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Seismic performance enhancement of reinforced concrete buildings utilizing fluid viscous dampers

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Professional paper

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Recent seismic events have highlighted the vulnerability of buildings in high-risk zones, resulting in substantial damage and economic loss. This study investigated the effectiveness of fluid viscous dampers in enhancing the seismic performance of a 10-story reinforced concrete building located in Jakarta, an area highly susceptible to earthquakes. A comparative analysis of the seismic responses of both conventional and damped buildings was conducted. A series of linear time-history analyses were performed employing seven spectrally matched ground motions, targeting the maximum considered earthquake level response spectrum. Key seismic performance parameters, including dynamic characteristics, base shear, roof acceleration, interstory drift ratio, and energy dissipation, were examined. These findings demonstrate that the incorporation of FVDs results in significant reductions in the fundamental period of a structure, base shear, and roof acceleration. Furthermore, a substantial reduction in the interstory drift ratios was observed, in conjunction with a significant increase in the overall energy-dissipation capacity of the building. These findings position FVDs as an effective and suitable solution for improving the structural resilience.

Key words:

fluid viscous dampers, seismic performance, seismic protection, time history analysis, reinforced concrete building

Stručni rad

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Povećanje seizmičke otpornosti armiranobetonskih zgrada korištenjem viskoznih prigušivača

Nedavni potresi ukazali su na ranjivost zgrada u visokorizičnim zonama, što je rezultiralo znatnom materijalnom štetom i ekonomskim gubicima. U radu se istražuje učinkovitost viskoznih prigušivača u povećanju seizmičke otpornosti deseterokatne zgrade od armiranog betona smještene u Jakarta, u području visoke seizmičke opasnosti. Provedena je usporedna analiza seizmičkih odgovora konvencionalne zgrade i zgrade s ugrađenim prigušivačima. Serija proračuna vremenske integracije provedena je korištenjem sedam potresnih zapisa prilagođenih spektru odgovora za maksimalni razmatrani potres. Ispitani su ključni parametri seizmičkog performansa, uključujući dinamičke karakteristike, poprečnu silu na temeljima, ubrzanje krova, omjer pomaka između katova te disipaciju energije. Rezultati pokazuju da ugradnja viskoznih prigušivača znatno smanjuje vlastiti period konstrukcije, poprečnu silu na temeljima i ubrzanje krova. Nadalje, zabilježeno je znatno smanjenje omjera pomaka između katova uz istodobno znatno povećanje ukupne disipacijske sposobnosti zgrade. Ti rezultati potvrđuju da su viskozni prigušivači učinkovito i primjenjivo rješenje za povećanje seizmičke otpornosti konstrukcija.

Ključne riječi:

viskozni fluidni prigušivači, seizmička otpornost, seizmička zaštita, proračun vremenske integracije, armiranobetonska zgrada

1. Introduction

Recent earthquakes have caused significant damage to buildings in countries with high seismic risks, contributing to major casualties and economic losses [1]. Numerous techniques are available to enhance structural seismic performance by reducing the impact of seismic forces, including conventional design approaches. However, conventional design for actively resisting earthquakes is comparatively more expensive and present some limitations such as requiring extensive repairs after an earthquake owing to accumulated damage. Several studies have exploited the principle of energy dissipation by adding damping devices to increase the damping capacity of a structure, thereby considerably reducing displacements and minimising damage. Dampers absorb and dissipate energy, improving the building's response to seismic forces via mechanisms such as friction, viscous fluid movement, and elastic deformation. Conventional seismic designs provide the foundational strength and stiffness required to withstand earthquakes. However, incorporating seismic protection devices such as seismic isolation or dampers into the design can offer additional benefits by reducing seismic demands through the isolation system [2-6] or actively controlling and dissipating seismic energy utilising dampers, resulting in reduced damage and improved building performance [7, 8]. Different types of dampers, including friction dampers, viscoelastic dampers, hysteretic dampers, and tuned-mass dampers, are used depending on the level of seismic risk and specific requirements [9-11].

Fluid viscous dampers (FVDs) are widely recognised as cost-effective energy-dissipation devices because of their ability to dissipate significant amounts of earthquake energy and minimise building vibrations through a viscous fluid. This efficacy led to their initial application in infrastructure buildings in the late 1980s, after which FVDs rapidly became pivotal for advancing seismic protection engineering by offering robust protection against strong seismic and wind events. Consequently, FVDs have become a well-established solution over the last four decades, significantly enhancing the performance of both new and existing buildings [12-14].

