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PERFORMANCE COMPARISON OF BUILDINGS EQUIPPED WITH SHEAR WALL SYSTEM AND VISCOUS DAMPERS

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Abstract

This study aims to evaluate and compare the structural stability and seismic performance of buildings that are equipped either with a shear wall system or buildings that are equipped with Fluid Viscous Dampers (FVD) as an energy dissipation mechanism. The stability parameters analyzed include displacement, drift ratio and storey drift. Meanwhile, the structural performance is analyzed based on the number of phases, hysteresis energy generated, and structural performance level. Numerical modelling of the building structure was conducted and then earthquake loading simulations were carried out using ChiChi, Kobe, and Yushu earthquakes that had been scaled according to the dynamic response analysis procedure. The results show that the application of FVD as an energy dissipation system has significant potential to improve the performance and stability of structures. The performance of this system is shown to match, and in some aspects even compete, the effectiveness of shear walls in reducing the seismic response of building structures. Therefore, FVDs can be considered as an efficient alternative in earthquake-resistant building design, especially in structures that require higher flexibility without sacrificing energy dissipation capacity.

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Keywords: ChiChi, Kobe, Yushu, FVD, Shear Wall

Introduction

Earthquakes are one of the natural disasters that can cause damage to building structures. An earthquake is a condition where vibrations occur on the ground caused by the movement of tectonic plates. The movement of the tectonic plates then creates seismic waves that radiate in all directions where if the waves reach the earth's surface, the vibrations will have the potential, one of which is to cause damage to infrastructure. Damage caused by earthquakes can vary from minor to moderate damage depending on the location (Bai et al., 2023; Hinojosa, 2023). As in Indonesia, the high earthquake potential causes the consideration of earthquake-resistant construction to be an important aspect in the planning of a building structure (Faridzi et al., 2024; Kharis Pratama et al., 2024). Indonesia is included in the earthquake-prone area due to its location on the world's Ring of Fire. Recorded between 1900 - 2021, Indonesia has experienced at least 150 earthquakes that have a magnitude greater than 7.0.

As a country located in the Ring of Fire, Indonesia has a high level of earthquake risk (Marbun et al., 2024; Oktaviana & Fithriasari, 2023). Therefore, the development and application of effective energy dissipation technology is an urgent need to minimise the risk of building damage due to earthquakes. The design of building structures that are able to reduce the impact of earthquakes has become a major concern in the field of Civil Engineering. One approach that is often used to improve the earthquake resistance of buildings is to implement energy dissipation systems, including through the use of seismic devices, especially in high-rise buildings (Kitayama & Constantinou, 2022; Suryawinata et al., 2023). Seismic devices themselves are generally divided into two, namely active seismic devices and passive seismic devices. The popularity of the use of passive energy dissipation systems in the world has increased recently due to its ability to improve structural performance through significant dissipation capabilities and to increase the damping ratio without changing the stiffness of the structure (De Domenico et al., 2019; Islam & Jangid, 2021; Kareem, 1997; Takewaki & Akehashi, 2021).

One type of passive seismic damping that has the advantage of a practical installation method is a fluid viscous damper (FVD). FVD is a suspense-shaped energy absorber that is able to maintain the elastic behaviour of the structure during an earthquake while not changing the stiffness of the structure itself (Sebaq et al., 2023; Tiwari et al., 2023; Zhang et al., 2023). Inspired by its good performance in the aerospace and military world, the use of FVDs is starting to be implemented in building structural components as an energy dissipation device both in the construction of new structures and the application of existing building structures (De Domenico et al., 2019). FVDs work by absorbing dynamic energy that occurs during earthquakes to reduce the structural response to lateral forces (Kazemi et al., 2021; Shmerling & Gerdts, 2023; Wahyu & Arini, 2024).

Several studies have been conducted to assess the effectiveness of FVDs in improving structural resilience. FVDs have been shown to reduce earthquake-induced vibrations by increasing damping, thereby reducing the dynamic response of the building and improving the overall stability of the structure (Hajati & Hanif, 2018; Li et al., 2020). Results from previous studies show that the use of FVDs can reduce the vibration time of structures by up to 47.2% when compared to structures that do not use FVDs (Vasile & Bugaru, 2023; Wahyu & Arini, 2024).

Other studies have shown that the use of FVDs in high-rise buildings can increase base shear force, reduce lateral deflection, and improve structural performance from damage control to immediate occupancy (Del Gobbo et al., 2018; Praja et al., 2022; Pribadi et al., n.d.; Yahya Mohammed Almajhali, 2018). Furthermore, other studies have revealed that the use of FVDs in combination with other damping systems can reduce the base shear force by more than 80% and reduce the structural acceleration by 54% (Belbachir et al., 2023; Fang et al., 2022). FVDs are also known to dissipate earthquake energy without affecting the stiffness of the structure (Zoccolini et al., 2023). They are also being considered for use as replaceable seismic dampening elements as a development of CBF structures (Elwardany et al., 2021).

