of building, and the quality of construction. The damage can be Non-Structural Damage (to non-structural components such as walls, ceilings, partitions, and MEP systems), and Structural Damage (to structural components such as the foundation, walls, floors, and roof). Structural damage is very dangerous as it can compromise the stability of the building and make it unsafe to occupy, in the worst case 'Building Collapse' can occur. This is the most severe type of seismic damage and occurs when the building is no longer able to support its own weight [2].

Moreover, earthquakes can also cause damage through collision of buildings referred to as 'Seismic Pounding'. Seismic pounding, also known as structural pounding, refers to the collision or impact between adjacent buildings or structural elements during earthquakes. It occurs when buildings with different natural frequencies or dynamic characteristics are subjected to strong ground shaking causing differential movements which can lead them to collide or pound into each other causing further damage and even collapse.

Therefore, the consequences of earthquakes can be severe and require several measures for safety. Adherence to proper building design and construction practices is essential, and for already constructed buildings seismic-resistant features need to be added.

1.2.2 Pakistan and Earthquakes

For Pakistan the study of earthquakes holds immense importance due to its geographical location in a seismically active region. Pakistan is situated at the intersection of the Indian Plate, Eurasian Plate and the Arabian Plate, making it prone to frequent seismic activity. As a result, understanding the characteristics and behavior of earthquakes is crucial for the country's disaster management and mitigation efforts.

One of the tragic earthquake events in Pakistan's history occurred in 2005, when a massive earthquake struck the northern parts of the country, primarily affecting the Kashmir region. With a magnitude of 7.6, the earthquake caused widespread devastation, resulting in the loss of at least 79,000 lives [3] and leaving hundreds of thousands of people displaced. The earthquake not only caused the collapse of numerous buildings but also triggered landslides and disrupted infrastructure, exacerbating the challenges faced during rescue and relief operations.

This catastrophic event served as a wake-up call for Pakistan, highlighting the urgent need to prioritize earthquake studies, improve infrastructure resilience, and enhance disaster preparedness. Since then, the country has made significant strides in earthquake research, monitoring, and mitigation strategies.

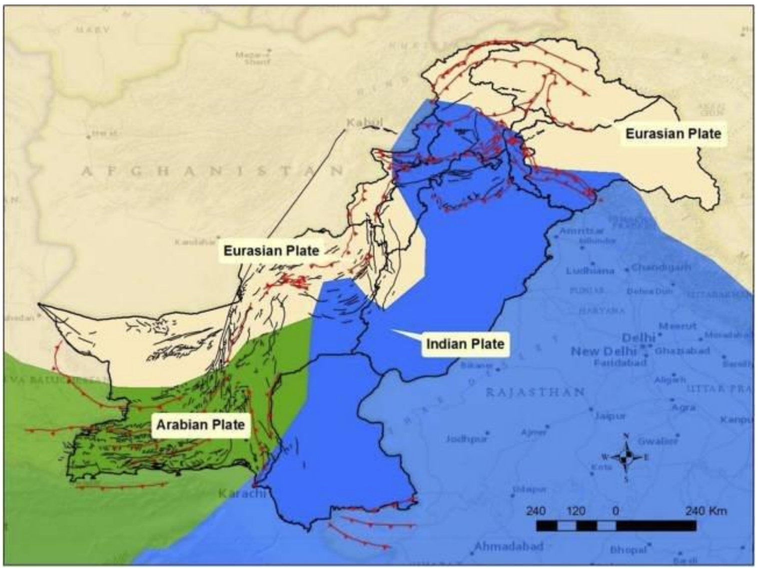


Figure 1.1: Seismic Map of Pakistan showing the Tectonic Plates [4]

Moreover, the Building Code of Pakistan (BCP) 2021 explains the heightened seismic activity in Pakistan as compared to Building Code of Pakistan (BCP) 2007. This underscores the urgent need to address the vulnerabilities of our existing buildings. Retrofitting these existing buildings to align with the updated code requirements is crucial for enhancing public safety, reducing the potential for casualties and property damage, and for building more resilient communities in the face of the growing seismic threats. Additionally, it’s worth noting that seismic pounding is a major concern in Pakistan. This is because adequate gap provisions are not always adhered to, and even if individual structures do not fail, their collision and impact with one another can lead to severe and dire consequences.

1.3 Seismic Fortification

With the increasing recognition of seismic hazards around the world, seismic fortification has become a crucial aspect of ensuring the safety and longevity of buildings in earthquake-prone regions. It is the process of enhancing the structural strength and resilience of existing buildings to improve their ability to withstand seismic forces. It involves evaluating the existing structural system of a building and identifying its weaknesses in relation to seismic loads. It then includes the implementation of retrofit measures to strengthen these vulnerable elements and improve the overall seismic performance of the building. Retrofitting techniques may vary depending on the specific characteristics of the structure and conditions of earthquake [5].

There are several ways for seismic fortification, but dampers and more specifically Fluid Viscous Dampers (FVDs) are among the more preferred seismic fortification techniques owing to several advantages which make them a superior choice. These advantages include improved energy dissipation, cost-effective, space efficiency, low maintenance, customization, enhanced safety, and minimal aesthetic impact.

1.4 Research Gap

Thorough research on the application of Fluid Viscous Dampers (FVDs) in existing buildings to enhance their seismic resilience is particularly scarce in the literature, particularly for the Pakistan region and buildings. Additionally, while various studies have been conducted on seismic pounding, the intricate interplay of ground motion characteristics, and building features make each pounding incident unique. As such there is a need for investigating the efficiency of FVDs for buildings and earthquake characteristics of Pakistan.

1.5 Problem Statement

In light of the gaps in the existing body of knowledge, this study delves into the effectiveness of Fluid Viscous Dampers (FVDs) in meeting the adequate seismic demands of a pre-constructed building located in Islamabad region. Moreover, it examines the feasibility and efficiency of implementing FVDs in buildings susceptible to seismic pounding, thereby contributing to the understanding and mitigation of such seismic-induced damages.

1.6 Research Objectives

The aims of this research are to understand the implementation and effectiveness of FVDs in seismically fortifying buildings. These results have also been expanded for seismic pounding. The objectives of the research are listed below:

1. Investigating the impact of incorporating FVDs on the seismic response of pre-designed buildings.
2. Evaluate the efficiency of FVDs in modifying building response through varied damper placements.
3. Enhance seismic resilience by aligning building response with vibration amplitude and damage susceptibility.
4. Implement damping strategies to alleviate structural damage arising from seismic pounding phenomena.

CHAPTER 2: LITERATURE REVIEW

2.1 Design of Buildings

The seismic design of buildings is done in accordance with ASCE 7-16, which is a standard developed by the American Society of Civil Engineers (ASCE), to establish minimum load requirements for structural design [6]. The seismic design provisions outlined in ASCE 7-16 play a critical role in ensuring the safety and stability of structures situated in earthquake-prone regions.

ASCE 7-16 provides two primary methods for seismic design: Equivalent Lateral Force (ELF) Procedure and Modal Response Spectrum Analysis (MRSA)[7]–[9].

The ELF Procedure, designed for regular-shaped buildings, employs a simplified approach to determine lateral forces [10]–[12]. Calculation for base shear (V) is shown in Eq 1:

$$V = C_s * W \qquad (1)$$

Where,

- C_s = Seismic Response Coefficient
- W = Total Weight of The Building.

Modal Response Spectrum Analysis (MRA), a more sophisticated method suitable for irregular structures, considers modal properties for a comprehensive analysis [13]. The base shear (V) calculation involves multiple parameters, as expressed by Eq 2:

$$V = \sum_{i=1}^{n} W_i * S_a(T_i) * R * I_e * \emptyset_i \qquad (2)$$

Where,

- W_i = Seismic Weight
- S_a = Spectral Response Acceleration
- T_i = Time
- R = Response Modification Factor
- I_e = Importance Factor
- Φ_i= Modal Participation Factor

For Site-Specific Ground Motion ASCE 7-16 provides procedures to determine the design ground motion based on the site's seismic hazard [14]. Response Modification Factor (*R*) accounts for the damping, overstrength, and ductility of the structure; Importance Factor (*Ie*) reflects the importance of the structure based on its use and occupancy; and ASCE 7-16 also provides several load combinations that consider seismic loads in conjunction with other loads.

To conclude the seismic design of buildings according to ASCE 7-16, it involves the application of either the Equivalent Lateral Force Procedure or Modal Response Spectrum Analysis, while also considering various factors such as seismic coefficients, modal properties, and site-specific ground motion [7]. Engineers should follow the standard's provisions to design buildings that can withstand the effects of earthquakes as it is crucial for ensuring the safety and resilience of structures in seismic-prone regions [10], [11]

2.2 Seismic Response of Buildings

Understanding the dynamic behavior of buildings under seismic events is crucial for implementing effective seismic response control strategies [15]. This section delves into the fundamental principles governing the response of buildings to seismic forces, exploring key concepts such as natural frequencies, modes of vibration, and the dynamic characteristics of structures subjected to ground motion.

2.2.1 Seismic Loading and Response Spectra

The dynamic response of buildings is characterized primarily by their natural frequencies and corresponding mode shapes. Natural frequencies represent the rates at which structures oscillate when subjected to seismic forces and mode shapes depict the spatial distribution of deformations during vibration, influencing the overall response of the structure [16]. For controlling the amplitude and duration of structural vibrations damping is a very important factor. By examining damping ratios, we can understand how energy dissipation affects the overall seismic response of buildings and achieve an accurate seismic analysis leading to the development of effective control strategies [17].

Also, seismic loading is influenced by various ground motion characteristics and response spectra of a structure. Ground motion characteristics include amplitude, frequency content, and duration. By studying the diverse nature of ground motions, we gain insights into the spatial and temporal variability of seismic forces, which is crucial for designing structures that can withstand a range of seismic events [18]. Response spectra illustrate the maximum response of a structure across a range of frequencies. Analyzing response spectra aids in understanding how different building configurations respond to seismic excitation. This information is instrumental in designing structures with specific performance objectives and in developing targeted seismic response control strategies [19].

2.2.2 Structural Vulnerabilities and Failure Mechanisms

The susceptibility of various structural elements to seismic forces varies and it is most important for critical structural elements. Columns, beams, and connections are critical components that may exhibit vulnerabilities during seismic events, as such identifying and understanding these vulnerabilities is essential for designing robust structures and implementing effective retrofitting measures [20]. Additionally, the nonlinear response and behavior of structures under severe seismic loading conditions can lead to significant deformations and damage. Investigating the nonlinear behavior of buildings helps in predicting potential failure mechanisms and developing advanced control strategies to mitigate the impact of extreme seismic events. [21]

2.2.3 Performance-Based Engineering Design

Examining real-world case studies offers valuable insights into the performance of buildings during seismic events, allowing for a detailed analysis of structure response in specific geographic regions and under varying seismic intensities [22]. This examination enhances our understanding of the effectiveness of existing designs and retrofitting measures. Concurrently, performance-based engineering involves the evaluation of structures during actual seismic events, utilizing this data to refine and enhance seismic design codes and standards [2], [14]. The incorporation of lessons learned from performance-based engineering ensures that future structures are designed with a more profound understanding of their expected behavior during seismic events, contributing to overall structural resilience and safety.

2.2.4 Building Design in Pakistan

In Pakistan, Building Code of Pakistan 2021 is utilized for design purposes. It utilizes spectral acceleration as a seismic hazard parameter for seismic design. According to BCP 2021 $\boldsymbol{S_s}$ and $\boldsymbol{S_1}$ are given to each site and are used for the calculation of base shear experienced by the building (BCP 2021).

The formulas of BCP 2021 used to calculate the base shear (V) of the building is given in Eq 3:

$$V = \frac{SD_s I}{R} W \tag{3}$$

Where,

$$SD_s = \frac{2}{3} F_a S_s \tag{4}$$

- SD_S = Design Spectral Acceleration Parameter
- F_a = Site Coefficient
- I = Occupancy Importance Factor
- R = Response Modification Factor
- W = Weight of The Building
- S_s = Mapped Spectral Acceleration short period at 2% probability of exceedance in 50 years
- S_1 = Mapped Spectral Acceleration long period at 2% probability of exceedance in 50 years

Initially, in BCP 2007 PGA (Peak Ground Acceleation) was used as seismic design parameter. But recent studies have shown that it did not adequately account for the heightened seismicity now recognized in the BCP 2021. The 2007 code might not have included design provisions and structural requirements that address the increased intensity of potential seismic events in Pakistan. As a result, these buildings may be vulnerable to damage and collapse during earthquakes, further highlighting the importance of seismic fortification [6], [23].