A fluid viscous damper (FVD) comprises a steel cylinder filled with a highly viscous silicone fluid. A piston head containing small orifices or a valving system moves within this cylinder. When subjected to an excitation such as a seismic event, the movement of the piston forces the fluid through these orifices. This action effectively dissipates the input mechanical kinetic energy of the seismic waves by transforming them into heat energy, which can be safely absorbed by the structure. A key characteristic of FVDs is that the rate of energy dissipation is directly proportional to the velocity of the piston movement [15-17].

Energy-dissipation devices are broadly categorised into two types depending on their response: active and passive. Although active FVDs dynamically adjust their properties to external excitations, they require sensors, a computerised control system, and a substantial power supply for operation, making them costly. By contrast, passive FVDs are designed to operate autonomously without relying on external power or intervention [18-20]. Given

these considerations, this study focusses on passive FVDs. Passive FVDs follow a fixed force-velocity curve, and their response is directly triggered by structural deformation [21]. FVDs do not increase the stiffness of a structure. Instead, they reduce the need for increased stiffness by providing additional damping. Moreover, FVDs are not significantly affected by changes in the temperature or frequency [22, 23]. This makes them a more reliable option than other passive-control devices.

Extensive analytical research has consistently validated the effectiveness and practical applicability of FVDs in structures subjected to seismic activity. For instance, Ijmulwar and Patro [24] demonstrated that integrating FVDs into a regular 11-story RC building resulted in a 30 % reduction in both the base and storey shear forces. Similarly, Miani et al. [13] investigated the effects of employing FVDs to retrofitting a 6-story irregular RC residential building and observed that 82 % of the total input seismic energy was absorbed by the dampers, leaving only 18 % of the energy to be dissipated inherent modal damping of the building. Their study also reported significant reductions in internal member forces, including a 43 % decrease in the bending moments on the beams and 58 % reduction in the shear forces on the columns. Furthermore, De Domenico et al. [25] demonstrated that FVDs in regular 6-story shear-type structures resulted in a 70 % reduction in the absolute floor acceleration values and 50 % reduction in the interstorey drift ratio compared with structures without FVDs. These findings highlight the suitability of FVDs for effectively reducing seismic forces and preserving structural integrity, particularly in multistorey MRF buildings.

In addition to their effectiveness in MRF systems, FVDs have also demonstrated substantial benefits for other structural systems. Lan et al. [26] investigated six-story frame-shear wall buildings equipped with viscous dampers and reported an approximately 23 % reduction in the roof displacement and a 19 % reduction in the base shear. Based on these results, Ahmed [27] examined a 40-story reinforced concrete core wall building and observed significant improvements, including a 33-36 % reduction in roof displacement, up to 44 % reduction in mid-height bending moments, 37 % reduction in racking shear deformation, nearly 69 % reduction in rotational demand at the wall base, and up to 100 % reduction in coupling beam rotations, in conjunction with a 450 % decrease in inelastic energy demand. More recently, Alhamdany and Dilsiz [28] evaluated a three-story reinforced concrete building retrofitted with FVDs and reported significant performance improvements. The interstorey drift ratios were reduced by approximately 62.5 % along the X direction and 65 % along the Y direction; the roof displacements decreased by approximately 85 % and 53 % along the X- and Y-directions, respectively; and the roof accelerations were reduced by approximately 43 % and 55 % along the two directions, respectively. These findings collectively underscore the versatility of FVDs in enhancing seismic performance across diverse building systems, thereby extending their applicability beyond conventional MRF configurations.

This paper describes the use of FVDs in passive damper systems for high-rise buildings. In this study, a model of a 10-story reinforced concrete (RC) building with a special moment-resisting frame

system (SMRF) was developed. The primary objective of this study is to compare the seismic performance of a conventional building with the use of FVDs under the same ground motion scenarios employing a series of linear time history analyses. The design procedure of the FVDs was based on the Damper Design Manual from Taylor Devices and FEMA P-1051 [29, 30]. These guidelines provide detailed procedures and requirements for designing structures with damping systems, incorporating factors such as the building characteristics, properties of the damping system, and intended performance objectives. Finally, the conclusions of this study are presented.