Overall, the research conducted has demonstrated that FVDs are a highly effective energy dissipation device in improving the resistance of buildings to earthquake loads. Although there have been several studies examining the effectiveness of FVDs, there are still limitations in comparing the performance of FVDs with other earthquake-resisting systems. Therefore, the current study aims to fill this gap by analysing the performance comparison of structures that apply FVDs with structures that use other lateral energy-dissipating elements such as shear walls. This research was conducted to evaluate and compare the performance of building structures using these two elements. The evaluation includes stability by analysing their displacement, drift ratio and storey drift. As for performance, the aspects analysed were hysteresis energy and structural performance level. This research is expected to make a significant contribution to a safer and more efficient design in anticipating earthquake energy.

Research Methods

Two modelled buildings are planned to have 12 floors, as shown in Figure 1, adopting the Jakarta Public Service Mall building (Jakarta Investment and One-Stop Integrated Service Office) with elevations as listed in Table 1. Materials are planned using concrete with a grade of 30 MPa and reinforcement with f_y 400 Mpa. The first building is modelled by applying shear walls as seismic devices as in the existing condition, while the other buildings are innovated by using FVDs. The FVD elements are assumed to be diagonal bracing that resists compressive and tensile axial forces due to external forces. The Fluid Viscous Damper (FVD) used belongs to the category of passive fluid viscous damping systems. The fluid viscous damper (FVD) device used is a product from the United States of America (USA), Taylor Devices Inc. The device used is a clevis-baseplate configuration type with force specifications of 500 kN, stroke ± 100 mm, and weight of 82 kg, as illustrated in Figure 3. The building structure with FVD is planned with the installation of FVD on each 2 floors on the right and left side portals of the building as shown in Figure 1. In the structural model, FVDs were modelled as nonlinear velocity-dependent element placed between selected stories of the building, typically in a diagonal configuration within bracing. The FVD simulated using element that available in structure analysis software, defined with custom damping properties. The FVD were characterized by manufacturer-provided parameter. The damping coefficient (Cd) and velocity exponent (α) were calibrated based on typical performance value which is 130 kN and 0.5 respectively. To analyze the earthquake loads using structural analysis software, response spectrum data and ground motion records are required. The recorded ground motion data were taken from the Kobe, Chi-chi, and Yushu earthquakes, all of which have similarities with the planned site, which is located on the Eurasian plate. The accelerograms of the three earthquakes are illustrated in Figures 2 for Chichi, Figures 3 for Kobe, and Figures 4 for Yushu. Each figures illustrates the earthquake in the X and Y direction, both in actual and scale. The spectral matching process was carried out to align the response spectra of real time earthquake records with the previously calculated design response spectrum. This process is carried out with the help of software application that allows modification of the response spectrum of each accelerogram to approach the shape of the target spectrum. The target spectrum in this case is the design spectrum of the Jakarta area calculated previously based on applicable codes. The naming of each modelled structure is as written in Table 2. CS indicates that the modelled structure is a concrete structure. The earthquake anticipation elements in the form of shear walls are labelled SW (shear wall) and FVD labels for other structures. Analysis was carried out on the displacement, drift ratio and storey drift, hysteretic energy, and performance level of the modelled structure. The analyses were conducted by reviewing the direction of the main axis of the earthquake load, which is in the Y-axis direction.

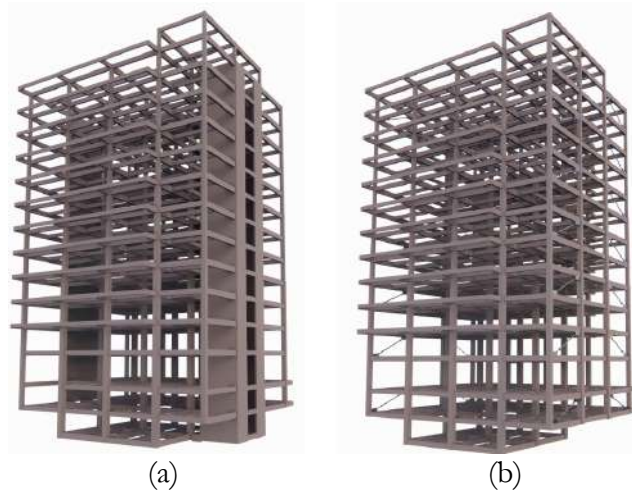


Figure 1. Structure modelling: (a) with the shear wall system, (b) with the application of FVD

Table 1. Building Modelling Elevation

Floor	Elevation (m)	Floor	Elevation (m)
GWT	-7,00	7th floor	+24,20
Basement	-3,50	8th floor	+28,00
1st floor	$\pm 0,00$	9th floor	+31,80
2nd floor	+5,00	10th floor	+35,80
3rd floor	+9,00	11th floor	+39,40
4th floor	+12,80	12th floor	+43,20
5th floor	+16,60	Roof Floor	+47,00
6th floor	+20,40	Roof	+51,27