To conclude, a deep understanding of the dynamic behavior of structures and earthquake features is essential to develop resilient and effective strategies for mitigating the impact of seismic forces on reinforced concrete buildings [15]. As such to safeguard structures seismic fortification or retrofitting of existing buildings is essential. This process involves strengthening the structural elements of buildings to enhance their ability to withstand seismic forces.

2.3 Seismic Fortification

Seismic fortification is the process of enhancing the structural strength and resilience of existing buildings to improve their ability to withstand seismic forces [24].

Fortification Techniques can be generally categorized into two main approaches:

- At the member level, efforts are made to enhance the seismic performance of individual structural members. This involves targeting the weakest structural member and increasing its capacity.
- At the structural level, the focus is on the entire building, aiming to enhance its resistance to seismic forces through the incorporation of new structural or substructural elements.

While seismic fortification is a highly effective method of mitigating seismic risks, it is important to note that the process requires careful engineering analysis and implementation[25]. Each building must be assessed individually, taking into account its unique characteristics and the local seismicity. Generally Structural level techniques are more preffered because they are better able to address the buildings response as a whole [26].

2.3.1 Common Fortification Techniques

Some of the common fortification techniques are discussed below:

Steel Bracing: Steel bracing is one of the popular seismic fortification techniques. This construction technique involves strategically placing steel members diagonally or vertically within a building's structural system to effectively distribute seismic forces and minimize the risk of structural damage [27]. Complying with stringent building codes, these bracing configurations not only enhance safety but also contribute aesthetically, showcasing the synergy between structural necessity and architectural design. [2]

Fiber-Reinforced Polymer (FRP) Wrapping: Fiber-Reinforced Polymer (FRP) wrapping is an innovative technique where fiber-reinforced polymer materials, such as carbon or glass fibers, are applied to existing structural elements like columns or beams. The meticulous wrapping process enhances the strength and ductility of these elements, creating a robust external layer that reinforces the structural integrity of the building by strategically distributing stresses and improving load-bearing capacities [28]. FRP wrapping significantly enhances the seismic performance of vulnerable structural elements, reducing the susceptibility to failure during seismic events. This method is particularly advantageous for its lightweight nature, ease of application, and corrosion resistance.

Base Isolation: Base isolation technique introduces a dynamic approach to enhance a building's resilience against earthquake forces. In this method, flexible bearing pads or isolators are strategically positioned between the structure's foundation and superstructure. These isolators act as shock absorbers [29]. The design of these isolators allows them to deform and absorb seismic energy during an earthquake, preventing the transmission of destructive forces to the superstructure. This innovative approach not only reduces the magnitude of lateral forces experienced by the building but also extends the period over which these forces act, mitigating the overall impact. Base isolation is particularly beneficial for preserving the integrity of critical structures, such as hospitals and emergency response centers, as it minimizes structural damage and facilitates rapid post-earthquake recovery [30].

Dampers: Dampers are devices that absorb or dissipate energy during an earthquake, reducing the intensity of vibrations and minimizing the potential for structural damage. Dampers, integral to advanced seismic engineering, play a pivotal role in fortifying structures against the destructive forces of earthquakes [31]. These devices function as energy absorbers, strategically incorporated into a building's structural system to mitigate vibrations and dampen seismic-induced motion. Commonly employed dampers include friction dampers, viscous dampers, and tuned mass dampers, each offering distinct mechanisms for dissipating seismic energy [32].

Friction dampers rely on the friction between moving components to absorb energy [33], while viscous dampers employ the resistance of fluids to damp vibrations [23]. Tuned mass dampers involve the controlled movement of masses to counteract the building's oscillations [34]. By effectively reducing the intensity of seismic forces and minimizing structural deformations, dampers enhance a structure's resilience.

Their versatility allows for tailored integration into various architectural designs, providing a dynamic solution to optimize seismic performance [35]. As an evolving field within earthquake engineering, the incorporation of dampers exemplifies a proactive approach to safeguarding buildings and critical infrastructure from seismic threats, contributing to the overall seismic resilience of communities in earthquake-prone regions. They are typically integrated into the building's structural system to enhance its overall seismic performance.[31]

In conclusion, seismic fortification of existing buildings plays a vital role in addressing the concerns of increasing seismic activity worldwide. By retrofitting vulnerable structures, we can enhance their resistance to seismic forces, reduce the risk to human life, and safeguard valuable assets [36]. Among fortification techniques, Fluid Viscous Dampers (FVDs) are a superior choice for fortifying structures owing to the reasons listed in the coming section. As such they have been chosen for our study.

2.4 Fluid Viscous Dampers (FVDs)

Fluid viscous dampers (FVDs) are among the predominant types of protective devices used in earthquake engineering. They regulate structural responses by absorbing energy imparted during earthquakes, thereby minimizing the energy demand for the primary structure to dissipate through plastic behavior. This effective energy dissipation leads to a reduction in structural damage [32], [35]. FVDs are typically preferred over the other mentioned seismic retrofitting techniques and damper types, as they provide reliable and stable performance over various seismic events [5], [23]. Some of their advantages are as follows:

- They can significantly reduce structural response, including displacement and acceleration, during an earthquake, thereby minimizing the risk of structural damage and collapse.
- Dampers help improve the overall stability and resilience of buildings, allowing them to better withstand seismic events.
- Dampers dampen individual building’s response to an earthquake thereby preventing possible collision between adjacent buildings.
- Dampers require minimal maintenance and have a long service life.
- Dampers can be retrofitted relatively easily into existing buildings, making them a valuable option for improving the seismic performance of older structures.

However, it is important to note that the design and implementation of dampers require careful engineering analysis and consideration of various factors such as building characteristics, seismicity, and performance objectives [31].

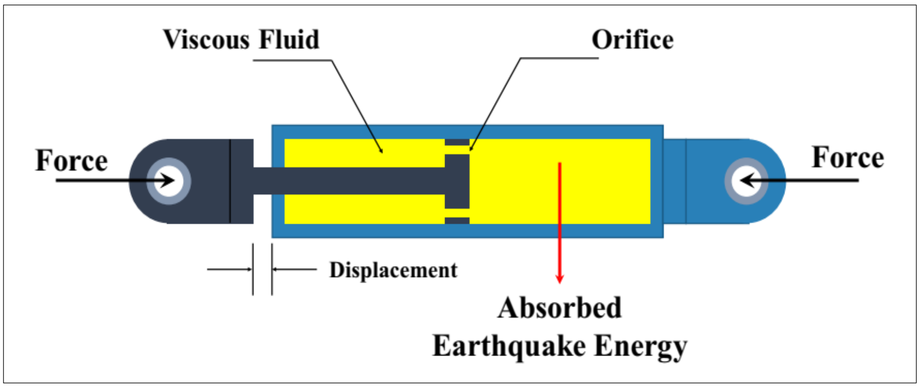


Figure 2.1: A simple schematic of a FVD [37]

2.4.1 Characteristics of Fluid Viscous Dampers

The damper produces power through the pressure difference acting on the piston head, induced by the input motion. This opposing force, known as the damping force, is directly linked to changes in fluid volume resulting from the product of the piston's displacement and its cross-sectional area during motion [38]. Given the predominantly compressible nature of the damper's fluid, the generation of the restoring force resembles that of a spring, developing due to the change in pressure as shown in Figure 2.2

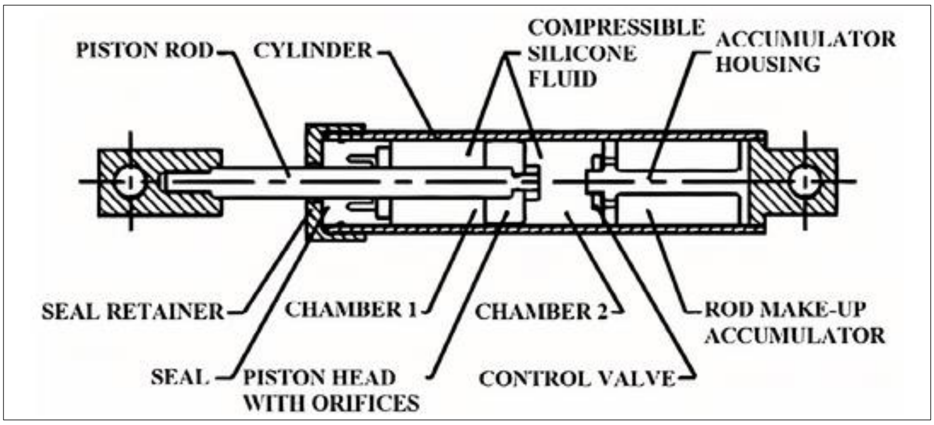


Figure 2.2: A labelled figure showcasing the inner workings of a typical FVD [38]

The resistive force of a damper is determined by multiple factors, such as the fluid viscosity, velocity of movement, and the size of the piston's orifices. Equation for determining the value of P, which relates to the resistance force (F) in FVDs, is given in Eq 5 [39]:

$$P = C_d * (U_d) * \propto * \sin(U_d * t) \tag{5}$$

Where,

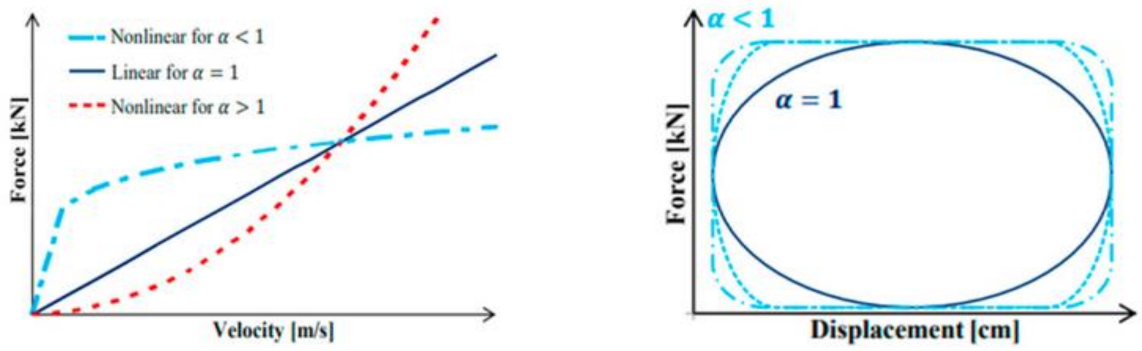
- C_d = Damping constant
- U_d = Velocity between the two ends of the damper
- A = Exponent which depends on the piston's viscosity and fluid's viscosity properties
- t = Time - the seismic energy during an earthquake.
- α = Exponent in the equation which determines the value of P in FVDs. It can be less than one or equal to one.

2.4.2 Linear FVDs vs Non-Linear FVDs

For analysis purposes FVDs can be modelled linearly or non-linearly. Linear FVDs are different from non-linear FVDs in regard to the relationship between the resistance force produced by the damper and piston's velocity. [40].

For a linear damper, the resistance force increases in direct proportion to piston's velocity, because the force is directly tied to the piston's speed. Whereas a non-linear damper generates a resistance force dependent on various factors, such as acceleration or displacement [41]. While both linear and non-linear FVDs utilize fluids with mostly similar properties, their intended applications may differ. In linear dampers, fluid viscosity is the primary factor influencing the damping force. Conversely, non-linear dampers employ non-Newtonian fluids with viscosities which change with stress or shear rate to achieve non-linear damping characteristics [38].

A linear viscous damper is characterized by an exponent of $\alpha = 1$, while a non-linear FVD has an exponent of $\alpha < 1$, effectively mitigating high-velocity shock [42]. Dampers with an exponent of $\alpha > 1$ are less commonly observed in practical applications. Careful consideration of the structure's behavior and desired performance is crucial for selecting the appropriate type of FVD for a specific application.



(a) **(b)**

Figure 2.3: Linear vs. non-linear FVDs (a) Force velocity relationship (b) Force displacement relationship [42]

As shown in Figure 2.3(a) the damper forces decrease by increasing the damper velocity for non-linear dampers. Additionally, non-linear viscous dampers dissipate more energy as compared to linear viscous dampers at the same excitation as shown in Figure 2.3(b) [42]

Generally, Non-Linear FVDs are preferred more than Linear FVDs because they more realistically describe the behavior of the building. Their advantages are:

- Non-linear dampers provide a limiting peak damper force at high velocities [43], as compared to linear dampers where the damping force rises with velocity [37].