2. Methodology

The primary objective of this study was to compare the seismic performances of conventional and damped buildings. The observed parameters compared were the dynamic characteristics (natural period and modal mass participation factor), base shear, roof acceleration, interstory drift ratio, and energy dissipation.

In this study, a linear time history analysis (LTHA) was adopted in accordance with the provisions of ASCE 7-16 [31]. Section 12.6 explicitly states that the linear response history procedure is an acceptable analysis method for seismic design, whereas nonlinear response history analysis is reserved for cases where detailed inelastic behaviour is required. Furthermore, Section 12.9.2 permits the use of a linear response history analysis to evaluate the dynamic response of structures under earthquake excitations, provided that the structural model remains elastic and all code requirements are satisfied. Because this study aims to investigate the effectiveness of fluid viscous dampers, which primarily operate within the elastic range by dissipating energy via velocity-dependent damping, LTHA provides an appropriate and code-compliant framework without the need for nonlinear modelling.

2.1. Building modelling

The reference structure of the case study, as shown in Figure 1, is a 10-story reinforced concrete moment-resisting frame (MRF) with a height of 41 m. The structure was designed as an

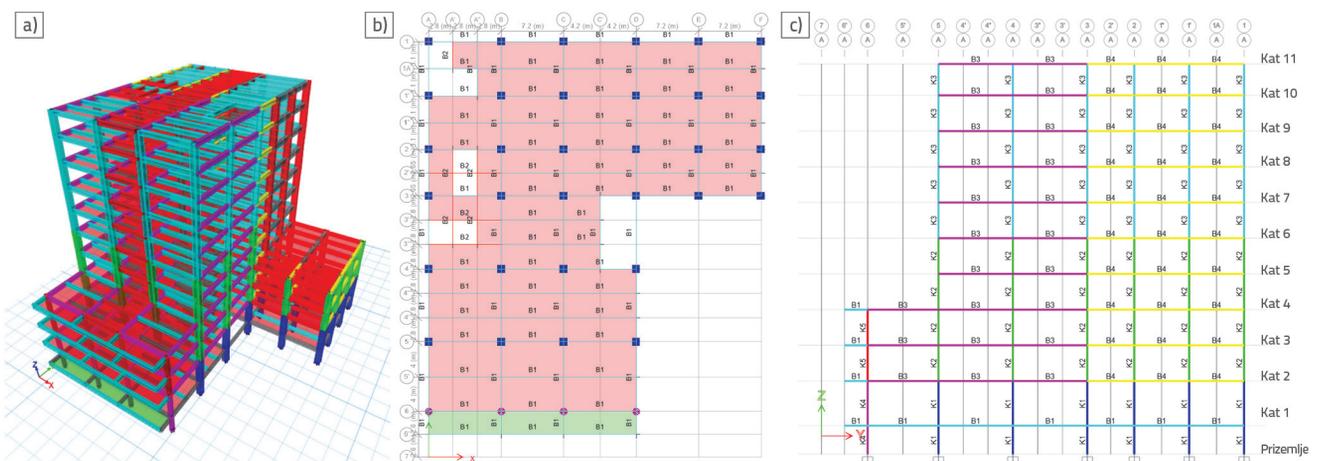


Figure 1. a) 3D view, b) plan view, c) cross-section view of the building model

educational building located in Jakarta City, which is classified as Risk Category IV with site class SD (medium soil). The primary material specifications of this structure include concrete with a standard compressive strength of 30 MPa (corresponding to an elastic modulus of 25,742 MPa according to the Indonesian normal-concrete code) and reinforcement bars with a yield tensile strength of 400 MPa. Beams and columns were modelled using frame elements, and plate elements were modelled using shell elements, assuming a linear elastic behaviour. The dimensions and reinforcement details of the beam and column elements are listed in Tables 1 and 2, respectively. For structural analysis, the superstructure was modelled employing a three-dimensional finite element method software and a linear analysis approach. The applied loads were classified as dead, superimposed dead, live, earthquake, and wind, all of which were determined according to the building code. The dead loads were determined based on the weights of the structural elements. Superimposed dead loads comprised floor finish, ducting, and façade, totalling 1.5 kN/m² for area loads, with infill walls contributing an additional 1 kN/m² for line loads. Live loads were assigned based on usage: 1.92 kN/m² for classrooms, 4.79 kN/m² on corridors, and 0.92 kN/m² for the roof floor.

