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Analytical Investigation of The Performance of Fluid Viscous Damper and Lead Rubber Bearing Isolator on A Multi-Storey Building

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Abstract

Earthquakes are devastating natural events that can cause substantial structural damage, often resulting in collapses due to inadequate seismic design. This study investigates the effectiveness of two seismic protection systems: fluid viscous damper (FVD) and lead rubber bearing (LRB) isolation, in improving the seismic performance of a structure. The initial research did not include any base isolator or link damper for earthquake protection. The results were then compared to a similar investigation of the same structure using FVD and LRB isolation. Significant differences in structural behavior were observed, with both systems demonstrating improved performance in mitigating seismic forces. The findings highlight the importance of incorporating advanced damping mechanisms, such as FVD and LRB, in building design to enhance earthquake resilience in prone regions. This study underscores the critical need for integrating such seismic protection systems to reduce structural damage and improve safety during earthquakes.

Keywords

Fluid viscous damper, base isolator, seismic performance, response spectrum analysis, earthquake protection

INTRODUCTION

Earthquakes are natural disasters triggered by the release of stress accumulated in the Earth's lithosphere due to the collision between tectonic plates. When the stress surpasses a certain threshold, the lithosphere fractures or shifts, leading to seismic activity. Structures must be engineered to withstand seismic forces by dispersing the kinetic energy caused by ground motion in the context of earthquake engineering. The primary objective of energy passive dissipators is to enhance structural damping, reduce demand on members, and minimize damage without external power [1]. In ductile structures, energy dissipation primarily occurs within designated fuse elements in beams rather than at beam-column connections, which are designed to remain intact to prevent brittle failure [2]. Recent studies, however, suggest that these fuse elements might not hold up well in situations involving cyclic loads, like those that occur during an earthquake. Increasing the height and complexity of structures is becoming commonplace in today's environment. However, these structures must be able to sustain a wide range of external loads, especially those brought on by wind and earthquakes. When structures are subjected to dynamic forces, they experience vibrations that, if not properly controlled, could lead to damage or even collapse [3]. Seismic performances of transfer storeys, i.e., storey drifts, mechanical elastoplasticity, have to be paid more attention to regarding their complications in stress distributions and deformations [4][5]. Under the actions of earthquakes, high-rise building structures with podium buildings suffered from collapse failure or severe damage on the bottom and transfer storeys [6]. A base isolation system isolates the base from the trembling ground by introducing some kind of support to prevent the base from vibrating during an earthquake. Seismic base isolation or base isolation system are other names for base isolation [7]. Also, improvement of seismic capacity could be achieved using fluid viscous dampers, concentrating mainly on their nonlinear behaviour [1].

A. Base Isolator

Base isolation offers design flexibility as it allows the structure to oscillate like a rigid body above the isolator, enabling modifications to the isolation system alone to meet new seismic requirements [7]. When the stress surpasses a certain thresh-old, the lithosphere fractures or shifts, leading to seismic activity. Structures must be engineered to withstand seismic forces by dispersing the kinetic energy caused by ground motion in the context of earthquake engineering. Base Isolation is a passive energy dissipation technique used to design earthquake-resistant structures. Controlling the flow of energy from the foundation to upper levels is beneficial [6]. Rubber and friction bearings are the two most prevalent types of bearings. Rubber and frictional isolators have many subtypes based on their materials and functionality. The usability of an isolator depends on its flexibility and energy dissipation capacity. The isolator should be a single device capable of extending the structure's natural time period

Figure 1 The seismic dampening widgets (Base Isolators) under the Utah State Capital building (Mike Renlund, 2008)

while also reducing its responsiveness [8]. Lead rubber bearings, introduced in the 1970s, provide superior horizontal flexibility. The performance of a structure during an earthquake is determined by the type and characteristics of base isolation. Proper modelling is necessary to understand the non-linear behaviour of the isolator and the force-displacement relationship for a typical LRB is nonlinear [6].

B. Fluid Viscous Damper (FVD)

In structural engineering, a Fluid Viscous Damper (FVD) is a device specifically designed to dissipate energy and reduce vibrations or movements in structures caused by dynamic forces such as wind or earthquakes. These dampers are widely used in seismic design to improve the performance of buildings and bridges during earthquakes. By converting kinetic energy into heat through the viscous flow of fluid inside the damper, FVDs effectively mitigate structural responses. Research indicates that incorporating FVDs can significantly reduce inter-story drifts, thereby enhancing safety and functionality during seismic events [9]. Additionally, studies conducted by [10] and [8] highlight the critical role of FVDs in minimizing structural damage by increasing damping ratios and controlling lateral displacements. The addition of fluid viscous dampers to a structure can provide damping as high as 30% of critical, and sometimes even more. It is well recognized that the combination of a structure's strength, flexibility, and deformability causes it to naturally absorb and release energy from external loads. By focusing primarily on their nonlinear behaviour, fluid viscous dampers could be used to increase this capacity [11]. This provides a significant decrease in earthquake excitation. The addition of fluid dampers to a structure can reduce horizontal floor accelerations and lateral deformations by 50% and sometimes more [12].