- Non-linear dampers enable more accurate and efficient vibration control, leading to improved overall performance and safety. This capability arises from their variable damping force, which can be adjusted to align with the unique vibration characteristics of a structure.

The conclusions drawn by various researchers consistently highlight the superior advantages of non-linear viscous dampers in comparison to traditional linear viscous dampers. Kaleybar et al. based on his investigation of moment frames subject to eleven ground motions concluded that for structures with the same damping coefficient nonlinear dampers had greater energy dissipation [44]. Similarly, Mevada et al. described a similar response of structures with increased nonlinearity of dampers, leading to reduced damages at design based and maximum considered earthquake [43].

2.4.3 Modelling of Non-Linear Fluid Viscous Dampers

The seismic response of structures with FVDs can be analyzed from the perspective of energy, particularly by understanding the distribution of energy terms over the height of the building. In these structures, the seismic energy imposed is primarily absorbed through two mechanisms: the structural plastic energy E_P and the energy dissipated by FVDs, denoted as E_{d2}. These parameters quantify the cumulative damage sustained by the structure and the seismic reduction effect of FVDs, respectively. Consequently, it becomes crucial to understand how these energy terms are distributed across the height of the building [17].

Previous investigations into buildings have yielded three categories of E_P distributions: uniform distribution, linear distribution, and distributions derived from nonlinear static pushover analysis.

For instance, Shen's research revealed that, for taller frames, the E_P demand tends to exhibit a uniform distribution along the height [45]. In contrast, Akbas et al. proposed a linear distribution of E_P in steel-moment frame buildings [46]. Similarly, Estes and Anderson observed that E_P in steel-moment frame buildings reaches its peak value on the first story and decreases with height [47]. Gupta and Krawinkler conducted a study on the E_P distribution across the height of 9- and 20-story buildings using nonlinear dynamic analyses. Their findings indicated that the E_P distribution is not uniform or linear but is strongly influenced by the structural properties and characteristics of the ground motion [48].

In conclusion, the E_P distribution is closely interrelated with the design of structures and FVDs. Ying Zhou, Mohammed Samier Sebaq, Yi Xiao [17] carried out an extensive examination involving four steel-moment resisting buildings of varying heights (3, 6, 9, and 20 stories, respectively), each fitted with either linear or nonlinear FVDs. The effect of structural property and FVDs properties, characterized by the supplemental damping ratio ξ_{add} and velocity power α, on the E_P and E_{d2} overall demand and distributions among stories were illustrated. These findings and results have been used for modelling the dampers for our study. The tables for these findings have been shown in the methodology section of this study.

CHAPTER 3: METHODOLOGY

3.1 Modelling and Projection of Building

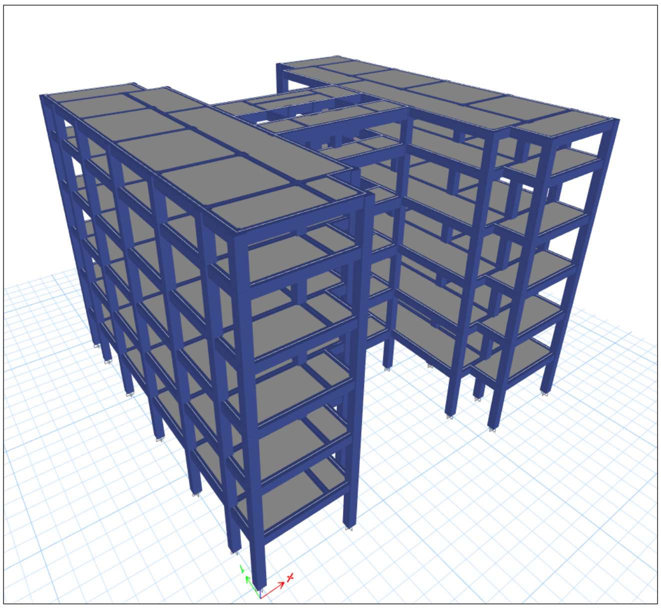
The initial step in this study involves the selection of a six-story reinforced concrete moment-resisting frame building. Subsequently, a finite element model for this structure is created using ETABS, as depicted in Figure 3.1a, 3.1b and 3.2c. The validation process includes fundamental assessments of time periods and evaluations of load paths.

Following the validation, a thorough examination is conducted to assess horizontal and vertical irregularities within the building. Structural design is based on the building code of American Concrete Institute for reinforced concrete (ACI 318- 19) and UBC 1997 with loads from ANSI/ASCE 7-10.

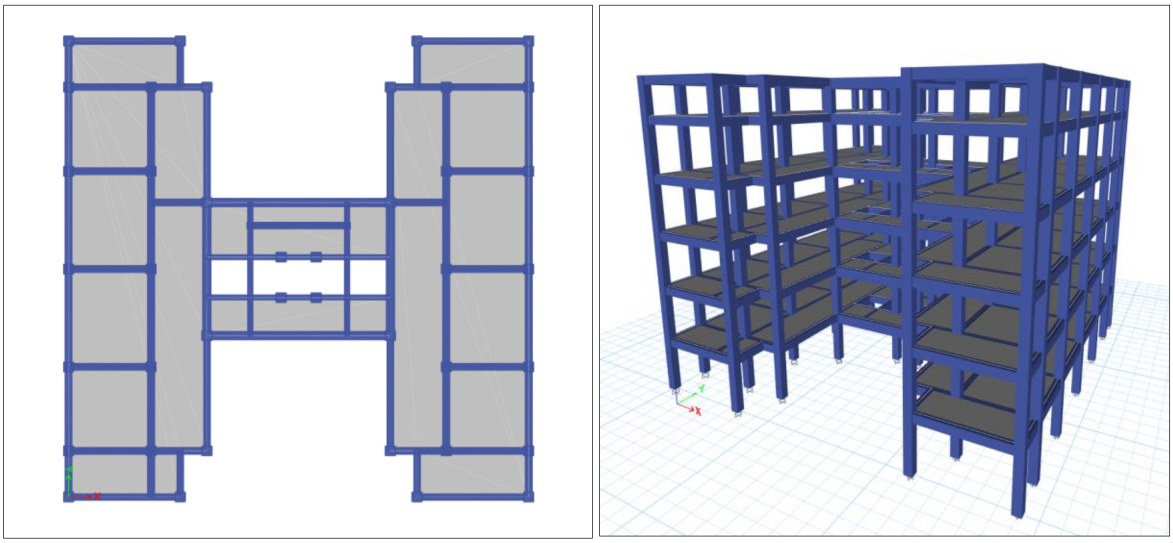
Building salient features are presented in Table 3.1 below.

Table 3.1: Modelled Building Salient Features and Properties

Building Height (ft)		53'6"
No. of Stories		6
Specified compressive strength of concrete f'_c	RC Walls	4000 psi
	RC Beams & Slabs	3000 psi
	RC Columns	4000 psi
Specified yield strength of longitudinal steel bar in RC walls & RC columns f_y (Grade 60 Steel)		60,000 psi



(a)



(b) **(c)**

Figure 3.1: (a) 3D View of the modelled building (b) Plan View of the modelled building (c) 3D View of the modelled building

3.2 Ground Motion Selection

For the time-history analysis, three distinct ground motions are carefully chosen, each possessing specific seismic parameters. These selected ground motions have been taken from the PEER Ground Motion Database, and their seismic parameters are outlined in Table 3.2.

Table 3.2: Ground Motions used for our study

EQ ID	Earthquake	M	Mechanism	Rjb (km)	Station
RSN341	Chi-Chi Taiwan	7.62	Reverse	41.99	CHY027
RSN1187	Chi-Chi Taiwan	7.62	Reverse	35.29	CHY015
RSN1196	Coalinga-01	6.36	Reverse	41.37	Parkfield Fault Zone 02

As the region and site chosen for our study is Islamabad, the selected ground motions are subjected to a spectral matching process to align them with the designed seismic intensity levels appropriate for the Islamabad region. Spectral matching is the process to modify an input ground motion accelerogram to closely match a target response spectrum [49]. This target spectrum represents the expected ground motion characteristics for a specific site and earthquake return period. For structural engineering and earthquake analysis, spectral matching is essential as it ensures the accuracy and reliability of seismic response assessments.

Seismo-match was used to spectrally match the selected ground motions to the response spectrum of Islamabad. The design response spectrum values are $S_s = 1.302g$, $S_1 = 0.381g$ and Site class D. Upon completing the spectral matching procedure, the resulting response spectra, reflecting the seismic characteristics of the chosen ground motions, are visually represented in Figure 3.3. Additionally, the corresponding matched time histories, which capture the dynamic behavior of the structure under these seismic conditions, are illustrated in Figure 3.2 for further analysis and evaluation.