Two types of earthquake analyses were conducted in this study. The first involved a linear response spectrum for preliminary analysis, and the second employed a linear time-history response analysis. The design response spectrum of this building was derived from the latest Indonesian seismic code with a 2500-year return period and 5 % damping, as shown in Figure 2.

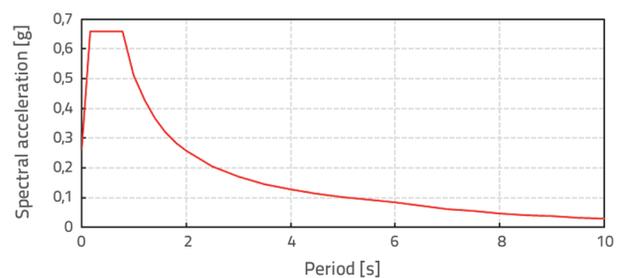


Figure 2. Design response spectrum for Jakarta

Table 1. Beam reinforcement details

Primary beam								
Type			Longitudinal bar			Stirrups bar		
Name	b [mm]	h [mm]	Location	n	D [mm]	n	D [mm]	s [mm]
B1	350	650	Support (Top)	5	22	2	10	100
			Midspan (Bot)	3	22			
B2	350	600	Support (Top)	4	22	2	10	100
			Midspan (Bot)	3	22			
B3	350	650	Support (Top)	6	22	2	10	100
			Midspan (Bot)	4	22			
B4	350	650	Support (Top)	5	22	2	10	100
			Midspan (Bot)	4	22			
B5	450	900	Support (Top)	8	29	4	10	100
			Midspan (Bot)	5	29			

Table 2. Column reinforcement details

Column							
Type			Longitudinal bar		Stirrups bar		
Name	b [mm]	h [mm]	n	D [mm]	n	D [mm]	s [mm]
K1	900	900	32	29	6	10	100
K2	900	900	24	29	4	10	100
K3	800	800	20	29	4	10	100
K4	800	-	29	29	4	10	100
K5	800	-	14	29	4	10	100
K6	900	900	32	29	5	10	100

Table 3. Selected ground motion records

Mechanism	Direction	Earthquake events	Magnitude [Ms]	Distance [km]	PGA [g]	Duration [s]
Benioff	X	Kocaeli, Turkey 1999	7.51	60.43	0.099	138.57
	Y				0.077	
	X	St. Elias, Alaska 1979	7.54	80	0.058	83.2
	Y				0.083	
	X	El Mayor, Mexico 2010	7.2	212.92	0.008	56.32
	Y				0.012	
Shallow Crustal	X	Imperial Valley, USA 1979	6.53	50.1	0.097	28.57
	Y				0.121	
	X	Bigbear, USA 1992	6.46	52.48	0.076	59.58
	Y				0.087	
Megathrust	X	Chi-Chi, Taiwan 1999	7.62	100.12	0.055	143.99
	Y				0.063	
	X	Denali, Alaska 2002	7.9	139.85	0.045	300
	Y					

This return period reflects the maximum seismic loading condition, that is, the risk-targeted MCER (2 % probability of exceedance in 50 years, 2475-year return period), which is typically used to capture the most critical structural demand scenario. The purpose of adopting the full MCER rather than the design-based earthquake (475-year return period) or two-thirds MCER was to highlight the effectiveness of dampers under rare, high-intensity shaking and to provide a conservative bound on seismic demands. Because the structural model is linear, the MCER responses are interpreted as upper-bound elastic estimates to evaluate robustness, with a focus on the relative performance improvements achieved by the FVDs. Time history analysis was employed to accurately simulate structural response to a broad range of ground motion characteristics. This method is particularly necessary for high-rise and special buildings that incorporate supplemental damping systems. A set of seven pairs of spectrally matched ground motions was selected to match the MCE level response spectrum, as shown in Figure 3.