BACKGROUND STUDY

The study compares the seismic response of a fixed-base building without dampers to a projected design that includes a fluid viscous damper (FVD) and lead rubber bearing (LRB) isolator. The study focuses on factors such as storey drift, storey shear, and mode periods under dynamic loading, using seismic analysis to evaluate the performance of RC buildings in high seismic zones.

Numerous researchers have conducted significant studies on the performance of FVDs and LRBs, with extensive findings highlighted throughout the literature. Etaldi et al. [12] investigated the torsional behaviour of asymmetric buildings with and without isolation devices. The study focused on three- and eight-story steel structures, using time history analysis and data from the Etabs, El Centro, and Bam earthquakes. The results showed that the use of isolation devices greatly reduced torsion in structures. Additionally, stiffening the flexible edge of the isolation system and the superstructure reduced torsional impacts. However, the isolation system's efficiency in minimizing torsion decreased as building eccentricity increased [12]. In our study, this behavior was observed in models with and without LRBs, where structures with LRBs exhibited reduced torsional effects.

In their 2013 study, Santhosh et al. [13] developed a lead plug rubber bearing (LRB) isolator specifically for a structure. They began by tabulating the LRB’s mechanical parameters, which were then utilized to study the building’s sensitivity to seismic activity. A response spectrum analysis was performed, which revealed that the LRB’s properties were quite effective. The study modelled a six-story building and compared the results to those of a regular construction and one fitted with the LRB isolation technology. The results showed that employing LRBs can improve the seismic performance of buildings [11].

Figure 2 Fluid viscous damper system in a building (Taylor devices inc. annual report, 2024)

Mujeeb et al. [14] used ETABS software to examine the seismic performance of a G+10 storey RCC building by comparing models with and without Fluid Viscous Dampers (FVDs). In accordance with IS standards, the study focused on assessing the structure's response using push-over and time history analyses in seismic zone IV. FVDs were suggested as a way to manage displacements, improve structural stiffness, and lower seismic energy. To maximize performance, the study also investigated the impact of positioning FVDs at various points across the structure. In our study, the placement of FVDs and LRBs was carefully selected based on structural response criteria. The FVDs were positioned at beam-column joints, while the LRBs were placed at base, to optimize damping efficiency and base isolation effectiveness.

For an in-depth performance analysis, two types of analysis were performed: static analysis and dynamic response spectrum analysis. This ensures consistency in evaluating the structure's behavior under seismic loading.

A. Design of Lead Base Isolator for Model NO: 3

The analysis involved using a lead rubber-bearing isolator as the type of base isolator. The properties of the isolator were determined through its design, as outlined below. Lateral Load for Response Spectrum Analysis (according to Bangladesh National Building Code (BNBC), 2020).

Seismic Force–Resisting System: dual systems: special moment frames capable of resisting at least 25% of prescribed seismic forces (with bracing or shear wall).
Seismic Zone Co Efficient: 0.36.
The Maximum Base Reaction: 3078 KN (from the analysis).
Design Time Period TD=2.5 sec (Assumed)

Design Displacement (D_D)

$$D_D = \frac{g}{4\pi^2} \times \frac{C_{VD} T_D}{B_D} \qquad (1)$$

$$= \frac{9.81}{4\pi^2} \times \frac{0.64 \times 2.5}{1} = 0.397m$$

Effective stiffness (K_{eff})

$$\mathrm{K_{eff}} = \frac{\mathrm{W}}{\mathrm{g}} \times \left(\frac{2\pi}{\mathrm{T_D}}\right)^2 \qquad (2)$$

Energy dissipated per cycle (W_D)

$$W_D = 2\pi K_{\mathrm{eff}} D_D^2 \beta_{\mathrm{eff}} \qquad (3)$$

$$= 2\pi \times 1981.89 \times 0.397^2 \times 0.05 = 98.13\mathrm{kN-m}$$

Force at design displacement or characteristic strength (Q)

$$Q = \frac{W_D}{4D_D} \qquad (4)$$

$$= \frac{98.12}{4 \times 0.397} = 61.78\ \mathrm{kN}$$

Stiffness in rubber (K_2)

$$\mathrm{K_2} = \mathrm{K_{eff}} - \frac{\mathrm{Q}}{\mathrm{D_D}} \quad [0.1 = \mathrm{K2/K1}] \qquad (5)$$

