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Unlocking Resilience: Examining the Influence of Fluid Viscous Dampers on Seismic Performance of Reinforced-concrete Structures in Earthquake-prone Regions

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Abstract
In high seismicity regions like Algeria, the seismic performance of structures is of paramount importance. This study investigates the effectiveness of fluid viscous dampers (FVDs) in enhancing the seismic resilience of a 12-story (G+12) reinforced concrete structure. By utilizing Etabs and SeismoSoft softwares, a comparative analysis is conducted between two structural configurations: one with a traditional fixed base and another incorporating fluid viscous dampers. The incorporation of FVDs aims to mitigate the seismic impact by dissipating energy, thereby reducing base shear, displacement, and acceleration during seismic events. The structure's location in a high seismicity zone necessitates robust design strategies to ensure safety and structural integrity. This paper presents a comprehensive analysis of the seismic response and advanced simulation framework providing detailed results on key parameters. The findings highlight the potential of fluid viscous dampers to significantly improve the seismic performance of reinforced concrete structures, offering a promising solution for earthquake-prone areas.

Keywords
seismic analysis, time history data, isolated structures, fluid viscous dampers

1 Introduction

Earthquakes pose significant risks to both human life and infrastructure, causing widespread devastation and economic losses globally. The design and engineering of structures in earthquake-prone areas require specialized considerations beyond typical structural norms. Architects and engineers are challenged to develop innovative techniques that can effectively mitigate the destructive impact of seismic forces on buildings.

Traditionally, earthquake-resistant design has focused on fortifying structures with elements such as shear walls [1], braced frames [2], or moment-resistant frames [3]. While effective in enhancing structural robustness, these methods can lead to undesirable consequences such as excessive floor accelerations or significant inter-story drifts during earthquakes. In response to these challenges, seismic isolation has emerged as a promising alternative.

In the realm of structural engineering and earthquake resilience, fluid viscous dampers (FVDs) have emerged as a pivotal technology for mitigating the adverse effects of dynamic loads [4–7]. These sophisticated devices leverage the principles of fluid mechanics to provide controlled energy dissipation, thereby enhancing the structural performance of buildings and infrastructure subjected to seismic activities [8, 9], wind forces [10], and other dynamic excitations. The integration of FVDs into structural systems is not merely a matter of innovation [11–13] but a necessity for safeguarding human lives and minimizing property damage in vulnerable regions.

Fluid viscous dampers operate by converting kinetic energy from structural movements into heat, which is dissipated through the viscous fluid contained within the damper. This process is facilitated by a piston moving

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through the fluid, generating resistance proportional to the velocity of motion [14, 15]. The result is a significant reduction in the amplitude of oscillations, contributing to the stability and longevity of the structure. The adaptability and effectiveness of FVDs make them an invaluable component in modern construction, offering a versatile solution to the challenges posed by natural and man-made forces.

As urban development intensifies and the quest for taller, more complex structures continues [16, 17], the role of fluid viscous dampers becomes increasingly critical. Fluid viscous dampers (FVDs) offer several notable benefits over other types of dampers. One of their primary advantages is their energy dissipation efficiency. FVDs are highly effective at dissipating energy over a wide range of frequencies and amplitudes [18], converting kinetic energy from structural movements into heat, which is efficiently dissipated through the viscous fluid. This provides consistent performance. In comparison, while friction dampers [19–21] also dissipate energy effectively, their performance can be less consistent due to wear and tear over time. Tuned mass dampers (TMDs) [22–24] are effective but typically target a narrow frequency range. Another advantage of FVDs is their adaptability. They can be tailored to specific damping requirements by adjusting the fluid viscosity and piston design [25], making them suitable for a variety of applications, from buildings to bridges. Other dampers, such as TMDs, are more specialized and usually designed for specific frequency ranges, limiting their adaptability. Friction dampers may require frequent adjustments and maintenance to maintain their effectiveness. FVDs also boast low maintenance requirements and long service lives due to their robust design and minimal wear components. In contrast, friction dampers often require regular maintenance to ensure the friction surfaces remain effective, and TMDs may need periodic tuning and inspection to ensure optimal performance. Additionally, FVDs provide reliable performance under various environmental conditions, including temperature variations and long-duration seismic events. The performance of friction dampers can be influenced by environmental factors such as humidity and temperature, which can affect the friction surfaces, while TMDs may be less effective in conditions that vary significantly from their design parameters.