Table 2. Naming of Modelled Specimens

Type of Structure	Naming of Specimen
Shearwall structure	CS-SW
FVD structure	CS-FVD

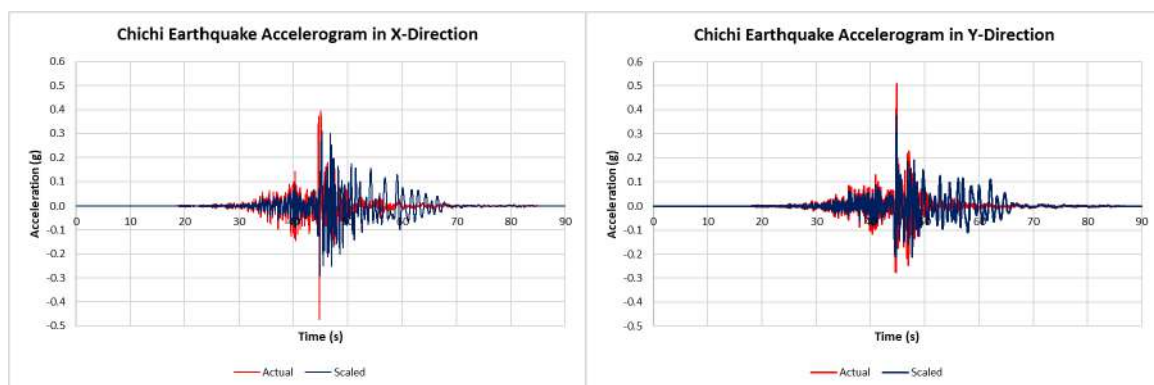


Figure 2. Actual and Scaled Earthquake Accelerogram of Chichi on : a) X direction, b) Y direction

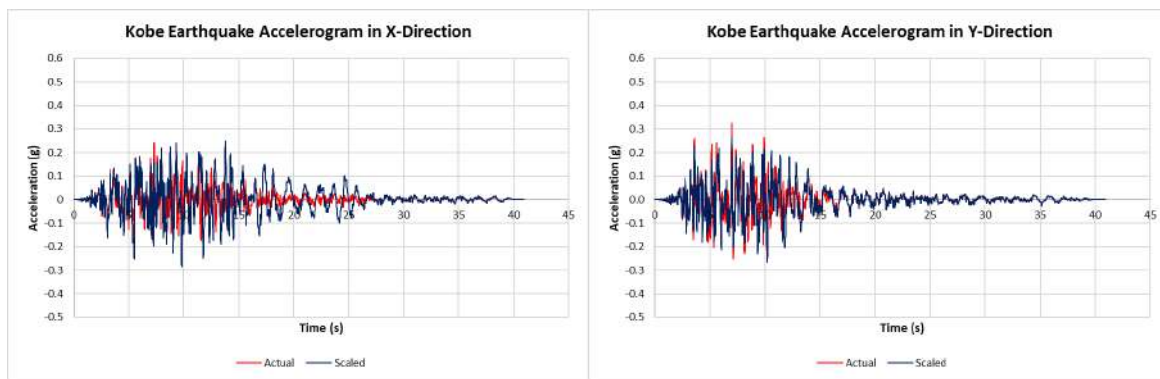


Figure 3. Actual and Scaled Earthquake Accelogram of Kobe on : a) X direction, b) Y direction

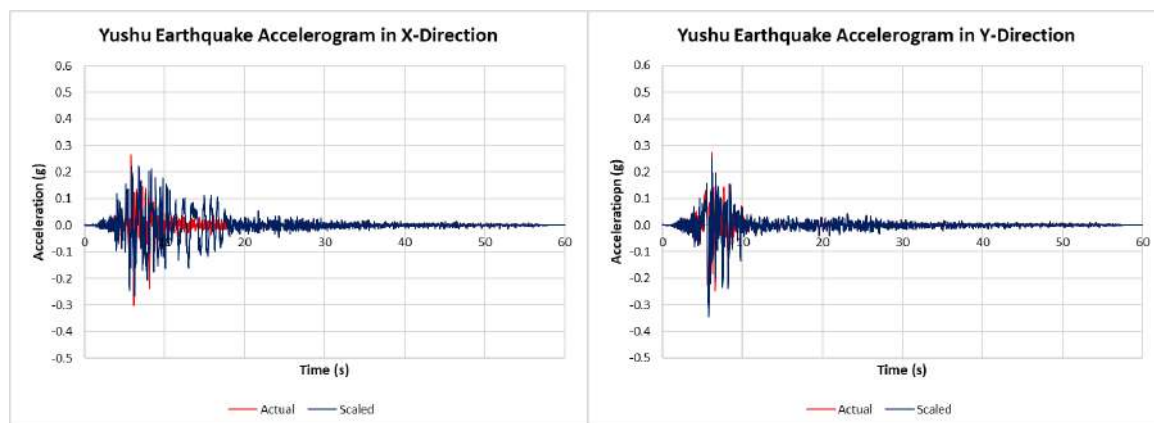


Figure 4. Actual and Scaled Earthquake Accelogram of Yushu on : a) X direction, b) Y direction