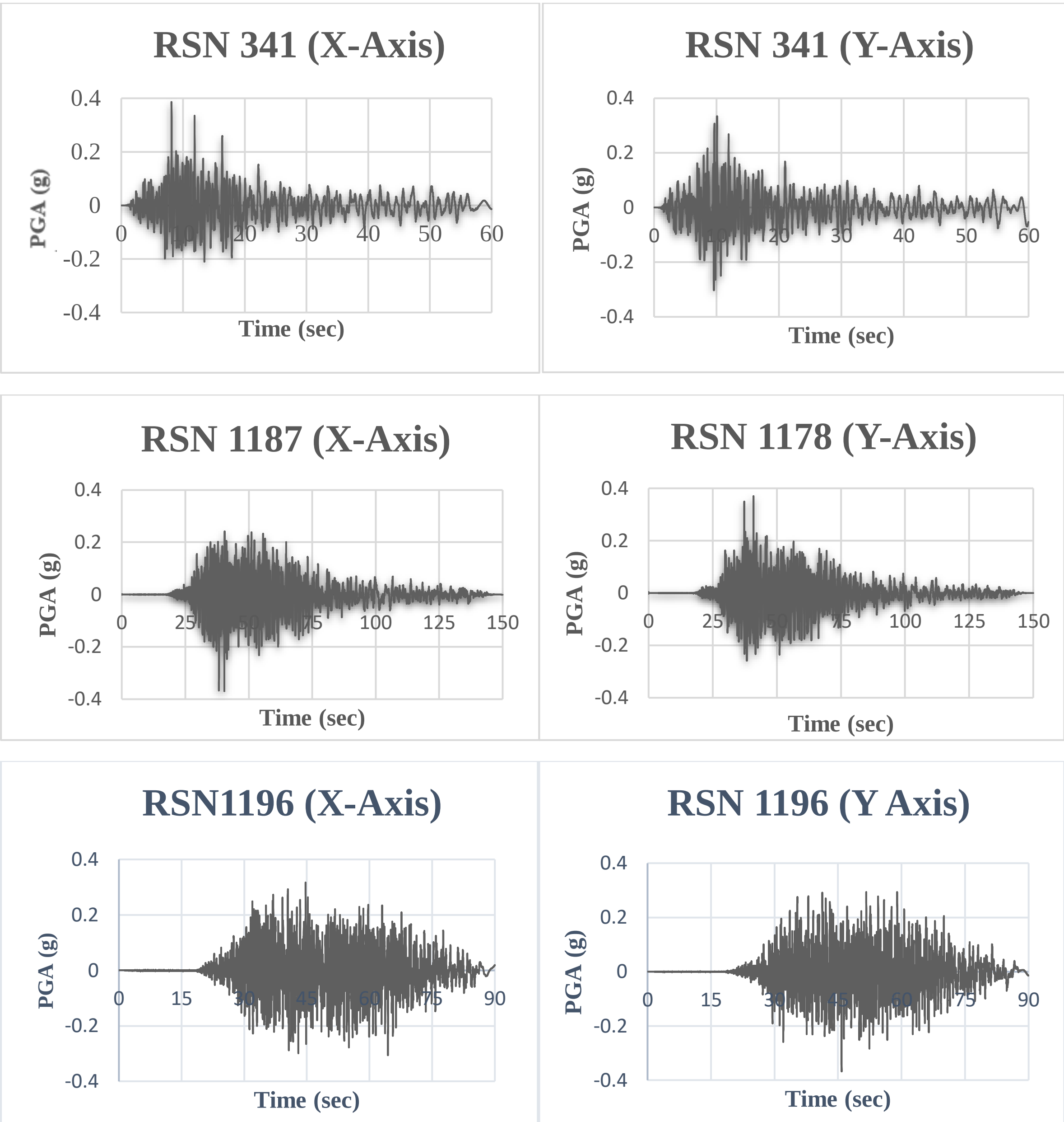


Figure 3.2: Matched time histories for Earthquakes RSN341, RSN1187, RSN1196

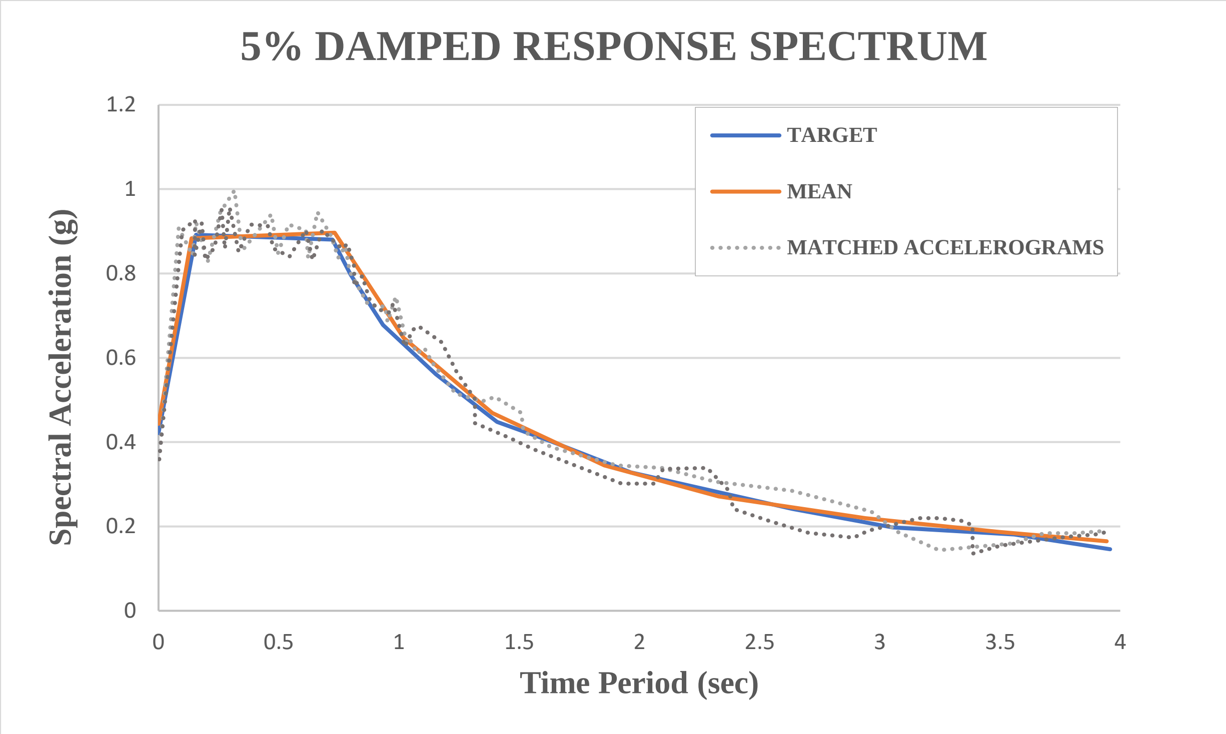


Figure 3.3: Matched Response Spectrum of Earthquakes RSN341, RSN1187, RSN1196 for Islamabad region

3.3 Modelling of Non-Linear Fluid Viscous Dampers

The parameters used for modelling the FVDs have been taken from the study of Ying Zhou, Mohammed Samier Sebaq, Yi Xiao [17]. The study conducted a comprehensive investigation for buildings with different heights (3-, 6-, 9-, and 20-stories, respectively) equipped with linear or nonlinear FVDs. Through the study, the effect of structural property and FVDs properties (characterised by ξ_{add} and α) on the E_P (Structural Plastic Energy) and E_{d2} (Energy dissipated by FVDs) overall demand and distributions among stories were illustrated.

These parameters lead to efficient design of FVDs, and the parameters for a 6-story building (our case) have been shown in Table 3.3. We used ξ_{add} (Supplemental Damping Ratio) of 20% and α (Velocity Power) of 0.5. The corresponding C_{NL} (FVD Coefficients) used have been highlighted as well in Table 3.3.

Table 3.3: FVD coefficients for a 6-story building based on α and ξ_{add} [17]					
ξ_{add} (%)	**Story Level**	**C_L ($kN - s^{\alpha}/mm^{\alpha}$)**	**C_{NL} ($kN - s^{\alpha}/mm^{\alpha}$)**		
		α = 1	**α = 0.7**	**α = 0.5**	**α = 0.3**
5	6	1	3.5	8	19
	5	1	4	11	28
	4	2	10	29	83
	3	2	11	34	105
	2	2	12	37	119
	1	3	17	52	160
10	6	2	7	15	32
	5	3	12	30	76
	4	3	14	40	113
	3	4	21	64	192
	2	4	22	70	218
	1	5	27	81	244
20	6	4	13	**28**	61
	5	5	19	**47**	114
	4	7	31	**83**	222
	3	7	34	**98**	279
	2	9	46	**138**	408
	1	10	50	**144**	418
30	6	6	19	41	88
	5	8	30	71	170
	4	10	42	109	282
	3	11	50	139	380
	2	13	63	180	512
	1	15	71	199	553

Where,

- ξ_{add} = Supplemental Damping Ratio
- α = Velocity Power
- C_L and C_{NL} = FVDs Coefficients

3.4 Placement of Dampers

Drawing from insights gleaned from prior research, it has been observed that passive dampers (such as in our case) tend to exhibit optimal performance when positioned along the outer periphery of the building structure. In this particular study, a comprehensive assessment is carried out, considering various orientations of these dampers at the building's periphery. These assessments take into account architectural considerations to ensure harmonious integration.

The outcome of this evaluation process is the development of a final model featuring FVDs. This model, encapsulating the selected damper orientations and architectural requirements, is visually presented in Figure 3.4 to provide a clear representation of the design**.**

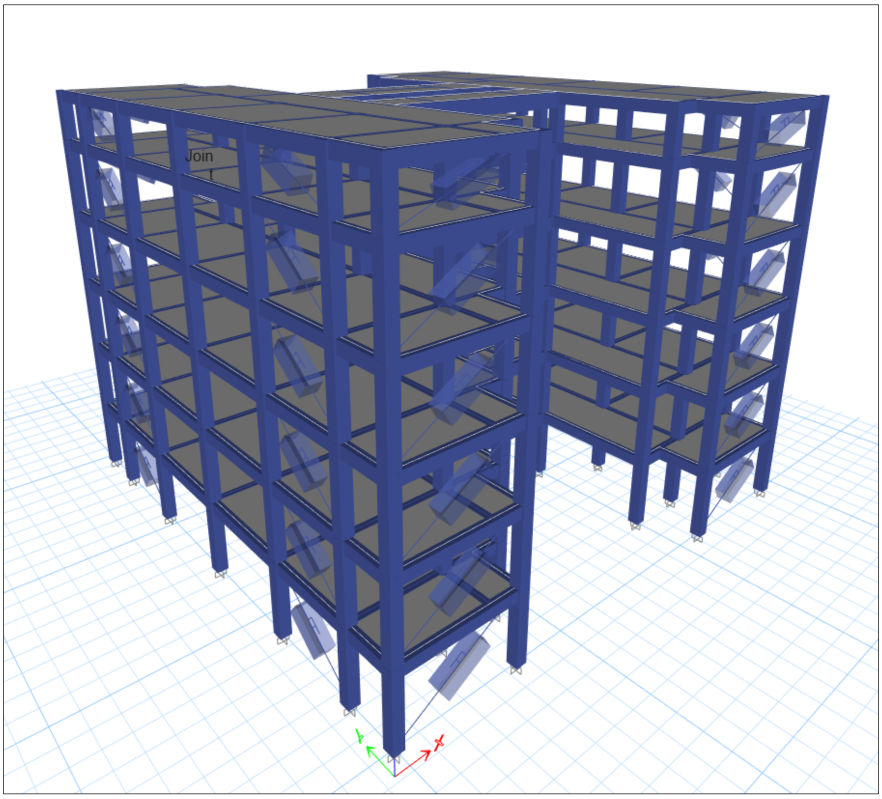


Figure 3.4: Model with 4 non-linear FVDs on the periphery of each story of the building in both x and y direction

3.5 Seismic Pounding

In this study the dampers designed have also been implemented in a seismic pounding study to determine the effectiveness of dampers in mitigating structural damage for pounding buildings. This portion of work was carried out in collaboration with another Final Year Project Group of NUST Institute of Civil Engineering Batch 2019-2023.

For the seismic pounding study, 3 hypothetical structures were designed using BCP 2021 representing the design spectrum of Islamabad. These structures were an 8-story structure, 6 story structure with same story heights, and 6 story structure with different story heights. Different cases were studied by placing these structures adjacent to each other for analysis:

- Case 01: 8 Story Structure adjacent to another 8 Story Structure with same story heights.

- Case 02: 8 Story Structure Adjacent to a 6 Story Structure with same story heights.
- Case 03: 6 Story Structure adjacent to another 6 Story Structure with different story heights
- Case 04: FVDs were attached to Case 2 to study the mitigation caused in the damage due to seismic pounding.

Gap element was defined using the link element property in ETABS and introduced into the model between two structures at all colliding nodes. Using the Non-Linear Time History Analysis (NLTHA) the set of performance results were extracted from the analysis for Pounding and No Pounding. These results were compared to study the significance of damage caused due to Pounding. FVDs were then introduced into the model and a NLTHA was carried out again to extract another set of performance results. The results were compared to study the mitigation in damage caused by the application of FVDs. Table 3.4 shows the parameters for modelling FVDs in the 8-story building. For the 6-story building the parameters already displayed in Table 3.3 are used.

Table 3.4: FVD coefficients for an 8-story building based on α and ξ_{add} [17]					
Ξ_{add} (%)	**Story Level**	**C_L (kN – s$^{\alpha}$/mm$^{\alpha}$)**	**C_{NL} (kN – s$^{\alpha}$/mm$^{\alpha}$)**		
		α = 1	**α = 0.7**	**α = 0.5**	**α = 0.3**
5	9	2	8	20	50
	8	2	9	24	64
	7	3	13	36	95
	6	3	13	36	101
	5	4	20	56	160
	4	5	26	76	206
	3	5	26	77	221
	2	5	26	77	227
	1	6	29	83	236
10	9	4	15	34	81
	8	5	21	53	134
	7	6	26	67	176
	6	6	26	69	182
	5	7	33	93	259
	4	9	44	126	360
	3	10	49	140	405
	2	10	49	140	405
	1	11	52	144	416
20	9	7	24	**54**	123
	8	9	35	**87**	213
	7	12	48	**121**	303
	6	13	54	**137**	350
	5	13	58	**158**	424
	4	19	87	**236**	645
	3	20	91	**241**	662
	2	20	91	**249**	678
	1	22	96	**257**	682
30	9	10	33	73	160
	8	15	55	132	313
	7	18	70	171	418
	6	19	75	188	467
	5	20	86	226	593
	4	29	124	327	855
	3	30	130	345	910
	2	31	135	358	947
	1	34	143	370	956

Where,

- ξadd = Supplemental Damping Ratio
- α = Velocity Power
- C_L and C_{NL} = FVDs Coefficients

CHAPTER 4: ANALYSIS AND RESULTS

In the final phase of our study, both linear and non-linear time history analyses were conducted to assess the building's performance under two conditions: with and without the inclusion of FVDs. The comparison of these analyses involved the examination of several key parameters. These key parameters have been discussed in this chapter.

4.1 Linear Analysis

Linear analysis is a simplified method in which we assume the structure behaves linearly under load. This means that the relationship between the load and the response of the structure is linear, and that the structure will return to its original shape after the load is removed.

To perform the linear analysis in ETABS, the following were defined: geometry of the building, material properties of the structural elements, and the support conditions. After which the seismic loads were inserted, and analysis was executed. The following parameters were extracted and the results for each have been discussed separately:

1. Time Period
2. Maximum Roof Acceleration
3. Maximum Base Shear
4. Maximum Roof Displacement
5. Drift Ratio
6. Overturning Moment

These parameters were assessed to gauge the building's behavior and structural response thereby offering valuable insights into the impact of FVDs on its seismic performance.

4.1.1 Time Period

Time period in seismic study of buildings is the time it takes for a building to complete one cycle of oscillation. It is a measure of the flexibility of a building and is influenced by the building's mass and stiffness. It is an important parameter in seismic analysis because it affects the response of the building to earthquake ground motions. Buildings with a longer time period are more flexible and will oscillate more slowly than buildings with a shorter time period. Taller buildings and buildings with more floors tend to have longer time periods, and such buildings are more susceptible to resonance, which can lead to excessive vibration and damage.