Structural damage analysis is essential for optimizing the design and placement of fluid viscous dampers (FVDs) in high-rise structures. By conducting a comprehensive impact analysis, engineers can understand how damage affects the overall performance and safety of a structure. This involves simulations or modeling to predict how the structure might behave under future dynamic loads or failure scenarios, allowing for precise placement of FVDs where they will be most effective. Based on the damage analysis [26–28], engineers can also plan and design appropriate repair and rehabilitation measures to restore and enhance the structure's functionality and safety. This ensures that FVDs are integrated in a way that addresses specific vulnerabilities identified during the analysis.

This article investigates the impact of fluid viscous dampers on the seismic response of a 12-story (G+12) reinforced concrete structure. Utilizing the advanced capabilities of Etabs [29] and SeismoSoft [30] softwares, the study examines two configurations: a conventional fixed-base structure and one enhanced with fluid viscous dampers. Positioned in a high seismicity zone in Algeria, the structure's performance under seismic loads is critically assessed. Key parameters such as base shear, displacement, and acceleration are meticulously analyzed. The results reveal that FVDs significantly improve the seismic resilience of reinforced concrete structures, offering a promising solution for earthquake-prone regions.

2 Modeling of the structure

The building in question is a reinforced concrete structure (G+12) with a basement, intended for residential and commercial use, located in the wilaya of Boumerdès, a high seismicity zone (Zone VI) classified in Group 2 according to the Algerian Seismic Regulations [31]. It comprises a shopping center on the ground floor, a parking garage in the basement, and includes both a staircase and an elevator shaft.

The plan and elevation dimensions are as follows:

- Building width: 14.1 m
- Building length: 27.3 m
- Total building height: 47.54 m
- Basement height: 3.06 m
- Ground floor height: 4.08 m
- Floor height: 3.40 m.

The structure, as shown in Fig. 1, is constructed on firm ground. The sections used for the columns are 30 × 45 cm^2 and 30 × 35 cm^2 for both principal and secondary beams that are in the X and the Y directions, respectively.

As for the columns, Table 1 illustrates the dimensions calculated.

The material properties used in the study are as follows:

- Concrete's compressive strength: f_{c28} = 25 MPa;
- Concrete's modulus of elasticity E_c = 32.164 MPa;

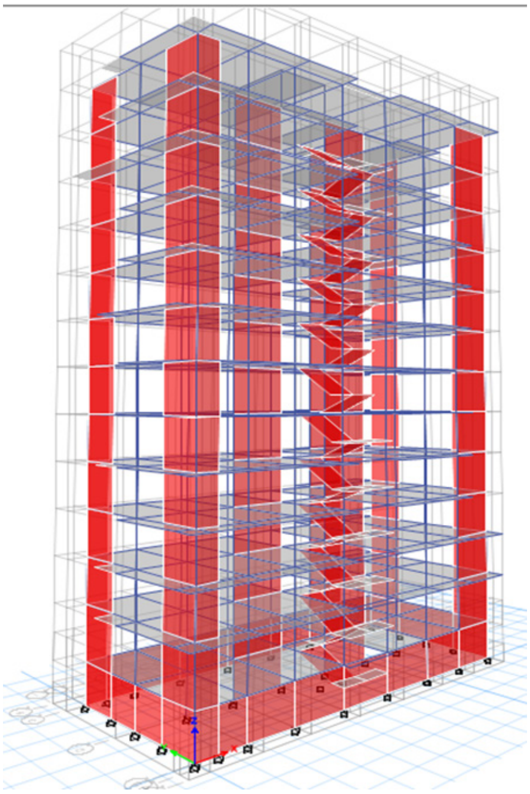


Fig. 1 Elevation view of the structure

Table 1 Column sections

Level	Sections (cm^2)
11	30 × 40
10	30 × 45
7-8-9	35 × 50
6	35 × 55
5	40 × 60
4	40 × 65
2-3	40 × 70
1	40 × 75
Ground floor	40 × 80
Basement	40 × 80