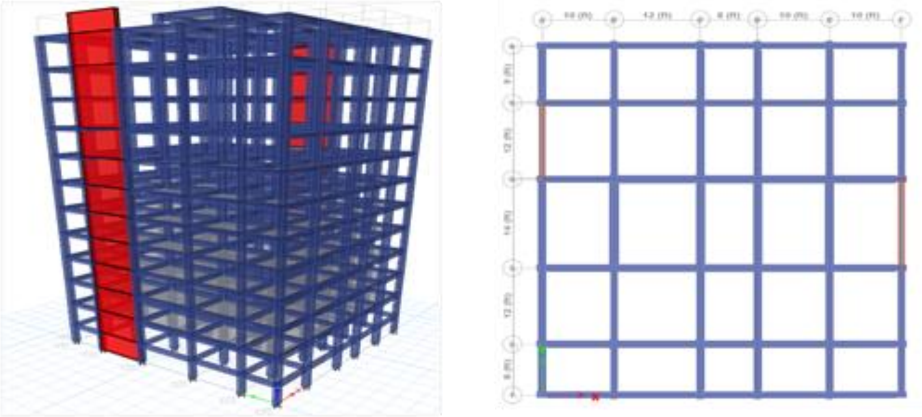

Figure 3 View of the model without damper (3D, Plan View)

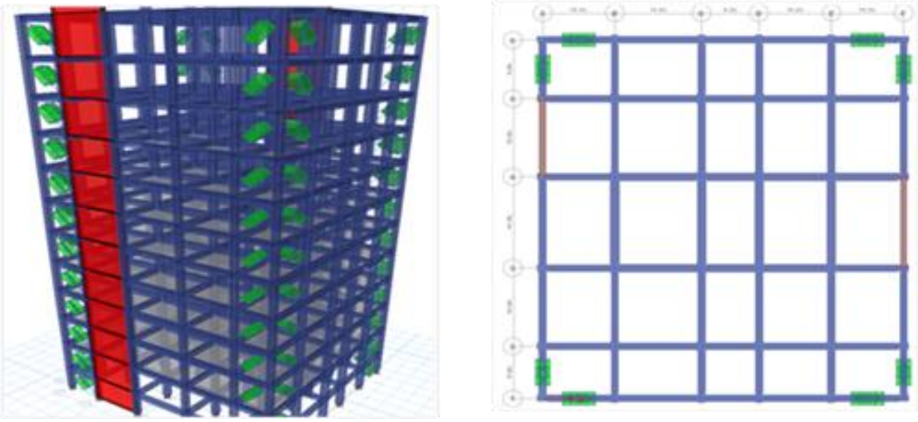

Figure 4 Fluid Viscous Damper (FVD) installed in the model (3D, Plan View)

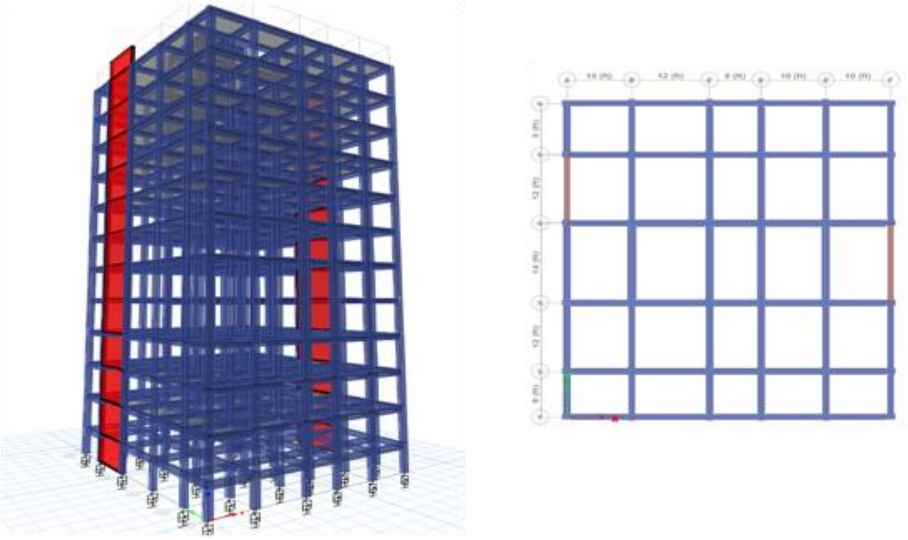

Figure 5 Lead Rubber Bearing Isolator installed in model (Plan, elevation view)

$$= 1981.89 - \frac{61.78}{0.397} = 1826.27\ kn/m$$

Where, $\frac{Q}{D_D}$ is the stiffness of lead core

Yield Displacement (D_Y)

$$D_Y = \frac{Q}{K_1 - K_2} \tag{6}$$

$$= \frac{Q}{10K_2 - K_2} = \frac{61.78}{9 \times 1826.27} = 0.00375\ m$$

Recalculation of Q to Q_R

$$Q_R = \frac{W_D}{4 \times (D_D - D_Y)} \tag{7}$$

$$= \frac{98.12}{4 \times (0.397 - .00375)} = 62.377\ kN$$

Calculating the lead plug's diameter and area lead has a yield strength of about 10 MPa, hence the required lead plug area is

$$A_{PB} = \frac{Q_R}{10 \times 10^3} \tag{8}$$

$$= \frac{62.377}{10 \times 10^3} = .00623\ m^2$$

Diameter of lead plug

$$d = \sqrt{0.00623 \times \frac{4}{\pi}} \tag{9}$$

$$= .0891m = 89.118\ mm$$

Revising Rubber stiffness K_{eff} to $K_{eff(R)}$ (after revising Q to Q_R)

$$K_{eff}(R) = K_{eff} - \frac{Q_R}{D_D} \tag{10}$$

$$= 1981.89 - \frac{62.377}{0.397} = 1824.76\ kN/m$$

Providing 35 mm thick 12 Nos rubber layer.