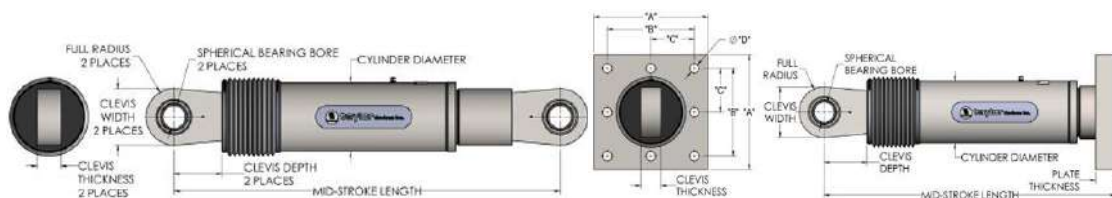


Figure 5. FVD specifications that modelled on this research

Research Results and Discussion

Structure Displacement, Drift Ratio and Storey Drift

Structural displacement is the lateral displacement at a point of a building caused by loads such as earthquakes and wind. This displacement is a crucial parameter used in evaluating the seismic performance of buildings. The amount of displacement that occurs is influenced by the characteristics of the structure including the lateral force-resisting system used (Akbar & Candra, 2018a). Figure 6 shows the amount of displacement generated from the modelling results. The result of displacement is observed at a height of 5500 mm or equivalent to the roof floor of the structure. From Figure 6(a), modelling results from SC-SW show that the combination of dead load, live load, and earthquake load produces a larger displacement when compared to other combinations. The largest horizontal displacement of the existing structure occurs at the top of the building due to the ChiChi Earthquake in the direction of the main axis of the building or the Y-axis direction of 95.06 mm. The result of the displacement due to the Kobe load is 80.01 mm and the displacement generated by the Yushu load is 77.18 mm. The same outcome is shown in CS-FVD where the same combination has a larger displacement. In CS-FVD, the displacement

produced by the ChiChi earthquake when viewed at the roof level was 91.54 mm. The displacement is 3.70% smaller when compared to the displacement that occurred in CS-SW. Likewise, the magnitude of the displacements generated by the Kobe and Yushu earthquakes was 6.56% and 5.51%, respectively, where 72.93 mm was the displacement generated by the Kobe earthquake and 74.67 mm was the displacement generated by the Yushu earthquake.

Figure 6(b) indicates that the placement of damping devices in the structure will affect the distribution of the strength as well as the mass of the structure. In the X direction, CS-SW, in all three earthquakes, show largest displacement when compared to the CS-FVD. Furthermore, when observed in CS-FVD, a spike in displacement occurs at 5000 m tp 5500 m which may indicate that at these heights there is a possibility of local soft-story due to irregular load distribution. From the results, it can be considered to attach earthquake dissipation device on the non-major axes to improve the structure's ability to control the displacement, so that the performance of the structure can be improved.

Considering the displacement, CS-FVD has a smaller displacement which indicates that CS-FVD has a smaller stiffness result when compared to CS-SW. The difference in earthquake dissipation system will affect the stiffness which will also affect the displacement, time period, and storey drift (Trimurtiningrum et al., 2021). Previous studies have indicated that structure utilizing shear walls as seismic energy dissipation mechanism tend to exhibit greater lateral displacement compared to those employing bracing systems, wherein Fluid Viscous Dampers (FVDs) can be considered an advanced evolution of conventional bracing components (Galvindy & Lim, 2023; Tatang & Tjong, 2022)(Riaz et al., 2023).

Drift ratio is the ratio of the lateral displacement of a floor to its height. This parameter is an important indicator used to evaluate the relative deformation between floors as well as the dynamic response caused by lateral loads (Mincigrucci et al., 2023; Peng et al., 2023) . The drift ratio is obtained by dividing the difference in displacement between floors by their height. The drift ratio is one aspect that needs to be controlled in structural planning, where previous research states that the drift ratio that can meet the ultimate limit requirements for building planning is 0.5% of the floor height (Gao & Lu, 2023).