- Concrete's shear modulus: $G = 13401$ MPa;
- Poisson's ratio: $v = 0.2$;
- Yield strength of longitudinal steel = 400 MPa;
- Yield strength of transversal steel = 215 MPa.

3 Fluid viscous dampers

Fluid viscous dampers (FVDs) as illustrated in Fig. 2 operate by applying a resistive force only when in motion, without adding stiffness to the structure or bearing any static load. However, stiffness can be incorporated into these dampers if needed.

An FVD consists of a piston moving through a viscous fluid, creating significant pressure. This piston is equipped with specially designed orifices to generate optimized pressure based on velocity. The higher the velocity, the greater the resistive force produced. This relationship is generally defined by the following equation:

$$F = CV^{\alpha}, \tag{1}$$

where:

- F: Axial damping force supported by the FVD;
- C: Damping constant;
- V: Velocity of the FVD;
- α: Damping exponent.

The rheological model frequently employed to depict the characteristics of fluid viscous dampers is the "viscous damping model" as illustrated in Fig. 3 [32], which incorporates both a spring element and a damper element. This combination accurately models the behavior of fluid viscous dampers across various loading scenarios.

3.1 Determination of nonlinear properties of the FVD

The data provided by the Etabs software include the axial resistive force F and the maximum velocity of our damper V. Both properties are important for the design of our damper, in our case they are given as follows: $F = 500$ kN and $V = 0.508$ m/s.

3.2 The damping exponent α

The damping exponent, represented by α, should be between 0.3 and 0.5 ($0.3 < \alpha < 0.5$). We will choose $\alpha = 0.3$ because a damping coefficient of 0.3 provides an optimal balance by retaining a significant amount of energy absorbed per cycle while minimizing stresses on surrounding structural elements.

3.3 The damping constant C_D

The resistance force and maximum velocity of our damper provided by the Etabs software are defined as $F = 500$ kN and $V = 0.508$ m/s, respectively. Table 2 provides the damping constant values for each force case.

3.4 The stiffness of the damper K_D

Table 3 provides the suggested stiffness values for Taylor's fluid viscous dampers [32]. For our case we will take $K_D = 164622.2$ kN/m.