Dimensions of Lead rubber bearing (LRB).

Let, thickness of shim plates be 2.8mm.

Number of shim plates = (12-1) = 11

End plate thickness is between 19.05 to 38.1; Adopt thickness of end plate as 25mm.

Total height of LRB

$$h = 12 \times 35 + 11 \times 2.8 + 2 \times 25 = 500.8\ mm$$
$$= 0.5008\ mm$$

Diameter of rubber layer

$$\emptyset = N \times t \tag{11}$$

$$= 12 \times 35 = 420\ mm = 0.420\ m$$

Area of rubber layer

$$A = \emptyset^2 \times \frac{\pi}{4} \tag{12}$$

$$= 0.1385\ m^2$$

Compression modulus

$$E_C = 6GS^2\left(1 - \frac{6GS^2}{K}\right) \tag{13}$$

$$= 6 \times 0.7 \times 1000 \times 8.33^2\left(1 - \frac{6 \times 0.7 \times 1000 \times 8.33^2}{2000 \times 1000}\right)$$

where, Bulk Modulus, K = 2000 Mpa

Horizontal stiffness, K_H

$$K_H = \frac{GA_{LRB}}{t_r} \tag{14}$$

$$= \frac{0.7 \times 1000 \times 1.03}{0.397} = 1816.12\ kN/m$$

Vertical Stiffness K_V

$$K_H = \frac{E_C A_{LRB}}{t_r} \tag{15}$$

$$= \frac{248.96 \times 1000 \times 1.03}{0.397} = 645916\ kN/m$$

Bonded Diameter = 0.667 m

Yield Strength (Fy)

$$Fy = 6178 + 1824.27 \times .00375 = 68.62\ kN$$

Post yield stiffness ratio = 0.1

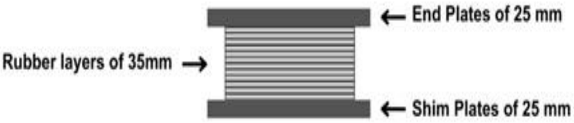

Figure 5 Lead Rubber bearing model for the analysis

COMPARATIVE ANALYSIS FOR THE SEISMIC PERFORMANCE

Model 1: Without Damper (General Model without anything)
Model 2: FVD (With Fluid Viscous Dampers)
Model 3: LRB (With Lead Rubber Bearing Isolator)
For the intense performance analysis two types of analysis has been done. Static analysis with loading combinations of

$$(1.2\times DL+LL+Ex) \tag{16}$$

$$(1.2\times DL+LL+Ey)\ (17) \tag{17}$$

And Dynamic response spectrum method also been used. Dynamic Response Spectrum Analysis (RSA) is a method for estimating the structural response to brief, nondeterministic, transient dynamic events. Earthquakes and shocks are prime examples of such phenomena. Here,
RSX = Response spectrum analysis at X direction.
RSY = Response spectrum analysis at Y direction.

A. Maximum Storey Shear Analysis for the Models

Storey shear means lateral force acting on a storey due to the forces such as seismic. From the figure No: 7, model with fluid viscous damper have less storey shear compare to the without damper condition of the model in response spectrum analysis method in both X and Y direction. Also, for the static analysis for the loading combo B model with fluid viscous model performs well. If the storey shear is high, it signifies that the lateral pressures at a certain level of the building are significant. This can lead to greater stresses in structural parts, thereby harming the overall stability and safety of the building. Also, it has been discovered that when a flexible base is used, storey shear increases at lower levels and reduces at higher levels. Having shear wall in the parallel X direction to the significantly reduces the storey shear along Y direction.

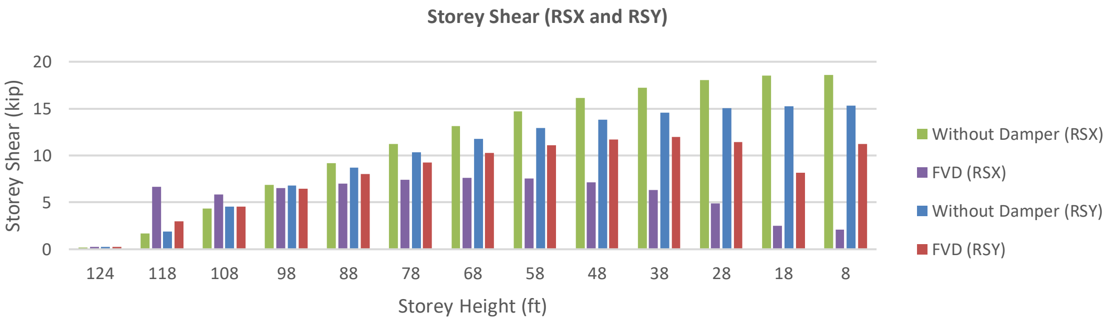

Figure 6 Maximum storey shear for the Model No. 01 (without damper) and Model No. 02 (FVD)