Figure 7 shows the drift ratio generated by the three types of earthquakes. Figure 5 (a) shows the results of the analysis in Y direction as the main axis. On the result of CS-SW, the ChiChi earthquake has a larger ratio when compared to Kobe and Yushu, which have ratio of 0.00174, 0.00146, and 0.00141, respectively. The same is observed in the drift ratio generated by CS-FVD, which ChiChi earthquake has the largest ratio and followed by Kobe and Yushu. The respective ratios obtained were 0.00167, 0.00133, and 0.00136. The drift ratios produced by both CS-SW and CS-FVD structures do not exceed the given limit of 0.0025. The similar behavior is shown in the X-axis. The drift ratio generated by CS-SW has a larger value when compared to CS-FVD, which for Chichi, the drift ratio in cs-sw reaches about 0.00121, while in CS-FVD, the resulting ratio is 0.00074. the Kobe earthquake exhibits a drift ratio of 0.00087 for CS-SW and 0.00076 for CS-FVD. While in Yushu, the ratio obtained in CS-SW reached 0.00098 and 0.00050 for CS-FVD. The recapitulated results of the modelling drift ratio are presented in Table 3.

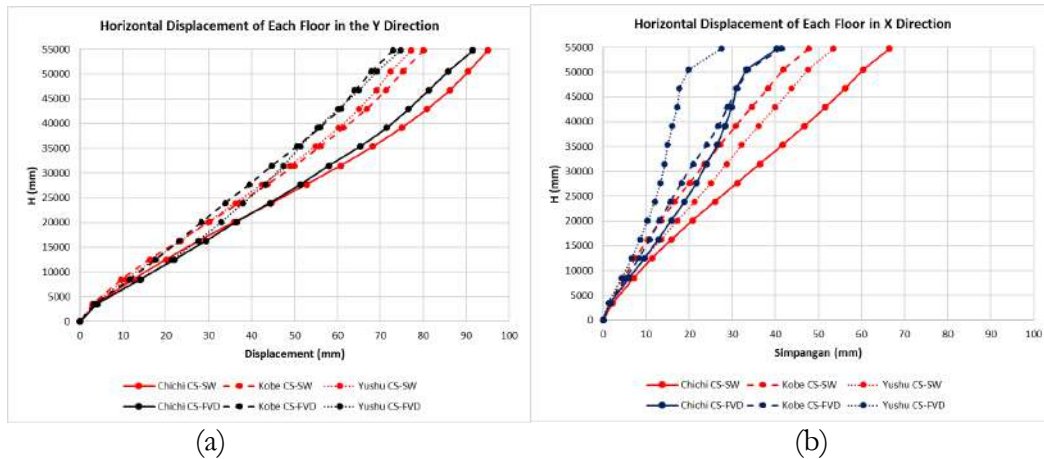


Figure 6. Horizontal Displacements that occur at: (a) Y Direction, (b) X Direction

Table 3. Drift Ratio that Obtained from Modelled Structure

Accelogram	Drift Ratio			
	Y Direction		X Direction	
	CS-SW	CS-FVD	CS-SW	CS-FVD
ChiChi	0,00174	0,00167	0.00121	0.00074
Kobe	0,00146	0,00133	0.00087	0.00076
Yushu	0,00141	0,00136	0.00098	0.00050