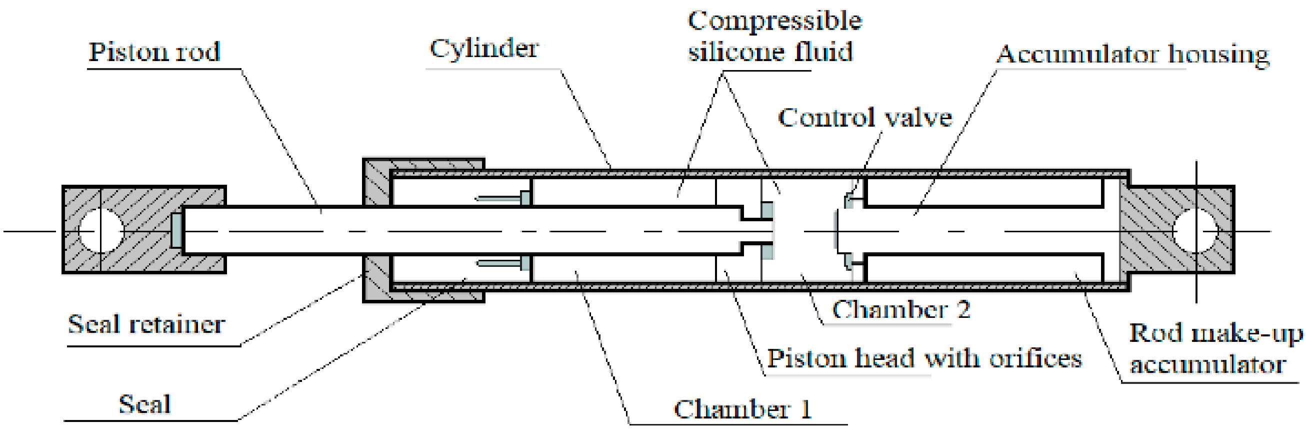


Fig. 2 Fluid viscous damper properties

Fig. 3 Rheological model for FVDs

Table 2 Damping constant C_D

Rated force (kN)	Suggested C values in kN - (s/m)$^{1/0.3}$ where $F = C^{*}\ (V)^{0.3}$			
	Maximum velocity			
	0.127 m/s	0.254 m/s	0.381 m/s	0.508 m/s
250	454.6	369.2	326.9	299.9
500	909.1	738.4	653.8	599.8
750	1363.7	1107.6	980.8	899.7
1000	1818.2	1476.8	1307.7	1199.6
1500	2727.3	2215.3	1961.5	1799.3
2000	3636.4	2953.7	2615.4	2399.1
3000	5909.2	4799.7	4250.0	3898.6
4000	7438.1	6041.6	5349.7	4907.3
6500	11983.6	9733.7	8618.9	7906.2
8000	14876.2	12083.2	10699.3	9814.6

* We will take C_D = 599.8 kN·s/m.

Table 3 Stiffness K_D

Taylor devices series number	Force (kN)	Stiffness (kN/m)
17120	250	110285.00
17130	500	164622.20
17140	750	245182.00
17150	1000	328368.80
17160	1250	490364.00
17170	1500	525390.00
17180	1750	840624.00
17190	2000	1050780.00
17200	2250	1707518.00
17210	2500	2101560.00

3.5 Determining the dimensions of the FVD

Table 4 provides the dimensions of the viscous dampers for each case of maximum resistive force. Based on Table 4, the dimensions of the FVD used are detailed in Fig. 4.

Following a comprehensive evaluation [17, 33–37], various arrangements and configurations of fluid viscous dampers (FVDs) were studied to achieve optimal performance and effectively limiting structural vibrations. Our research included testing different positioning options while considering practical constraints and engineering principles. After careful analysis and rigorous testing, we concluded that placing the FVDs diagonally across the height of the structure yielded the best results (see Fig. 5).

This arrangement maximized damping efficiency while minimizing vibration transmission throughout the structure, significantly reducing structural response and enhancing system stability under dynamic loads.

4 Results and discussion

In our study, we obtained seven accelerograms from the National Center for Seismic Engineering, recorded at seven different stations during the Boumerdès earthquake on May 21, 2003, which had a magnitude of 6.8 on the Richter scale. As per the requirements of Eurocode 8 [38], these accelerograms were processed using SeismoSoft v21 software to derive equivalent artificial accelerograms. Fig. 6 depicts a sample of the artificial accelerogram generated specifically for Dar El Beïda (Algeria).

4.1 Hysteresis of FVDs

Fluid viscous dampers function by dissipating energy through the passage of fluid through orifices. They utilize the resistance generated by this flow to reduce the effects of seismic forces. Fig. 7 shows the characteristic hysteresis loops of these dampers, representing the relationship