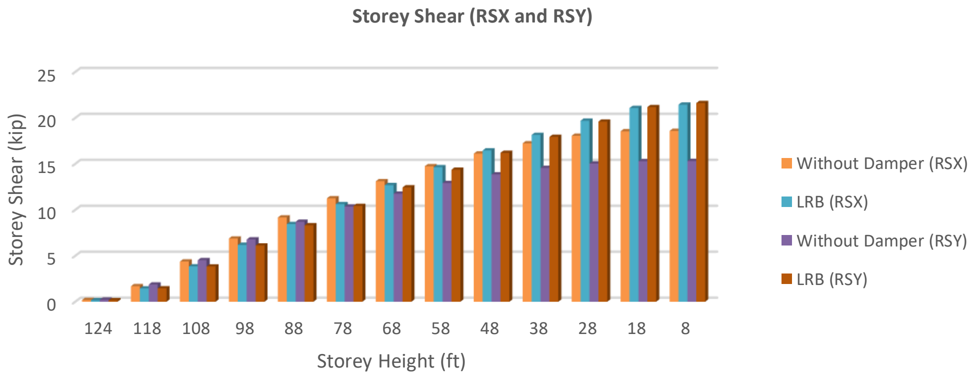

Figure 7 Maximum storey shear for the Model No. 01(without damper) and Model No. 03 (LRB)

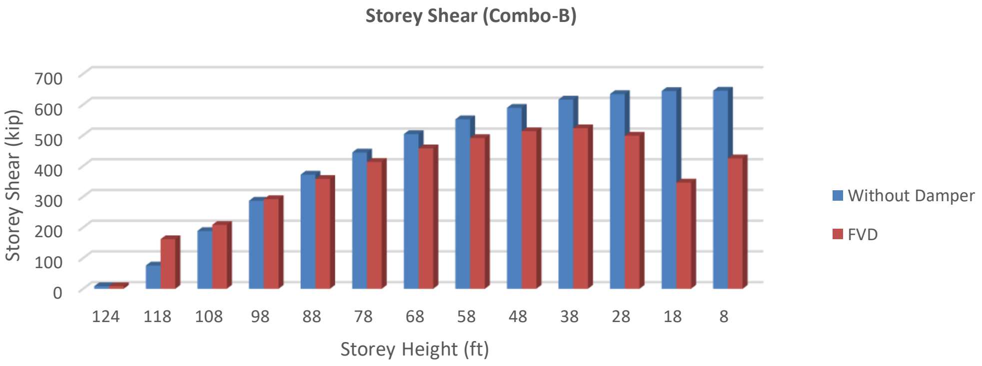

Figure 8 Maximum storey shear for the Model No. 01(without damper) and Model No. 02 (FVD).

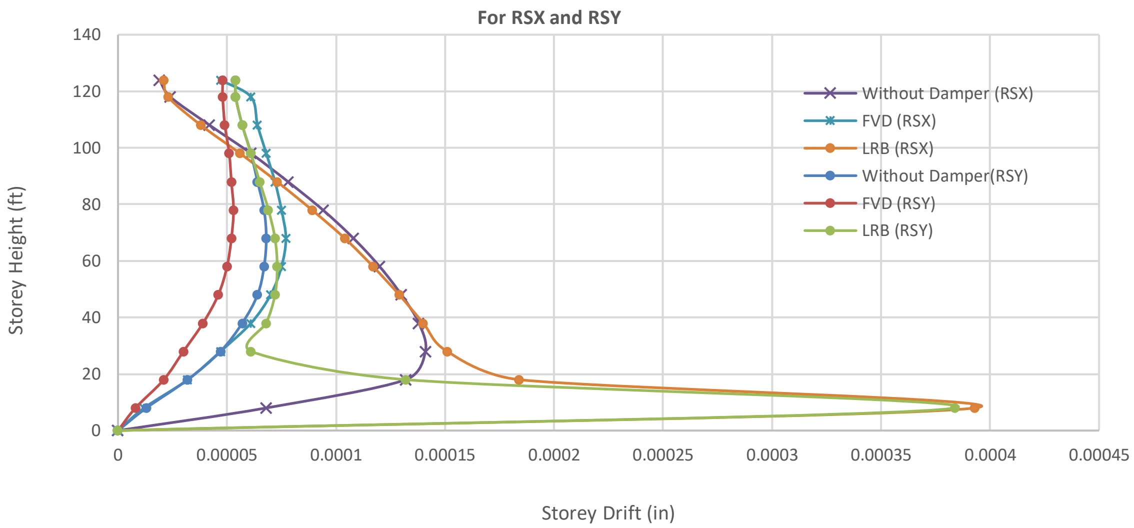

Figure 9 Maximum storey drift for all the models

B. Maximum Storey Drift Analysis for the Models

Story drift is the horizontal displacement or deflection of one floor of a building relative to the floor directly below it produced by lateral loads such as wind or seismic pressures. It essentially measures how much a floor moves in comparison to the floor under-neath it when subjected to such forces.