In our study, through the implementation of FVDs, we notice a decrease in the Time Period for both x and y axis. Because inclusion of dampers increases the damping ratio which facilitates faster dissipation of seismic energy and shorter oscillation periods thereby reducing the amplitude of vibrations. Dampers also help mitigate the effects of resonance. The results are presented in Table 4.1 and are shown in Figure 4.1.

Table 4.1: Linear Analysis of Time Period (With & Without FVDs)

Units: Seconds	X Axis	Y Axis
Without Dampers	0.743 seconds	0.745 seconds
With Dampers	0.453 seconds	0.518 seconds

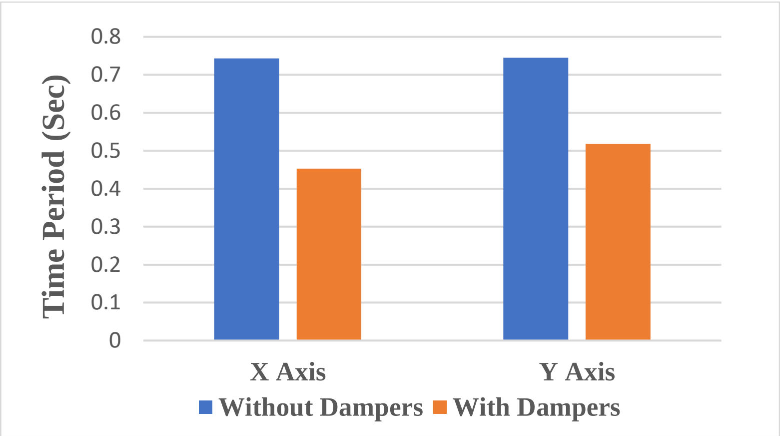


Figure 4.1: Comparison of Time Period as per Linear Analysis for our modelled building (With & Without FVDs)

4.1.2 Maximum Roof Acceleration

Maximum Roof Acceleration is the peak horizontal acceleration that is expected to occur at the roof level of a building during an earthquake. It is important in the design of earthquake-resistant buildings, as it determines the forces that the building must be able to withstand. The maximum roof acceleration that a building can withstand without collapse is known as its ultimate roof acceleration. In most seismic design codes, the maximum roof acceleration that a building must be designed to withstand is specified as a percentage of the peak ground acceleration (PGA).

In our study, through the implementation of FVDs, we notice a decrease in the Maximum Roof Acceleration for both x and y axis. The results are presented in Table 4.2 and are shown in Figure 4.2. This decrease is due to the damping of the structure vibrations.

Table 4.2: Linear Analysis of Maximum Roof Acceleration (With & Without FVDs)

	EQ 01 – RSN 341		**EQ 02 – RSN 1187**		**EQ -03 – RSN 1196**	
Units: mm/sec^2	X-Axis	Y-Axis	X-Axis	Y-Axis	X-Axis	Y-Axis
Without Dampers	30892	33551	35835	38919	26876	35417
With Dampers	26711	27295	29649	34118	23719	32753

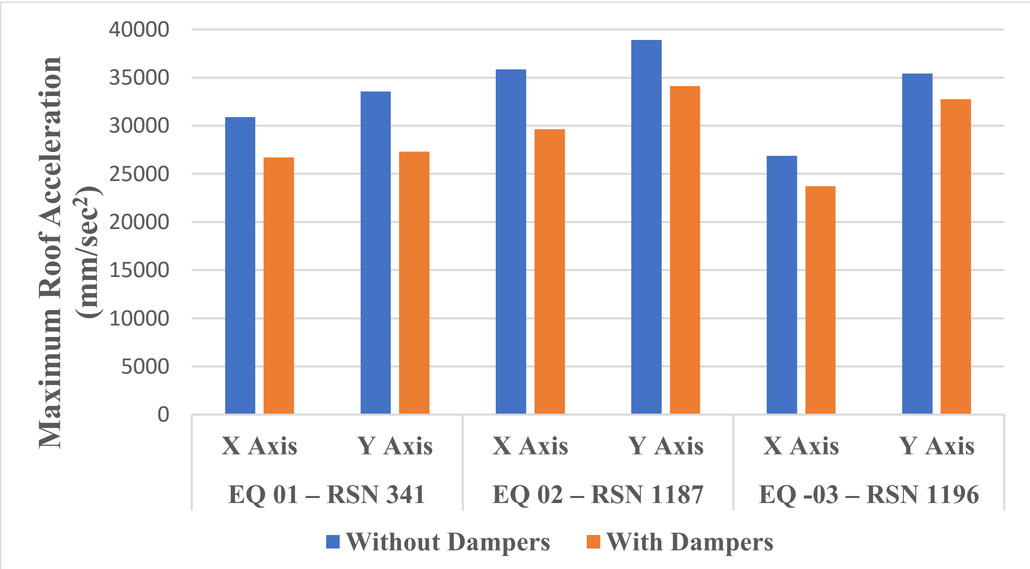


Figure 4.2: Comparison of Maximum Roof Acceleration as per Linear Analysis for our modelled building (With & Without FVDs)

4.1.3 Maximum Base Shear

Maximum base shear in the seismic study of buildings is the maximum lateral (horizontal) force that is expected to occur at the base of a building during an earthquake. For design of earthquake-resistant buildings, it determines the strength and stiffness requirements of the building's foundation and structural system. The maximum base shear that a building can withstand without collapse is known as its ultimate base shear. In most seismic design codes, the maximum base shear that a building must be designed to withstand is specified as a percentage of the weight of the building. This percentage is known as the base shear coefficient.

In our study, through the implementation of FVDs, we notice a decrease in the Maximum Base Shear for both x and y axis. This is because dampers dissipate seismic energy which helps reduce the overall seismic forces transmitted to the structure thereby reducing the peak lateral forces. Dampers also help mitigate the effects of resonance, preventing the structure from vibrating at its natural frequency which would have amplified the seismic forces experienced by the structure. The results are presented in Table 4.3 and are shown in Figure 4.3.

Table 4.3: Liner Analysis of Maximum Base Shear (With & Without FVDs)

	EQ 01 – RSN 341		**EQ 02 – RSN 1187**		**EQ -03 – RSN 1196**	
Units: kN	X-Axis	Y-Axis	X-Axis	Y-Axis	X-Axis	Y-Axis
Without Dampers	19271	17447	21391	21809	17113	20936
With Dampers	16067	15060	18638	17470	13978	15898

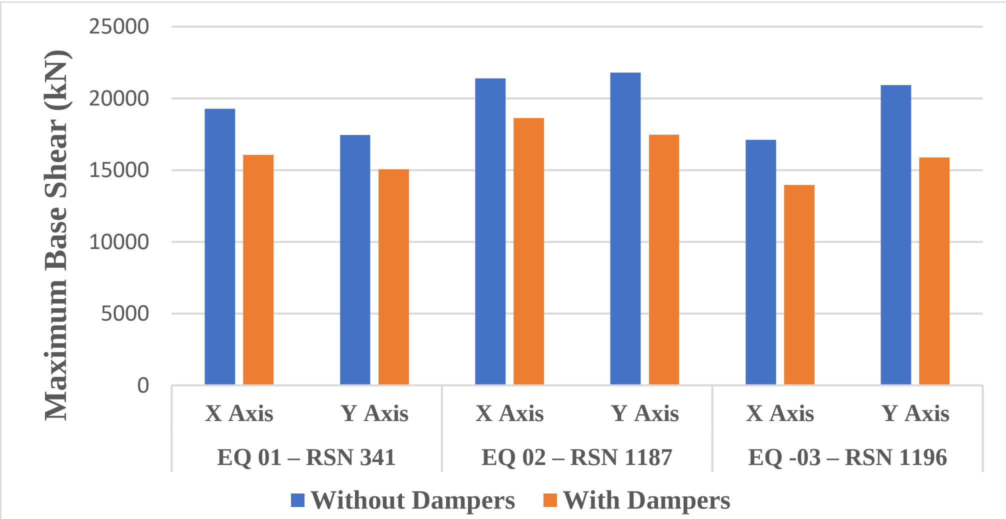


Figure 4.3: Comparison of Maximum Base Shear as per Linear Analysis for our modelled building (With & Without FVDs)

4.1.4 Maximum Roof Displacement

Maximum roof displacement in seismic study of buildings is the maximum horizontal displacement of the roof of a building relative to its base during an earthquake. It is typically measured in millimeters or inches. In general, taller and more flexible buildings will experience higher maximum roof displacements than shorter and stiffer buildings. The allowable maximum roof displacement for a building is typically specified in the local building code and it depends on the building's occupancy type and the acceptable level of risk. It is mostly used to determine the potential for damage to non-structural components, such as cladding, partitions, and ceilings.

In our study, through the implementation of FVDs, we notice a decrease in the Maximum Roof Displacement for both x and y axis because dampers reduce the amplitude of structure vibrations. This is due to the increased damping ratio, faster dissipation of energy and mitigation of resonance effect. The results are presented in Table 4.4 and are shown in Figure 4.4.

Table 4.4: Linear Analysis of Maximum Roof Displacement (With & Without FVDs)

	EQ 01 – RSN 341		**EQ 02 – RSN 1187**		**EQ -03 – RSN 1196**	
Units = mm	X-Axis	Y-Axis	X-Axis	Y-Axis	X-Axis	Y-Axis
Without Dampers	238	258	321	353	346	383
With Dampers	150	176	225	272	245	268

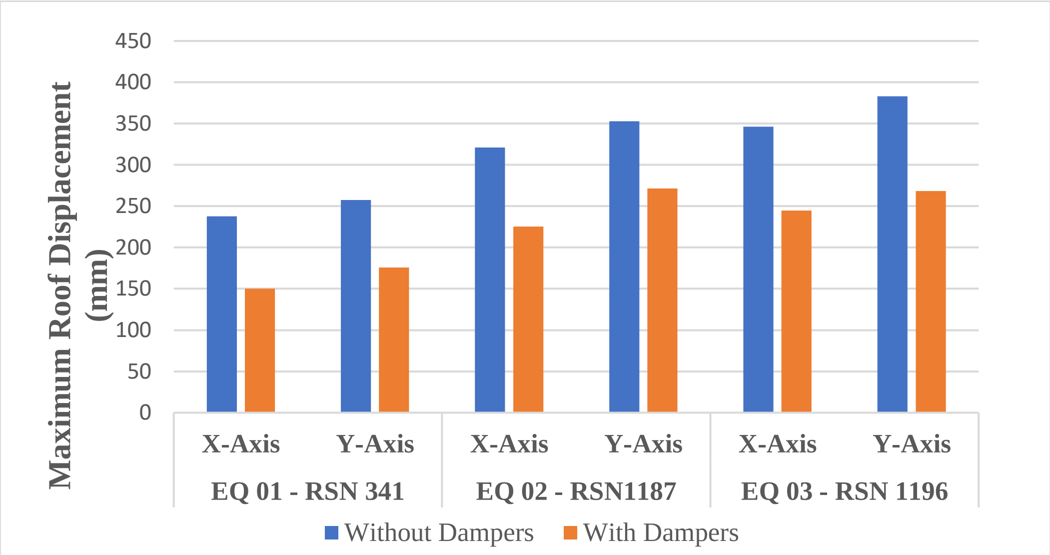


Figure 4.4: Comparison of Maximum Roof Displacement as per Linear Analysis for our modelled building (With & Without FVDs)

4.1.5 Drift Ratio

Drift ratio is the ratio of the relative displacement between two floors to the height of the lower floor. It is typically expressed as a percentage and is influenced by earthquakes as well as building characteristics. In general, taller and more flexible buildings will experience higher drift ratios than shorter and stiffer buildings. Buildings with a high fundamental period (i.e., natural period of vibration of the building) will also experience higher drift ratios. The allowable drift ratio for a building is typically specified in the local building code depending upon the building's occupancy type and acceptable level of risk.

In our study, through the implementation of FVDs, we notice a decrease in the Drift Ratio for both x and y axis. This is because by increasing the overall damping ratio of the structure, dampers facilitate faster dissipation of vibrational energy contributing to a controlled lateral response and a lower drift ratio. Additionally, dampers mitigate resonance effects and alter the natural frequency, preventing excessive lateral displacements.

The results are presented in Table 4.5, 4.6, 4.7 and corresponding graphs are shown in Figure 4.5, 4.6, 4.7 for each story and each earthquake separately.