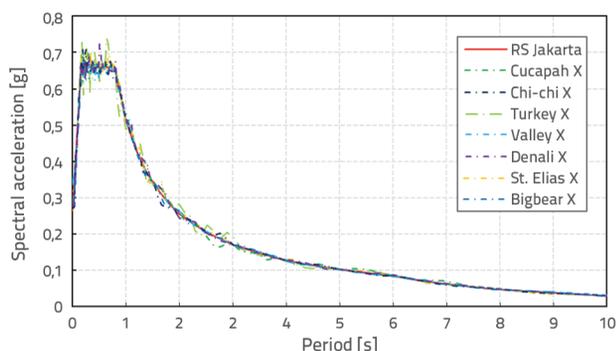


Figure 3. Spectrally matched ground motion history employed for linear time-history analysis

The ground motions were selected based on a seismic hazard deaggregation procedure consistent with the Indonesian

seismic code. The details of all seven pairs are listed in Table 3. Each record was individually spectrum-matched to the target spectrum following a conservative spectrum verification approach, ensuring compliance with the ASCE 7-16 requirements, eliminating the possibility of underestimating seismic demands, and reducing spectral scatter variability. This provided a consistent input for evaluating the effectiveness of the FVD system.

2.2. Fluid viscous damper modelling

The parameters and configuration of the FVDs were established via a rigorous iterative design process. The damper design was based on the MCER, corresponding to a 2500-year return period, as stated in the Indonesian seismic code and damper design guidelines. This design is influenced by the target damping ratio, structural stiffness, fundamental period of the structure, FVD installation angle, and number of FVDs installed. The iteration process concluded once the selected parameters satisfied the acceptance criteria; that is, when the required damping remained below the damping capacity of the proposed model. Determining the required damping capacity at the initial stage is crucial to achieve the desired performance, and the designed damping ratio used in this study was set to 30 %. The required damping capacity for each floor and the selected FVD models are presented in Table 4.

To optimise cost-effectiveness without compromising performance, FVDs were installed only up to the 7th floor. This partial installation strategy was adopted following the assessment that dampers on all stories were not necessary to meet performance objectives. The geometrical arrangement of the FVDs in the building is shown in Figure 4, where their positions are represented by black squares. For accurate structural analysis using finite element software, it is crucial to define specific FVDs parameters replicate the physical behaviour of dampers. These mandatory parameters include the effective

Table 4. Storey-wise arrangement and damping capacity of FVDs

Story	K_x [kN/m]	K_y [kN/m]	C_x	C_y	F_x [kN]	F_y [kN]	FVD specification	
							Model number	Damping capacity [kN]
Krov	265899.5	434415.5	1961.0	2906.8	444.9	726.8	-	-
10	334271.5	523329	2465.3	3501.8	635.6	995.0	-	-
9	353656.1	550058.6	2608.3	3680.6	672.4	1045.8	-	-
8	359562.4	559045.5	2651.8	3740.7	683.6	1062.9	-	-
7	365871.4	563229.7	2698.3	3768.7	695.6	1070.9	17170	2000
6	393139.8	588504.7	2899.5	3937.9	747.5	1118.9		2000
5	435525.3	611045.1	3212.1	4088.7	828.1	1161.8		2000
4	541776.6	748031.5	3995.7	5005.3	1030.1	1422.2	20875	3000
3	560689.1	739221.6	4135.2	4946.4	1066.0	1405.5		3000
2	572483.7	689003.4	4222.1	4610.3	1360.6	1637.5		3000
1	2341892	2706012	17271.8	18106.8	3562.1	4116	17200	6500