Here it is evident that using Fluid Viscous Damper and Lead Rubber Bearing isolator can significantly reduce the story drift. The story drift for the base isolator is very high

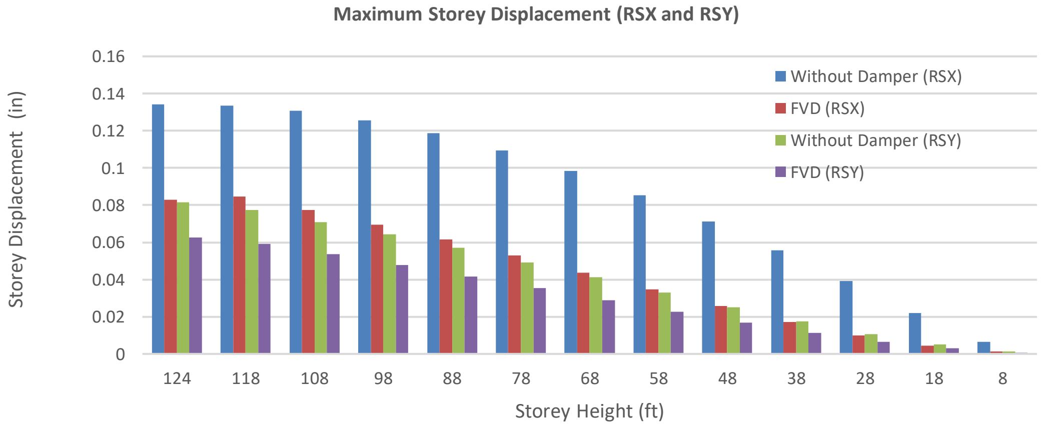

Figure 12 Maximum storey displacement for Model No. 01(without damper) and Model No. 02 (FVD)

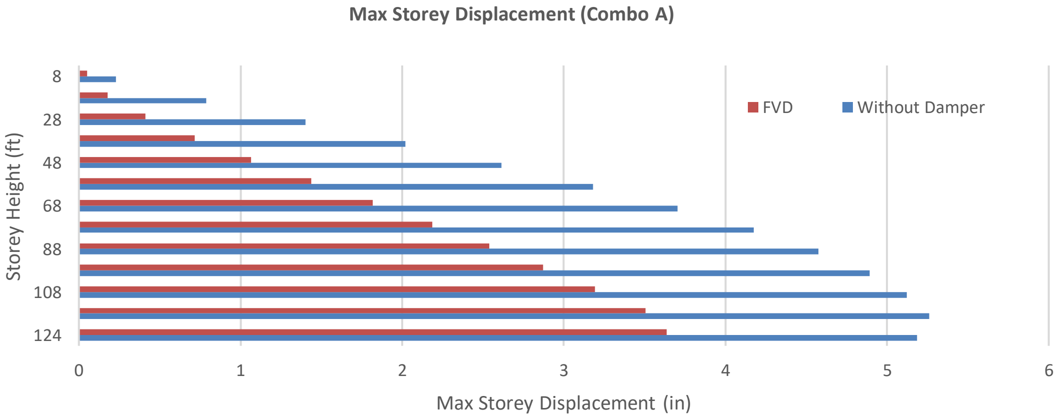

Figure 13 Maximum storey displacement for Model No. 01(without damper) and Model No. 02 (FVD) by static analysis method of load combination (A)

in lower story but it can ignorantly help to reduce the storey drift of upper storey.

Story displacement refers to the displacement that occurs at each story level. In multi-story buildings, maximum storey displacement occurs at the top storey. As the height increases, the storey displacement will reach its maximum value. The analysis for model 03 has been neglected because of high displacement (as expected) for the flexible base.

C. Maximum Storey Displacement Analysis for the Models

Story displacement refers to the displacement that occurs at each story level. In multi-storey buildings, maximum storey displacement occurs at the top storey. As the height increases, the storey displacement will reach its maximum value. The analysis for model 03 has been neglected because of high displacement (as expected) for the flexible base.

The comparison for Lead Rubber Bearing (LRB) Isolator has been omitted in the storey displacement section because it does not have any significant impact.

From the bar chart it is evident that maximum displacement in the lower storey is low and high at the upper storey. By introducing fluid viscous damper, the maximum displacement has been reduced compare to the model 01 which has no dampers.