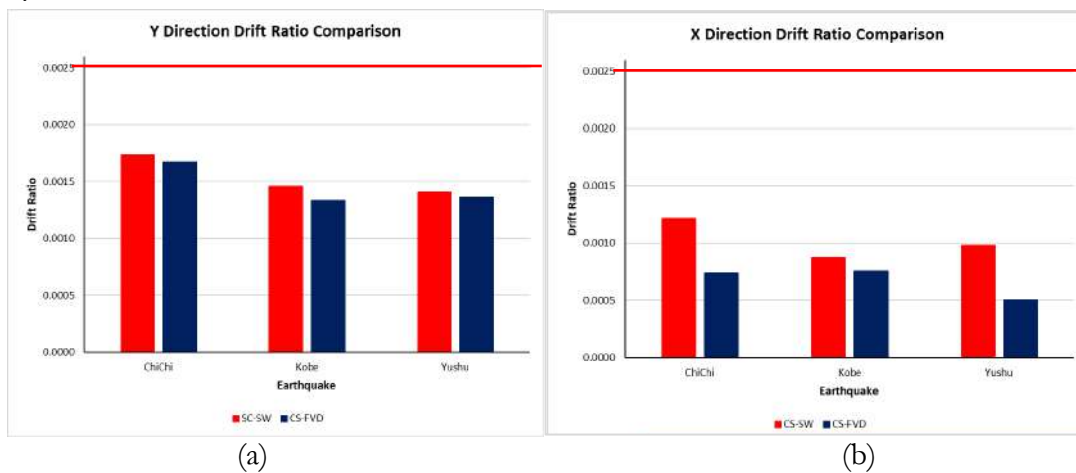


Figure 7. Drift Ratio that Generated from: (a) Y Direction, (b) X Direction

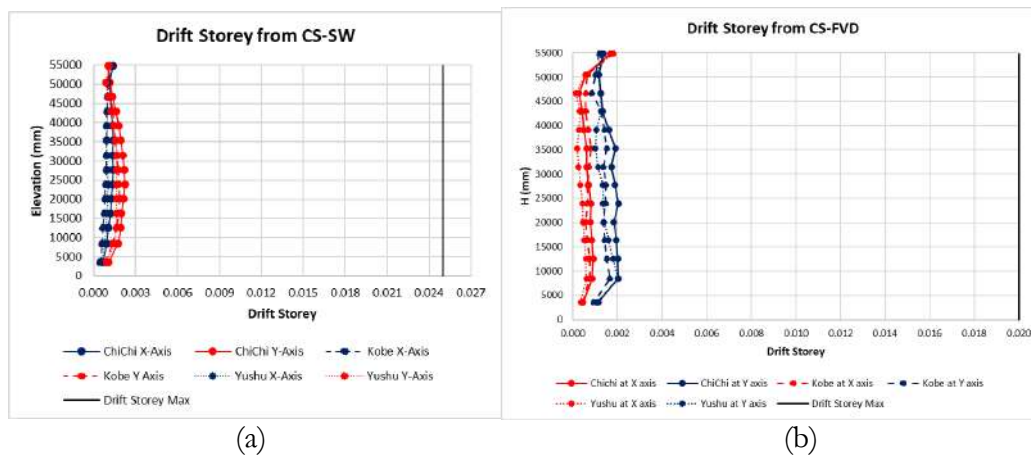


Figure 8. Drift storeys that Occur at: (a) CS-SW, (b) CS-FVD

Storey drift is the difference in lateral displacement between two consecutive storeys in a building structure caused by lateral loads. Storey drift is able to evaluate the seismic performance of a building because it indicates the relative deformation that occurs between floors, which can affect the stability of the structure. Standards define that the permissible storey drift in buildings of risk categories I and II should not exceed the 2% limit to reduce the risk of structural collapse (Akbar & Candra, 2018).

Figure 8 shows the storey drift that occurs in CS-SW and CS-FVD. From Figure 8 (a), it is found that the storey drift tends to increase from the base of the structure to a height of 25000 mm. This shows that the structure experiences higher relative deformation when compared to the structure at the ground floor and roof floor. The largest storey drift is shown in the Y-direction ChiChi earthquake graph which is 0.00226 located at the 6th floor. The is able to fulfil the requirement of not exceeding the of 0.025.

The different displacement behavior is shown in Figure 8(b). Figure 8(b) shows a higher degree of irregularity compared to Figure 8(a). In Figure 8(b), the highest storey drift is at a height of 23900 mm with value of 0.00204. However, it should be noted that the graph has a spike in displacement that occurs at a building height of 10000 mm. When viewed at a height of 10000 mm, the CS-SW structure with the ChiChi earthquake has a storey drift of 0.00173, while CS-FVD produces a 17% greater of 0.00202. This shows that the use of FVD makes the structure more flexible when receiving earthquake loads, especially on the 1st and 2nd floor structures since these locations are the first floors where FVD was installed.

Hysteresis Energy, Structure Performance Level

Hysteresis energy is the energy absorbed and dissipated by the structure during the lateral load cycle, especially during inelastic deformation due to dynamic loads. The calculation of hysteresis energy is done by calculating the area formed from the hysteresis curve formed from the force and displacement diagram. This area represents the total energy absorbed and released by the structure during the deformation process. There are several parameters that can affect the amount of hysteresis energy, one of which is the earthquake resisting system used on the structure (Azhar et al., 2024; Ras & Boumechra, 2016). Energy dissipation is a concept that describes the loss or reduction of energy in a structure under dynamic loading. If the structure is loaded by a lateral load, the structure will deform by an amount equal to the applied load (Kumalasari et al., 2022).