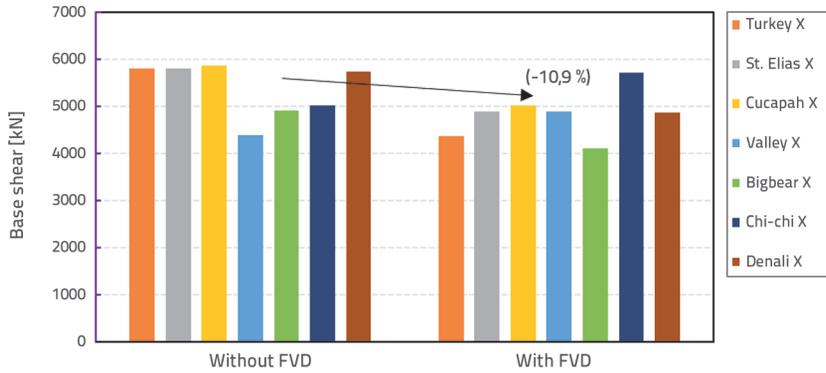


Figure 5. Comparison of base shear forces of building along the X-direction

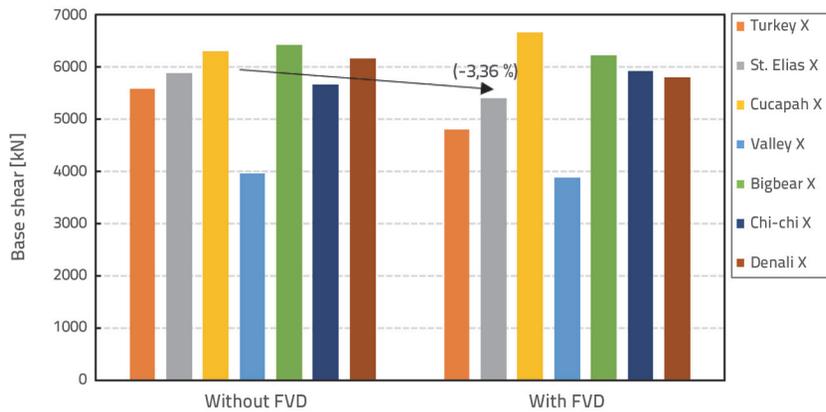


Figure 6. Comparison of base shear forces of building along the Y-direction

3.2. Base shear

Base shear represents the total lateral forces transmitted to structures and is a critical indicator for assessing seismic demand. Figures 5 and 6 illustrate a comparison of the average peak base shear forces for the two models subjected to seven ground motions along the X- and Y-directions. The average values of base shear along the X-axis for conventional and damped systems were 5358.71 kN and 4831.94 kN, respectively. Correspondingly, in the Y-direction, the average values for both the systems were 5703.20 kN and 5517.40 kN. Overall, the figure clearly shows that the addition of FVDs resulted in a 10.9 % and 3.36 % decrease in the base shear force along the X- and Y-directions, respectively. This observed reduction in base shear is attributed to the inherent damping effect of FVDs on the structure, which enhances the structural dissipative capacity during seismic events. However, an increase in the base shear in the model with the FVD was observed for specific ground motions, namely Chi-Chi X, Chi-Chi Y, Imperial Valley X, and Cucapah Y. This can be attributed to the frequency of these records and their

interaction with the dynamic properties of the structure. These earthquakes exhibited relatively high peak ground accelerations and dominant spectral contents that were close to the fundamental periods of the building. When the predominant frequencies of the input motion approach the natural frequencies of the structure, resonance effects may occur, amplifying the inertial forces and consequently increasing the base shear, even when viscous fluid dampers are installed. In such cases, the dampers still function effectively by dissipating seismic energy, which facilitates in reducing displacements and accelerations. However, the base shear response remains dependent on the spectral characteristics of the ground motion. This explains the higher base shear values in ground motion records than in conventional systems, whereas, on average, the inclusion of fluid viscous dampers still resulted in a significant reduction in the structural response.

3.3. Roof acceleration

Roof acceleration is a crucial factor for ensuring the serviceability and integrity of a building by minimising damage to nonstructural components during an earthquake. Figures 7 and 8 show the results of the peak accelerations on the roof storey subjected to the selected earthquake along both horizontal directions. For the X direction, the average roof acceleration decreased from 0.22 g in the conventional system to 0.18 g in the damped system. Similarly, for the Y direction, the values also decreased from 0.19 g to 0.17 g. This resulted in a reduction of 20 % along the X-direction and 10 % along the Y-direction with the installation of FVDs,