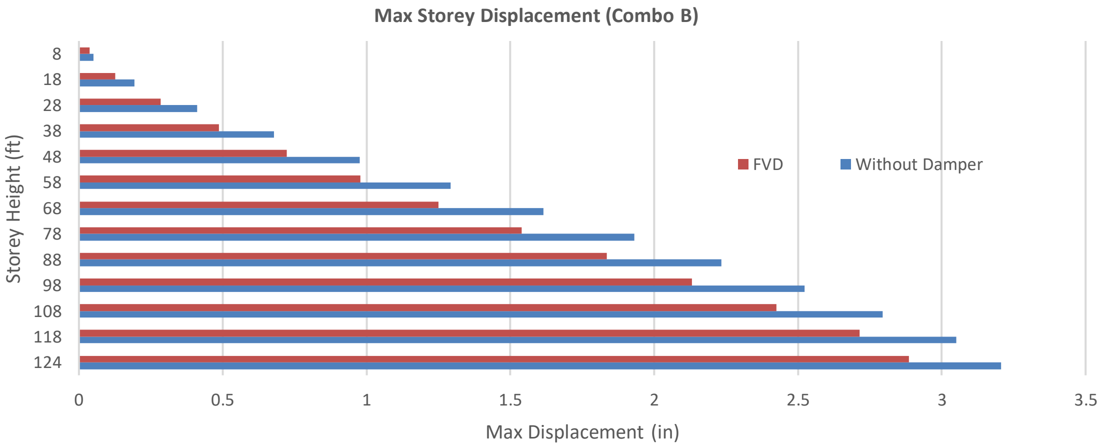

Figure 14 Maximum storey displacement for Model No. 01(without damper) and Model No. 02 (FVD) by static analysis method of load combination (B)

Table 1 For the RSX and RSY analysis for the storey shear between Without damper and FVD Consisting Model

	RSX Analysis			RSY Analysis		
Storey Name	Without Damper	FVD	Storey Shear Decrease	Without Damper	FVD	Storey Shear Decreased
Water Tank	0.182	0.248	0%	0.222	0.242	0%
Roof	1.688	6.63	0%	1.866	3.011	0%
Story10	4.372	5.856	0%	4.52	4.524	0%
Story9	6.869	6.528	4.96%	6.775	6.48	4%
Story8	9.163	7.021	23.38%	8.698	7.99	8%
Story7	11.246	7.425	33.98%	10.347	9.259	11%
Story6	13.107	7.633	41.76%	11.749	10.297	12%
Story5	14.735	7.572	48.61%	12.912	11.106	14%
Story4	16.115	7.16	55.57%	13.843	11.682	16%
Story3	17.227	6.309	63.38%	14.55	11.971	18%
Story2	18.045	4.915	72.76%	15.028	11.453	24%
Story1	18.538	2.505	86.49%	15.28	8.156	47%
GF	18.584	2.118	88.60%	15.302	11.217	27%

Table 2 For the RSX and RSY analysis for the storey shear between Without damper and LRB Consisting Model

	RSX Analysis			RSY Analysis		
Storey Name	Without Damper	LRB	Storey Shear Decrease	Without Damper	LRB	Storey Shear Decreased
Water Tank	0.182	0.161	12%	0.222	0.169	24%
Roof	1.688	1.51	11%	1.866	1.549	17%
Story10	4.372	4.002	8%	4.520	4.032	11%
Story9	6.869	6.413	7%	6.775	6.390	6%
Story8	9.163	8.718	5%	8.698	8.623	1%
Story7	11.246	10.899	3%	10.347	10.728	0%
Story6	13.107	12.943	1%	11.749	12.705	0%
Story5	14.735	14.837	0%	12.912	14.555	0%
Story4	16.115	16.573	0%	13.843	16.283	0%
Story3	17.227	18.138	0%	14.550	17.894	0%
Story2	18.045	19.52	0%	15.028	19.400	0%
Story1	18.538	20.705	0%	15.280	20.815	0%
GF	18.584	20.995	0%	15.302	21.192	0%

Table 3 For the RSX and RSY analysis for storey drift between Without damper and FVD Consisting Model

	RSX Analysis			RSY Analysis		
Storey Name	Without Damper	FVD	Storey Drift Decrease	Without Damper	FVD	Storey Drift Decreased
Water Tank	0.000019	0.000047	0%	0.000054	0.000048	11%
Roof	0.000024	0.000061	0%	0.000054	0.000048	11%
Story10	0.000042	0.000064	0%	0.000057	0.000049	14%
Story9	0.000061	0.000068	0%	0.000061	0.000051	16%
Story8	0.000078	0.000072	8%	0.000064	0.000052	19%
Story7	0.000094	0.000075	20%	0.000067	0.000053	21%
Story6	0.000108	0.000077	29%	0.000068	0.000052	24%
Story5	0.00012	0.000075	38%	0.000067	0.000050	25%
Story4	0.00013	0.00007	46%	0.000064	0.000046	28%
Story3	0.000138	0.000061	56%	0.000057	0.000039	32%
Story2	0.000141	0.000047	67%	0.000047	0.000030	36%
Story1	0.000132	0.000032	76%	0.000032	0.000021	34%
GF	0.000068	0.00002	82%	0.000013	0.000008	38%