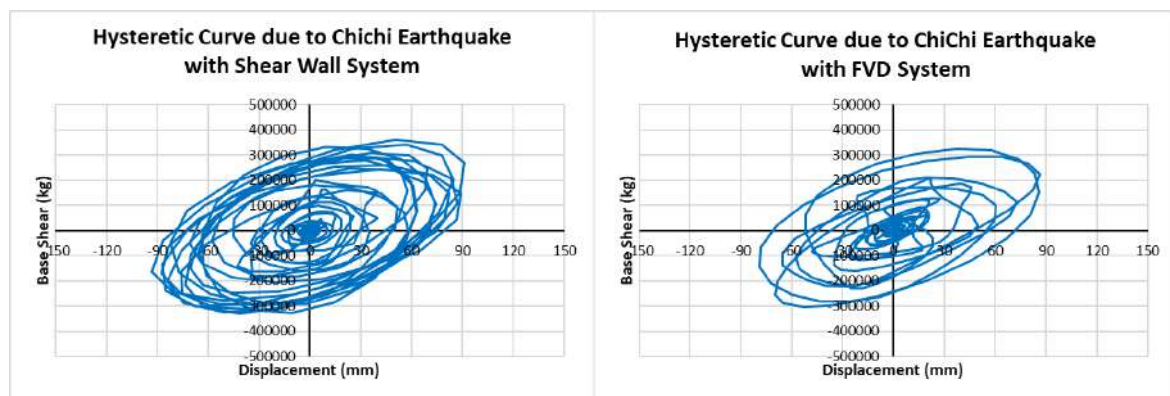
The hysteresis curves formed during loading are illustrated in Figures 9, 10, and 11, from which it can be seen that the CS-DW structure is able to dissipate more energy when compared to the CS-FVD. In the ChiChi earthquake, the hysteresis energy absorbed by the CS-FVD was 68,993,560.46 kgmm, while the CS-FVD structure dissipated 87,644,153.08 kgmm, which is 21% greater than the CS-FVD. A similar pattern was observed for the Kobe earthquake, where the hysteresis energy of the CS-SW reached 57501448.10 kgmm, 36% greater than that of the CS-FVD at 36522871.99 kgmm. Meanwhile, for the Yushu earthquake, the hysteresis energy of the CS-SW structure was obtained at 59,627,175.50 kgmm, while the CS-FVD obtained an energy absorption of 37,088,591.76 kgmm. The hysteresis energy that obtained by the structures are listed in Table 4.

Table 4. Hysteresis Energies Occured at the Structure Modelled

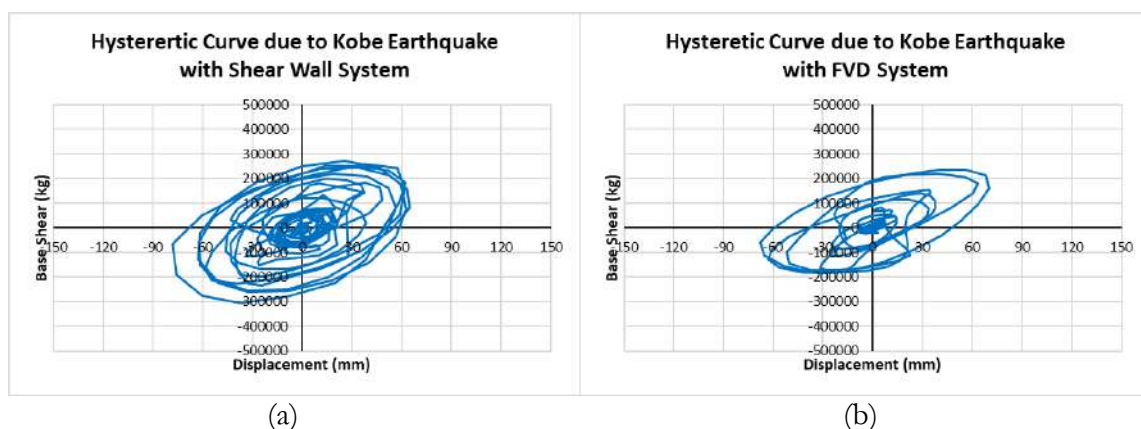
Earthquake	Hysteresis Energies (kg-mm)	
	CS-SW	CS-FVD
ChiChi	87.644.153,08	68.993.560,46
Kobe	57.501.448,10	36.522.871,99
Yushu	59.627.175,50	37.088.591,76

In addition to the ability to dissipate energy, the hysteresis curve is also able to show the value of the shear force that the structure can resist. In the ChiChi earthquake, the maximum shear force that CS-SW was able to resist was 388794.14 kg while CS-FVD was able to resist a maximum shear force of 327687.55 kg. While in the Kobe earthquake, as illustrated in Figure 9, the CS-SW structure was able to resist a maximum shear force of 277304.28 kg. The shear force that the CS-FVD was able to resist due to the Kobe earthquake was 207295.84 kg, which was 25% drift of the CS-SW. Meanwhile, in Figure 9, CS-SW is able to resist the maximum shear force of 329032.87 kg with a difference of 35.78% compared to CS-FVW which is 211300.22 kg.

The performance level of a structure is the ability of the building structure to withstand earthquake loads. These parameters can be used to evaluate the performance of the structure after an earthquake. Table 5 and Table 6 show the performance levels of the structures after being loaded by lateral forces. CS-SW and CS-FVD were able to stay within the Immediate Occupancy (IO) performance level for all three earthquake scenarios analysed, namely the ChiChi, Kobe and Yushu Earthquakes. This indicates that both systems were able to maintain their structural reliability with no significant damage, so that the buildings could still be used after the earthquakes without requiring major repairs. However, there are differences in the maximum displacement values and drift ratio between the two systems. CS-FVD decreased the maximum displacement and drift ratio values when compared to CS-SW, indicating that the use of FVD can provide better performance in controlling structural deformation.