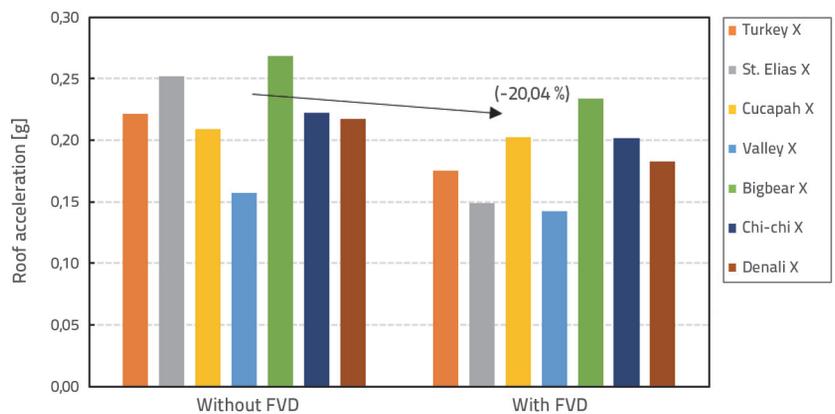


Figure 7. Comparison of roof acceleration of the building along the X direction

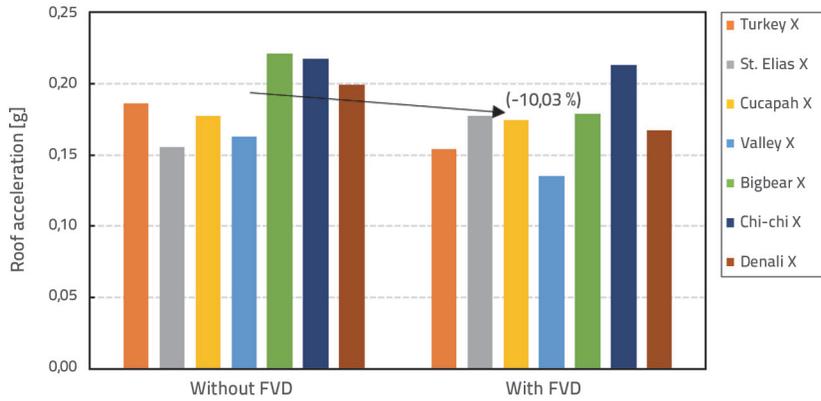


Figure 8. Comparison of roof acceleration of the building along the Y-direction

thereby contributing to enhanced building occupant comfort. All acceleration results for both models remained below the acceptable limit of 0.3 g, as stated in the Japanese design practice, thereby ensuring the serviceability of the building during seismic events [32].

the X-direction, the conventional models exhibited maximum drift values of 0.36 %, whereas the damped models yielded values of 0.22 %, with both occurring at the 5th floor. For the Y-direction, Figure 9 shows the maximum values of 0.28 % and 0.20 % for both models, with these values occurring on the 2nd floor. The application of FVDs to the building resulted in a significant reduction of 63.63 % and 40 % in the maximum drift values along the X- and Y-directions, respectively. These results clearly indicate that the addition of FVDs enhances the structural performance and minimises the inertial forces acting on the building.

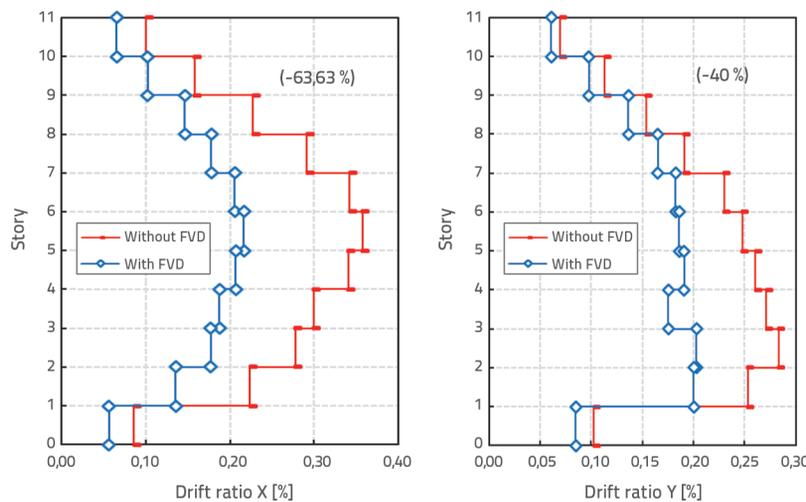


Figure 9. Comparison of interstory drift ratio of building along both directions

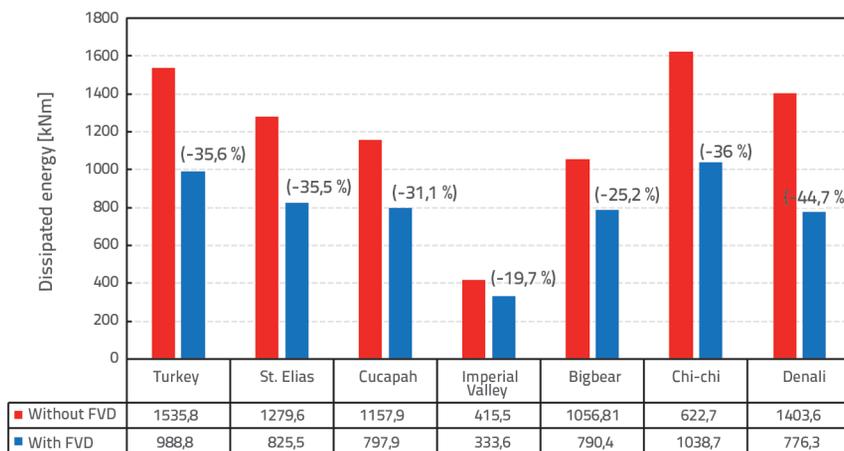


Figure 10. Comparison of the energy dissipated by the inherent structures of the building for both systems