This study used a comprehensive comparative seismic analysis to determine the effectiveness of lead rubber bearings (LRB) as a base isolation system and fluid viscous dampers in lowering the seismic response of reinforced concrete buildings. The results show that using LRB greatly minimizes story shear, effectively minimizing the seismic forces pressing on the building. This indicates the feasibility of base isolation as a means of minimizing seismic damage. Furthermore, the study emphasizes the efficiency of fluid viscous dampers in minimizing seismic response, which improves the structural resilience of structures

CONCLUSIONS

Three reinforced concrete (RC) structural models—Model 1 (without dampers), Model 2 (with fluid viscous dampers, FVD), and Model 3 (with lead rubber bearings, LRB)—have had their seismic performance thoroughly examined in this study in order to assess how well they can reduce seismic forces. Critical factors as storey shear, drift, and displacement were evaluated using both dynamic analyses using the Response Spectrum Method (RSA) and static load combinations.

When comparing the models, both FVDs and LRBs significantly reduced the lateral forces (storey shear) caused by seismic activity. Model 2 (FVD) consistently outperformed the others, especially at the upper storeys where seismic forces tend to be the most intense. According to the RSA analysis, FVDs reduced storey shear at the lower levels by as much as 88.60%, which highlights their remarkable ability to dissipate energy. On the other hand, Model 3 (LRB), with its flexible base design, was effective in isolating seismic stresses at the base. While this approach reduced storey shear at lower levels, it caused an increase at the higher storeys. This trade-off shows how critical it is to carefully optimize LRB designs to achieve a balanced seismic response.

Storey drift and lateral displacement are essential indicators of a building's performance during earthquakes. The comparison between Model 2 (FVD) and Model 3 (LRB) highlights the strengths of these systems in improving seismic resilience, albeit with distinct approaches and outcomes.

Model 2 (FVD) demonstrated consistent reductions in storey drift across all levels, showcasing its effectiveness in enhancing structural damping. Its performance was particularly remarkable in the second storey during the RSX analysis, where it achieved a 67% reduction in drift. This substantial improvement is attributed to the robust energy dissipation capabilities of fluid viscous dampers, which enhance structural stiffness while maintaining the flexibility needed to accommodate seismic motion. Additionally, FVDs achieved significant reductions in lateral displacements, especially at the top storey, where a 48.61% decrease was recorded under static load combinations. This performance highlights their suitability for tall buildings, where controlling top-storey displacements is critical for ensuring both safety and occupant comfort [15]; [16].

In contrast, Model 3 (LRB) effectively reduced drift in the upper storeys by decoupling the superstructure from ground motion, a characteristic feature of base isolation systems. However, its performance at lower levels was less consistent, likely due to the trade-offs inherent in the base isolation approach, which focuses on reducing energy transfer to the superstructure while allowing controlled movement at the base. Despite these challenges, LRB systems excel in minimizing structural damage and extending the service life of buildings in earthquake-prone regions [17]; [18]; [19].

In summary, both systems achieved significant improvements in mitigating seismic responses but are better suited for different applications. FVDs are ideal for retrofits and new constructions requiring uniform performance across all storeys, particularly in high-rise buildings. On the other hand, LRBs are more effective for low-to-mid-rise structures or buildings with critical operational needs, such as hospitals or data centers, where minimizing upper-storey acceleration is a top priority. Ultimately, the choice between these systems depends on specific design requirements, performance goals, and site conditions [20]. This comparative analysis demonstrates that both FVDs and LRBs play a critical role in enhancing the seismic resilience of RC structures, each offering unique benefits. FVDs provide consistent performance, making them versatile for various applications, while LRBs are particularly beneficial for high-rise buildings that require base isolation. These findings offer valuable insights for engineers and researchers, supporting the design and construction of safer, more earthquake-resistant buildings.

FUTURE RECOMMENDATIONS

Selecting an appropriate seismic protection system requires careful consideration of factors such as building height, geographical location, and intended performance goals to achieve optimal outcomes. Fluid Viscous Dampers (FVDs) are particularly suited for retrofitting older buildings, mid-rise to high-rise structures, and urban settings where consistent seismic performance is essential. In contrast, Lead Rubber Bearings (LRBs) are better suited for new high-rise constructions in earthquake-prone regions, offering effective base isolation and a significant reduction in upper-storey motion.

To further strengthen seismic resilience, future research should focus on hybrid systems that combine the uniform performance of FVDs with the base isolation advantages of LRBs. Such integrated solutions could harness the unique strengths of both technologies, providing a balanced approach to seismic protection. Moreover, studies should delve into the effects of soil-structure interactions and varying ground motion characteristics on the performance of FVDs and LRBs. These findings would contribute to refining the design and implementation of seismic protection systems, enabling the construction of safer, more resilient buildings across diverse seismic environments. Practical application efforts should focus on cost-effective and reliable optimization methods, particularly in regions experiencing diverse seismic conditions

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