Table 4.5: Linear Analysis of Drift Ratio (With & Without FVDs) – EQ 01 RSN341

	X Axis		Y Axis	
	Without Dampers	With Dampers	Without Dampers	With Dampers
Story 00	0	0	0	0
Story 01	0.4	0.21	0.8	0.36
Story 02	0.7	0.49	1.24	0.82
Story 03	0.91	0.67	1.46	1.04
Story 04	1.03	0.76	1.65	1.14
Story 05	1.07	0.79	1.55	1.01
Story 06	0.85	0.5	1.12	0.68

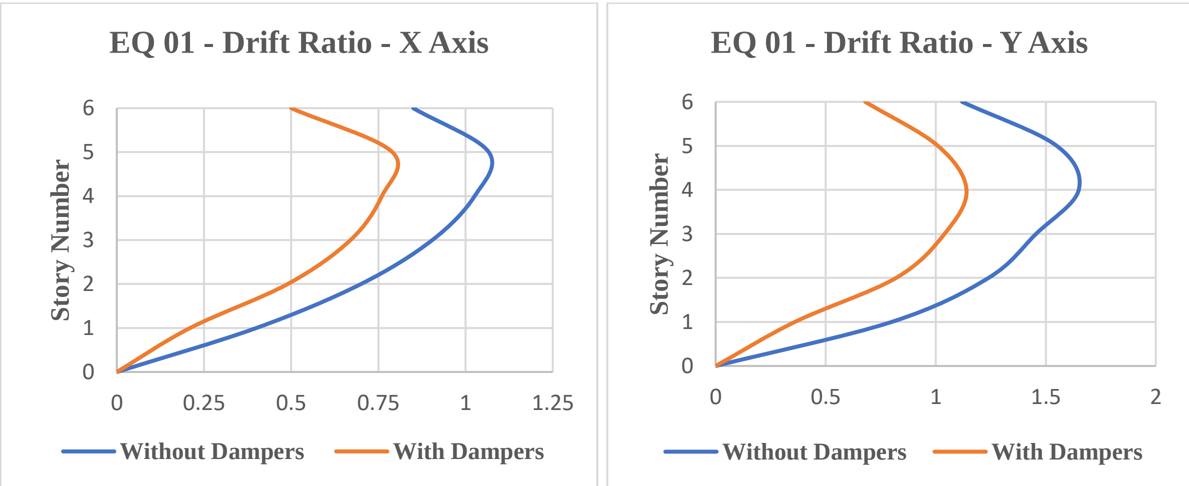
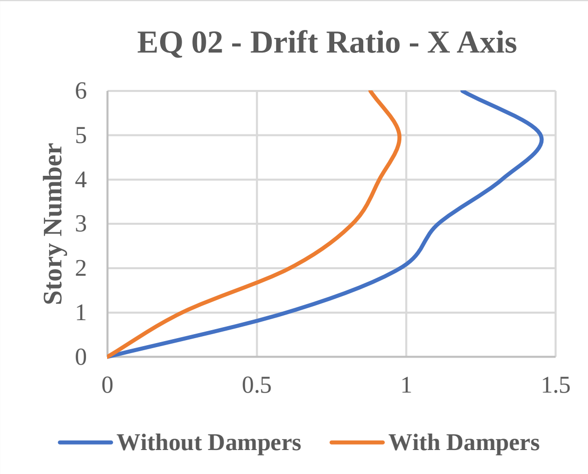


Figure 4.5: Comparison of Drift Ratio as per Linear Analysis for our modelled building (With & Without FVDs) – EQ 01 RSN341

Table 4.6: Linear Analysis of Drift Ratio (With & Without FVDs) – EQ 02 RSN1187				
	X Axis		Y Axis	
	Without Dampers	With Dampers	Without Dampers	With Dampers
Story 00	0	0	0	0
Story 01	0.6	0.25	1.88	0.88
Story 02	0.98	0.61	2.4	1.75
Story 03	1.11	0.82	2.46	1.93
Story 04	1.32	0.91	1.78	1.5
Story 05	1.45	0.98	1.95	1.68
Story 06	1.19	0.88	1.6	1.1



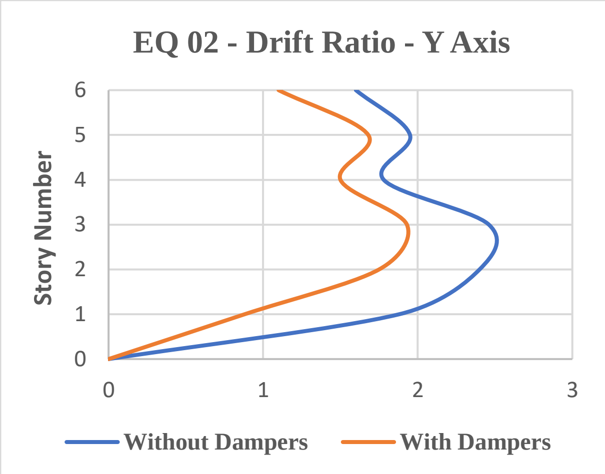


Figure 4.6: Comparison of Drift Ratio as per Linear Analysis for our modelled building (With & Without FVDs) – EQ 02 RSN1187

Table 4.7: Linear Analysis of Drift Ratio (With & Without FVDs) – EQ 03 RSN1196				
	X Axis		Y Axis	
	Without Dampers	With Dampers	Without Dampers	With Dampers
Story 00	0	0	0	0
Story 01	0.62	0.35	0.98	0.56
Story 02	1.35	0.95	1.8	1.24
Story 03	1.57	1.16	2.05	1.52
Story 04	1.68	1.19	1.6	1.45
Story 05	1.36	0.93	2.2	1.61
Story 06	1.21	0.77	1.48	1.15

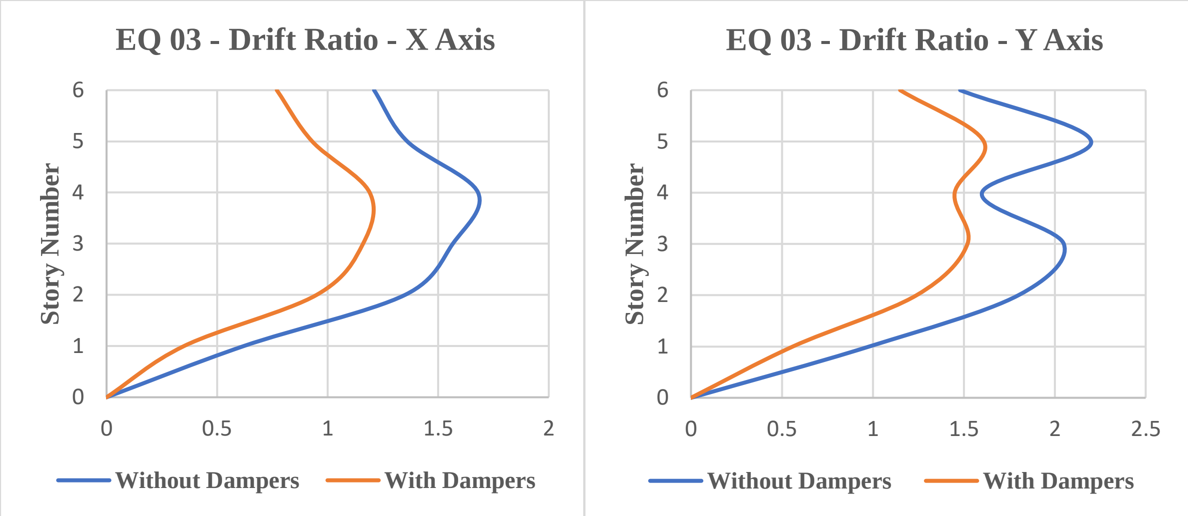


Figure 4.7: Comparison of Drift Ratio as per Linear Analysis for our modelled building (With & Without FVDs) – EQ 03 RSN1196

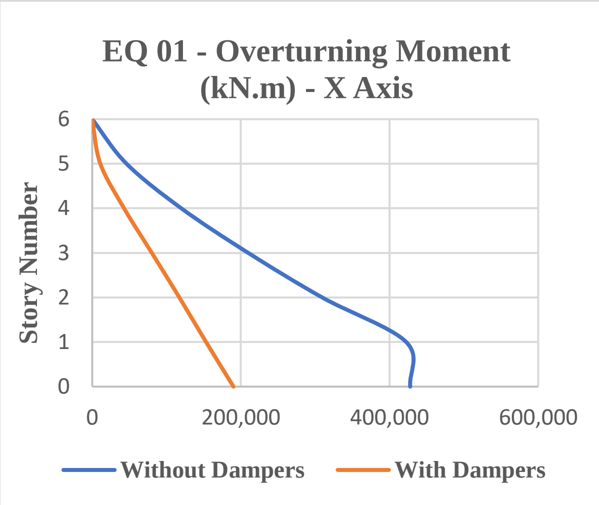
4.1.6 Overturning Moment

The overturning moment of a building is the tendency of the building to rotate about its base during an earthquake. It is calculated by multiplying the building's weight by the distance from the center of gravity of the building to the edge of the foundation. It is influenced by building height, building weight, distribution of weight, soil conditions, and earthquake magnitude. The overturning moment is a critical factor in the design of earthquake-resistant buildings, as it determines the strength and stiffness requirements of the building's foundation and structural system.

If the overturning moment exceeds the resisting moment of the building, the building will overturn. Important to note is that overturning moment is not a constant value throughout the building, it is highest at the base of the building and decreases with height.

By the implementation of dampers, we notice a decrease in the Overturning Moment as the inclusion of dampers decreases the displacement of the structure as well as the seismic forces transmitted to it. The results are shown in Table 4.8, 4.9, 4.10 and corresponding graphs are shown in Figure 4.8, 4.9, 4.10 for each story and each earthquake.

Table 4.8: Linear Analysis of Overturning Moment (With & Without FVDs) – EQ 01 RSN341				
	X Axis		Y Axis	
Units: kN.m	Without Dampers	With Dampers	Without Dampers	With Dampers
Story 00	427,830	190,054	498,881	203,884
Story 01	422,447	153,190	493,247	167,762
Story 02	309,453	117,243	371,442	129,222
Story 03	209,905	80,189	281,689	86,349
Story 04	119,839	42,811	210,984	44,475
Story 05	46,167	10,906	137,650	11,240
Story 06	0	0	0	0



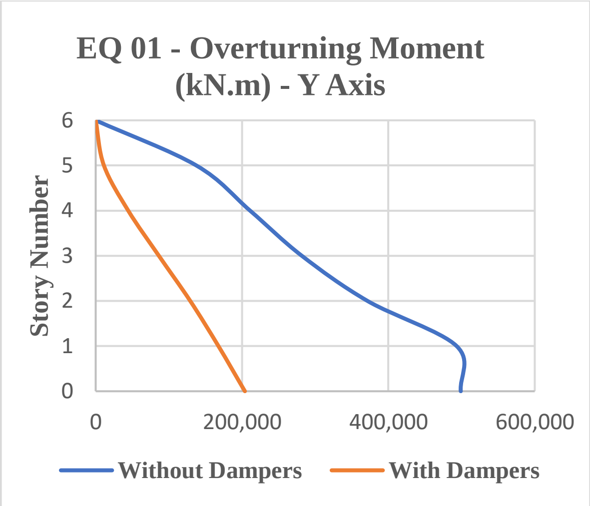


Figure 4.8: Comparison of Overturning Moment as per Linear Analysis for our modelled building (With & Without FVDs) – EQ 01 RSN341

Table 4.9: Comparison of Overturning Moment (With & Without FVDs) – EQ 02 RSN1187				
	X Axis		Y Axis	
Units: kN.m	Without Dampers	With Dampers	Without Dampers	With Dampers
Story 00	543,723	260,089	389,570	247,496
Story 01	516,038	213,185	362,331	231,425
Story 02	377,918	162,782	309,523	179,288
Story 03	265,009	112,406	240,950	120,965
Story 04	155,019	61,245	157,769	63,442
Story 05	61,185	15,940	67,236	16,105
Story 06	0	0	0	0