3.4. Interstory drift ratio

The inter-story drift ratio is defined as the relative horizontal displacement between two consecutive floors divided by the story height. This parameter is a key performance indicator of evaluating structural damage and seismic safety. In this study, the Chi-Chi earthquake was selected for comparison because it produced the most significant drift values compared with the other six pairs of earthquake events. Figure 9 shows the interstory drift ratios along both directions in the two models. For the X-direction, the conventional models exhibited maximum drift values of 0.36 %, whereas the damped models yielded values of 0.22 %, with both occurring at the 5th floor. For the Y-direction, Figure 9 shows the maximum values of 0.28 % and 0.20 % for both models, with these values occurring on the 2nd floor. The application of FVDs to the building resulted in a significant reduction of 63.63 % and 40 % in the maximum drift values along the X- and Y-directions, respectively. These results clearly indicate that the addition of FVDs enhances the structural performance and minimises the inertial forces acting on the building.

3.5. Energy dissipation

The primary objective of incorporating FVDs is to increase the energy-dissipation capacity of structures by absorbing a substantial portion of the input seismic energy. This reduces the energy transmitted to structural elements, such as beams and columns, thereby lowering internal demand on primary structural components. Figure 10 shows the total dissipated energy in the inherent structures with and without FVDs. The most significant reduction in dissipated energy was observed under the Denali earthquake record, showing a 44.7 % decrease from 1403.6 kNm to 776.3 kNm. Other notable reductions were also evident in Chi-Chi and Turkey, with reductions of 36 % and 35.6 %, respectively. Conversely, the lowest reduction occurred under the Imperial Valley earthquake, with a 19.7 % decrease from 415.5 kNm to 333.6 kNm. These results demonstrate that the FVDs

reduce the energy dissipated by the inherent structural system, thereby enhancing the capacity of the structure to absorb seismic energy without causing significant damage during an earthquake. Overall, these findings highlight the effectiveness of FVD devices in improving structural performance by significantly reducing seismic energy; however, their efficacy may vary depending on the geometrical arrangement and characteristics of the FVDs.

4. Conclusion

This study provides a comparative analysis of the seismic performance of conventional and damped systems subjected to a series of linear time-history analyses to investigate the effectiveness of adding FVDs to a 10-story RC building. Based on these results, the following conclusions can be drawn.

Based on modal analysis, the implementation of the damped system using FVDs resulted in a minor reduction in the fundamental period of the structure. The fundamental periods, which were initially 1.758 s (X direction) and 1.595 s (Y direction), decreased by approximately 10 % for both directions to 1.581 s and 1.434 s, respectively. This reduction in the fundamental period is attributed to the stiffening effect of the FVDs. The modal mass participating ratios remained largely unchanged because the addition of FVDs exerted an insignificant effect on these parameters.

Based on the linear time history analysis of the observed parameter results, the installation of FVDs resulted in

improvements across all performance metrics: base shear was reduced by 10.9 %, roof acceleration by 20 %, interstory drift by 63 %, and energy dissipation by 44.7 % compared with those of the conventional models. This observed increase in seismic performance is primarily attributed to the energy-dissipation mechanism inherent in FVDs. During an earthquake, the FVDs actively absorb and dissipate a significant portion of the seismic energy input and transform it into heat. By effectively dissipating this energy, FVDs reduce all the observed parameter results, leading to an enhanced ability of the structure to withstand seismic loads more efficiently. This makes FVDs suitable alternatives for seismic protection of buildings.

The demonstrated seismic performance improvement of a damped system with FVDs can reduce expected losses during earthquakes and enable rapid restoration to normal operational conditions. Superior seismic performance reduces the risk of exposure for building occupants, thereby contributing to safer and more resilient built environments.

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