(a) (b)
Figure 9. Hysteretic curves derived due to ChiChi Earthquake loading by (a) CS-SW, (b) CS-FVD



(a) (b)
Figure 10. Hysteretic curves derived due to Kobe Earthquake loading by (a) CS-SW, (b) CS-FVD

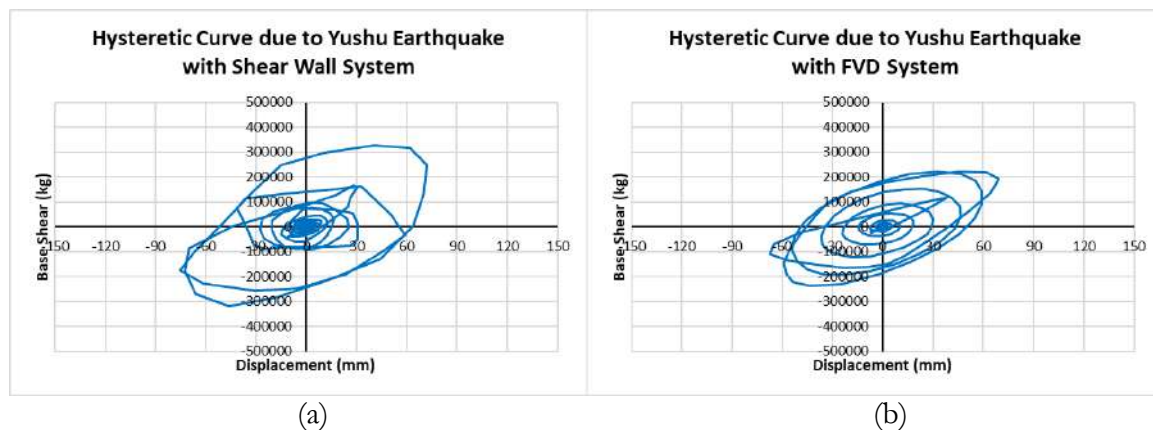


Figure 11. Hysteretic curves derived due to Yushu Earthquake loading by: (a) CS-SW, (b) CS-FVD

In the ChiChi Earthquake, the maximum displacement that occurred in CS-SW was 93.11 mm, while in CS-FVD it decreased to 86.15 mm. The drift ratio also reduced from 0.00170 to 0.00157. A similar trend was observed for the Kobe and Yushu Earthquakes, where the maximum displacement and drift ratio in CS-FVD were smaller than those in CS-SW. This reduction in displacement and drift ratio indicates that FVD can enhance earthquake energy dissipation more effectively than conventional shear wall systems. In other words, structures with FVDs have the potential to reduce the risk of non-structural damage and can be used as an alternative seismic energy dissipation system in the design of earthquake-resistant structures, especially for buildings that require higher flexibility in reducing lateral forces due to earthquakes.

Table 5. Performance Level on CS-SW

Earthquake	Maximum Displacement	Drift Ratio	Performance Level
ChiChi	95,061	0,00174	Immediate Occupancy (IO)
Kobe	80,014	0,00146	Immediate Occupancy (IO)
Yushu	77,180	0,00141	Immediate Occupancy (IO)

Table 6. Performance Level of CS-FVD

Earthquake	Maximum Displacement	Drift Ratio	Performance Level
ChiChi	91,536	0,00167	Immediate Occupancy (IO)
Kobe	72,933	0,00133	Immediate Occupancy (IO)
Yushu	74,669	0,00136	Immediate Occupancy (IO)

Conclusion

Based on the analysis of structural stability, it can be concluded that FVD can be used as an alternative energy dissipation system that is effective in improving structural performance and stability. This is shown by the decrease in horizontal deviation in CS- FVD, which was 0.12% in the ChiChi and 3.54% in the Kobe Earthquake. However, in the Yushu Earthquake, the horizontal deviation increased by 5.84% compared to CS-SW. In terms of drift ratio, CS-FVD showed a reduction in drift ratio performance level to 0.07% due to the ChiChi, 0.10% due to the Kobe, and 0.20% due to the Yushu Earthquake. The average storey drift also decreased with a reduction of 2.65% due to the ChiChi, 7.63% due to the Kobe, and 0.99% due to the Yushu Earthquake. In addition to structural stability, the comparison of structural performance shows that CS-FVD has a good performance when compared with CS-SW although in some aspects the resulting value is relatively small. The amount of hysteresis energy that occurs in CS-FVD reflects its effectiveness in dissipating earthquake energy, with a difference of 0.21% due to the ChiChi, 0.36% due to the Kobe, and 0.72% due to the Yushu Earthquake. Based on the results of the research conducted, the use of FVD can be considered as a replaceable earthquake energy dissipation element that can

facilitate the repair process in the event of post-earthquake damage. Thus, this system is expected to improve the efficiency of installation, maintenance, and service life of buildings, as well as provide a more flexible solution in mitigating earthquake impacts on building structures in the future.

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