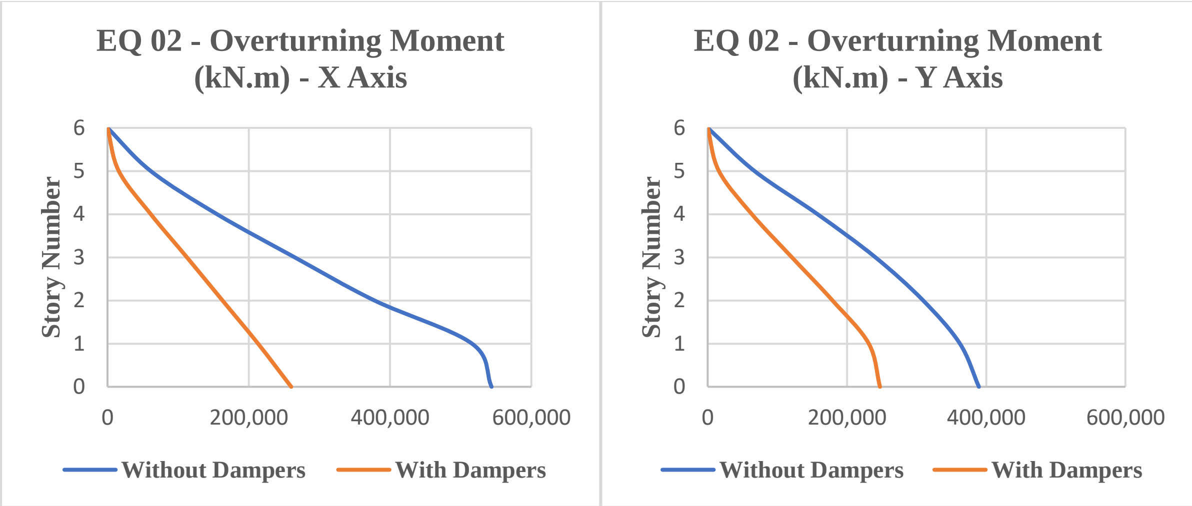


Figure 4.9: Comparison of Overturning Moment as per Linear Analysis for our modelled building (With & Without FVDs) – EQ 02 RSN1187

Table 4.10: Linear Analysis of Overturning Moment (With & Without FVDs) – EQ 03 RSN1196				
	X Axis		Y Axis	
Units: kN.m	Without Dampers	With Dampers	Without Dampers	With Dampers
Story 00	583,944	281,973	635,616	302,283
Story 01	547,076	243,810	549,644	267,206
Story 02	431,465	199,764	463,816	223,088
Story 03	296,882	144,068	304,940	158,517
Story 04	213,590	80,734	249,122	84,151
Story 05	82,930	16,129	171,610	21,813
Story 06	0	0	0	0

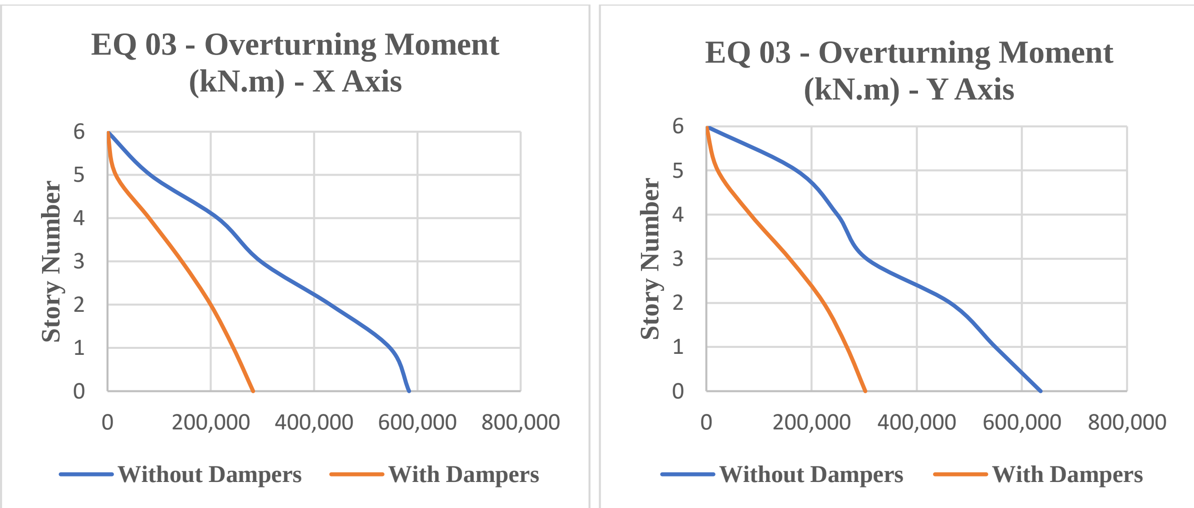


Figure 4.10: Comparison of Overturning Moment as per Linear Analysis for our modelled building (With & Without FVDs) – EQ 03 RSN1196

4.2 Non-Linear Analysis

Although, linear analysis is a powerful tool that can be used to design safe and efficient buildings. But it is important to note that linear analysis is a simplified method, and it does not always accurately predict the behavior of buildings under load.

Nonlinear analysis more accurately and realistically models the behavior of buildings, due to which it offers several advantages over linear analysis, including [50], [51]:

- **More accurate representation of structural behavior**: Nonlinear analysis takes into account the nonlinear behavior of materials and structural elements, such as yielding, buckling, and cracking. This allows for a more accurate prediction of the building's response to loads.
- **Better understanding of structural capacity:** Nonlinear analysis can be used to assess the building's capacity to resist various loads, including earthquakes, windstorms, and explosions. This information can be used to design more robust and resilient buildings.
- **Identification of weak links:** Nonlinear analysis can be used to identify the weakest links in the building structure. This information can be used to prioritize strengthening and retrofitting efforts.
- **Assessment of damage and collapse mechanisms:** Nonlinear analysis can be used to assess the potential damage to a building under various load scenarios, and to identify the collapse mechanisms that may lead to failure.

Linear analysis is still widely used in engineering practice, but nonlinear analysis is becoming increasingly common, especially for complex and high-risk structures. The steps for non-linear analysis are mostly identical to linear analysis, just that for non-linear analysis non-linear properties are assigned to the structure and structure components.

For the non-linear analysis, the following parameters were extracted:

1. Acceleration Time History
2. Base Shear Time History
3. Displacement Time History
4. Energy Dissipation

For non-linear analysis, the results for EQ 01 - RSN341 are presented as the representative for all three earthquakes as they all displayed similar results.

4.2.1 Acceleration Time History

Acceleration time history of a building is a graphical representation of the acceleration of the building at a specific point in time during an earthquake. It is generated through time history analysis, using recorded earthquake ground motion record as input to simulate the response of the building to the earthquake. Acceleration time history is used to assess the seismic performance of the building and to identify any areas of the building that are particularly vulnerable to damage. It can also be used in the design of energy dissipation devices to protect the building from earthquake damage.

The acceleration time history of the top story of structure for EQ 01 – RSN 341 is shown in Figure 4.11. FVDs effectively reduced the peak acceleration time history owing to the increased damping ratio which facilities lower displacements, reduced seismic forces and mitigation of resonance effect.

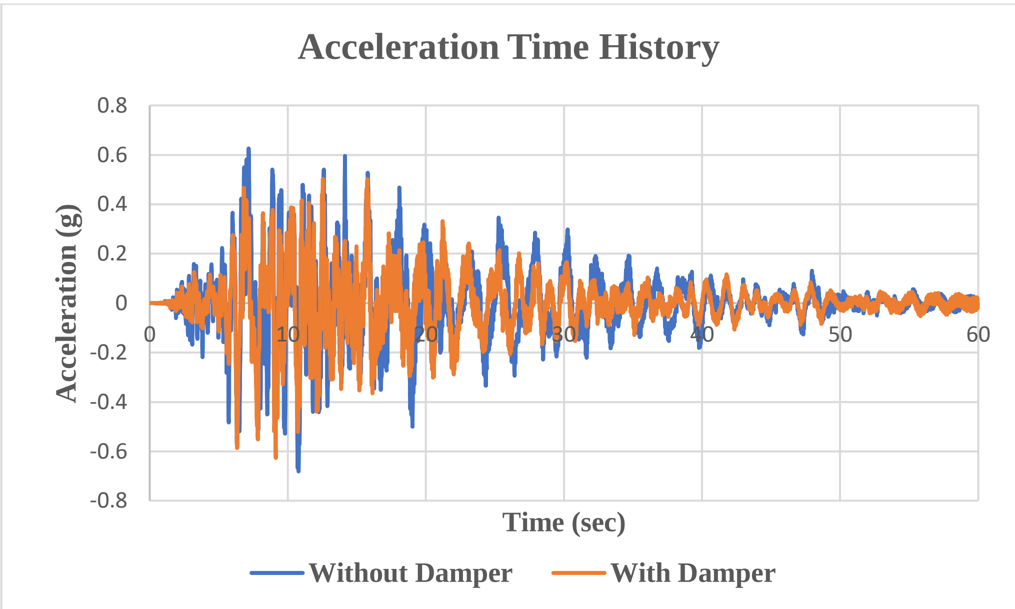


Figure 4.11: Acceleration Time History Response (With & Without FVDs)

4.2.2 Base Shear Time History

Base Shear Time History provides a dynamic and graphical representation of the lateral forces acting on a structure's base over time during an earthquake. It is also generated through time history analysis and is a key parameter in guiding the design process as it accounts for factors such as building mass, stiffness, and the characteristics of the underlying soil. It helps identify critical moments when the building experiences peak lateral forces, aiding in the design of structural elements to withstand these maximum loads.

The base shear time history of the structure for EQ 01 – RSN 341 is shown in Figure 4.12**.** We observe a decrease in the peak shear by the inclusion of dampers owing to their damping effect which reduces the seismic forces transmitted to the structure.

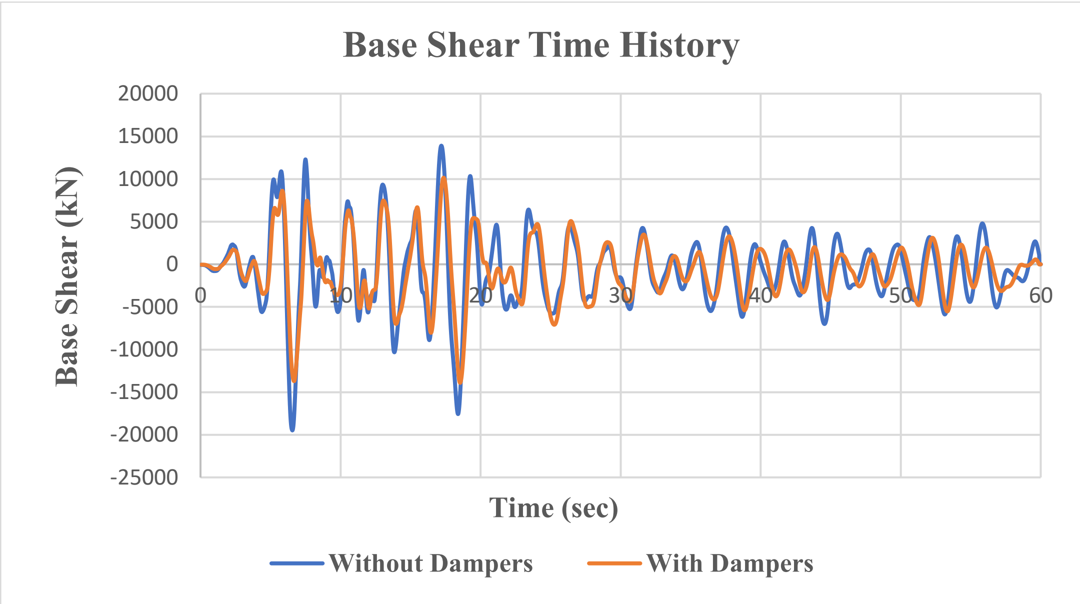


Figure 4.12: Base Shear Time History Response (With & Without FVDs)

4.2.3 Displacement Time History

Displacement Time History of a building is a graphic representation of the displacement of the building at various points during seismic events, and unlike static analysis, which assumes a constant lateral force, it allows us to accurately capture the dynamic response of a building. It is influenced by building characteristics, soil conditions, and the intensity of seismic waves. It is particularly used to assess the maximum displacements that structures may experience during an earthquake. This information is fundamental for designing resilient buildings capable of accommodating significant deformations without compromising safety.

The displacement time history of the top story of structure for EQ 01 – RSN 341 is shown in Figure 4.13**.** FVDs effectively reduced the peak displacement owing to their damping effect.

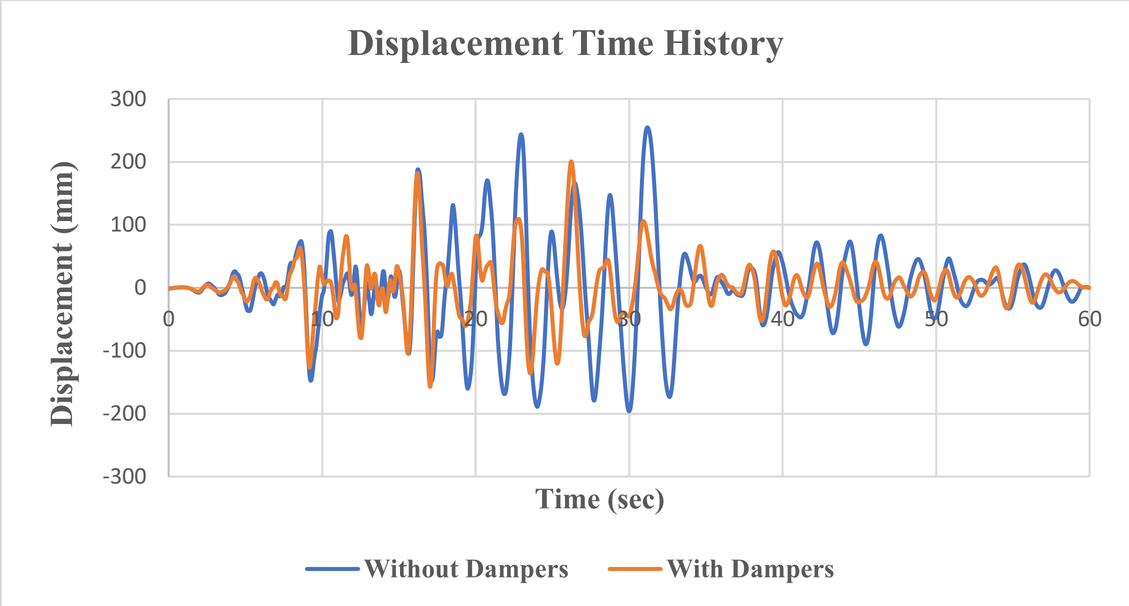


Figure 4.13: Displacement Time History Response (With & Without FVDs)

4.2.4 Energy Dissipation

By the addition of FVDs to the structure, we observe that about 48% of the energy was dissipated by the FVDs. Because of this the structure stability was increased as the structural elements, i.e. shear walls, beams and columns remain safe from yielding as when FVDs are not present, energy is dissipated through inelastic behavior of shear walls, beams and columns. The energy dissipated by the addition of dampers in the structure for EQ 01 - RSN 341 is shown in Figure 4.14.

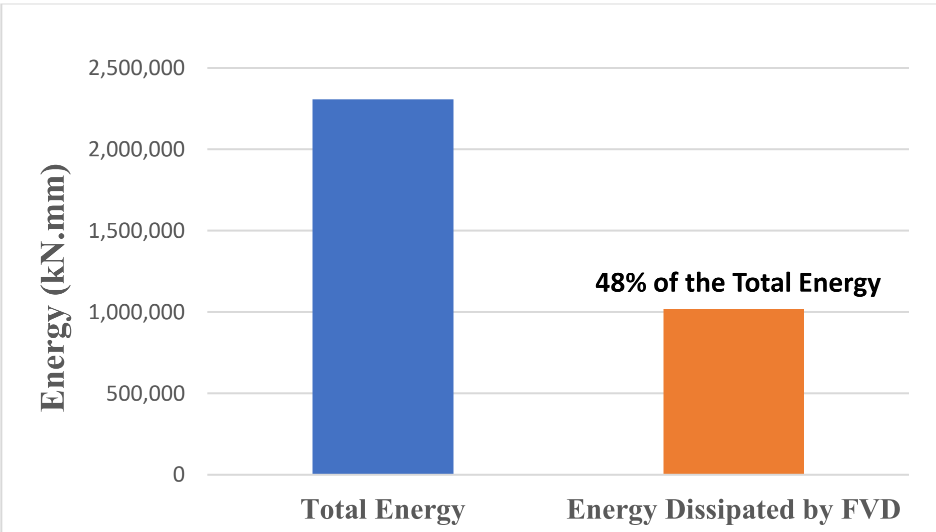
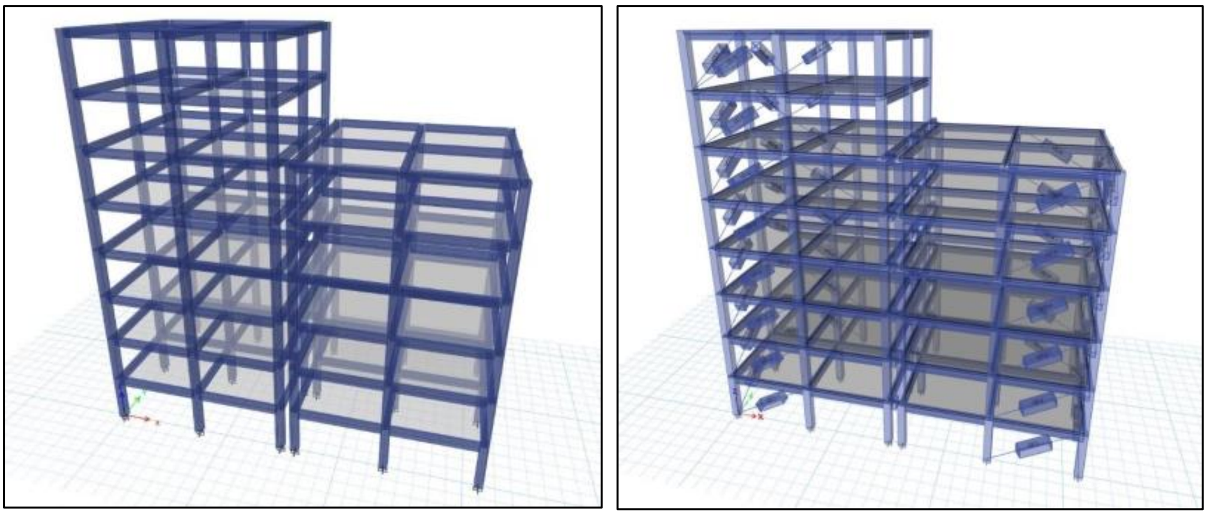


Figure 4.14: Energy dissipated by FVD

4.3 Seismic Pounding Analysis

In this study the dampers designed have also been implemented in a seismic pounding study to determine the effectiveness of dampers in mitigating structural damage for pounding buildings. This portion of work was carried out in collaboration with another Final Year Project Group of NUST Institute of Civil Engineering Batch 2019-2023. The results of the analysis are discussed in this section.

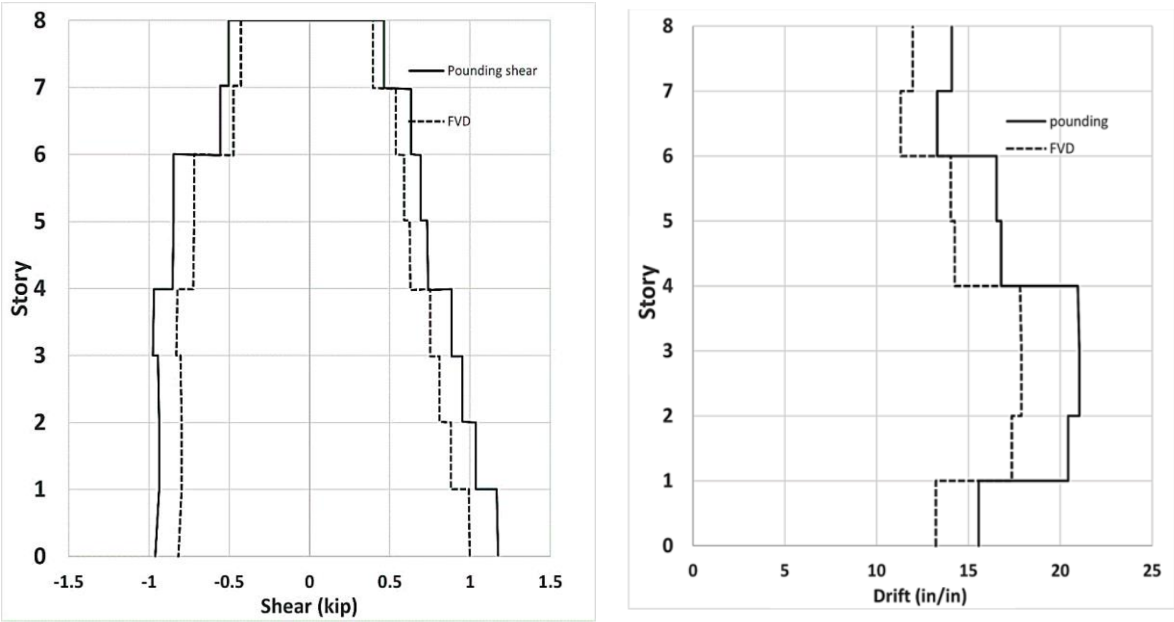
The analysis considered an eight-story structure adjacent to a six-story structure. The story heights of both the structures were kept equal i.e., 11 feet. Gap element was introduced, and it was connected at story-to-story nodes. Geometric nonlinearity and Material Nonlinearity were the two types of nonlinearities considered for the models. Afterwards, Non-Linear Time Analysis was conducted initially without dampers, and afterwards with dampers and the results are compared to determine the effectiveness of FVDs.



(a) (b)

Figure: 4.15: Seismic Pounding - 8 Story Structure Adjacent to a 6 Story Structure with same story heights - 11ft (a) Without Dampers (b) With Dampers

Following graphs display the results of the analysis, dotted lines represent FVDs case whereas the solid line represents pounding case.



(a) (b)

Figure 4.16: Seismic Pounding (a) Comparison of Story Shear with and without dampers (b) Comparison of Story Drift with and without dampers

Figure 4.16(a) indicates that a significant reduction has been achieved in shear forces by the application of FVDs, a reduction in global shear responses means the structures will undergo significantly less damage. The inter story drift ratios have also been reduced significantly by the application of FVD as shown in Figure 4.16(b). This finding is important, as it signifies the need for retrofitting of adjacent structures where gap provisions are not followed as per the code. Failure to address this issue may result in severe damage during a powerful earthquake event, posing life-threatening risks if neglected. Overall, we see that the FVDs reduced the global responses of the structure by up to 15%.

CHAPTER 5: CONCLUSION AND DISCUSSION

5.1 Discussion on Results

Our study focused on understanding the implementation of FVDs and assessing their efficiency in enhancing the seismic resilience of RC buildings. We examined various placements and orientations of FVDs, determining the most optimal orientation. We analyzed the effectiveness of FVD in terms of Building Time Period, Acceleration, Displacement, Overturning Moment, Shear and Drift Ratio. We also expanded our findings for a building case undergoing seismic pounding. We observe that the incorporation of FVDs played a crucial role in fortifying the building against seismic hazards.

The findings from our study lead us to the following conclusions:

1. Compared to alternatives like lateral bracing systems and seismic retrofitting jacketing, FVDs stand out for their easy installation, low maintenance, and long service life. Notably, FVDs seamlessly integrate into a building's existing structure without substantial changes to appearance or functionality, making them an efficient retrofitting method.
2. The introduction of non-linear FVDs in the seismic retrofitting of the examined building has substantially enhanced its performance regarding displacement, shear, inter-story drift, overturning and acceleration response when subjected to seismic loads. We observed a 40% reduction in displacement, 25% reduction in shear, and 15% reduction in acceleration,
3. The installation of the FVDs at the periphery of the building is more beneficial as it yields more favorable results.
4. The structural time period of the building equipped with non-linear FVDs decreased about 30% as compared to the building lacking such dampers. This reduction can be attributed to the heightened stiffness of the structure.
5. FVDs in the retrofitted structure dissipate approximately 48% of the energy under seismic loading conditions. This keeps the structural elements, including columns, beams, and shear walls more resilient, avoiding inelastic yielding.
6. Our findings were expanded for a seismic pounding case of buildings. Normally pounding can increase global shear responses & drift ratios up to 50%. We observe that

FVD’s reduced the global responses of the structure by up to 15% owing to reduced shear and drift ratio.

In conclusion, the findings of this study propose that enhancing existing buildings with non-linear FVDs is a promising strategy that significantly enhances the seismic resilience of structures in earthquake-prone regions.

5.2 Future Recommendations

For future studies it is recommended that the retrofitting of existing RC structures with non-linear FVDs coupled with bracing and other fortification techniques be investigated. Additional analysis for other modelled buildings can also be carried out to further analyze the effectiveness of FVDs. Moreover, the modelled buildings can be projected onto other regions to analyze buildings under multiple seismic conditions.

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