Table 4 Dimensions viscous dampers for each case of max resistive force

Force (kN)	Taylor devices model	Spherical bearing bore diameter (mm)	Mid-stroke length (mm)	Stroke (mm)	Clevis thickness (mm)	Maximum clevis width (mm)	Clevis depth (mm)	Bearing thickness (mm)	Maximum cylinder diameter (mm)	Weight (kg)
250	17120	38.10	787	±75	43	100	83	33	114	44
500	17130	50.80	997	±100	55	127	102	44	150	98
750	17140	57.15	1016	±100	59	155	129	50	184	168
1000	17150	69.85	1048	±100	71	185	150	61	210	254
1500	17160	76.20	1105	±100	77	205	162	67	241	306
2000	17170	88.90	1346	±125	91	230	191	78	286	500
3000	17180	101.60	1441	±125	117	290	203	89	350	800
4000	17190	127.00	1645	±125	142	325	273	111	425	1088
6500	17200	152.40	1752	±125	154	350	305	121	515	1930
8000	17210	177.80	1867	±125	178	415	317	135	565	2625

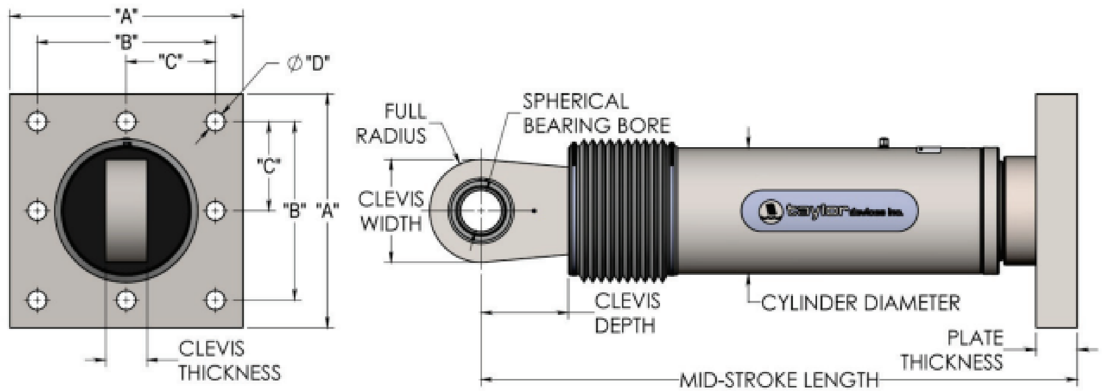


Fig. 4 Fluid viscous damper details

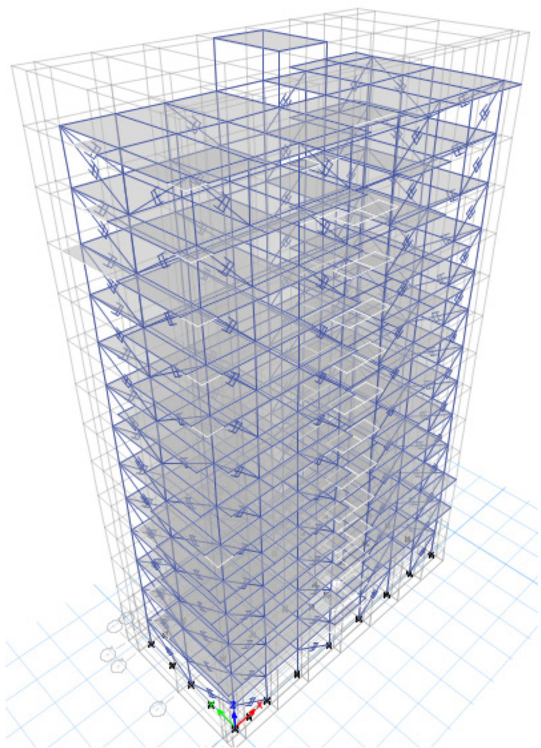


Fig. 5 FVDs placement in the structure

between the applied force and the resulting displacement during oscillation cycles. The large hysteresis loops demonstrate the significant capacity of these dampers to dissipate energy. When the structure oscillates due to earthquakes, the fluid circulating through the orifices creates resistance, thereby absorbing a substantial amount of energy.

This dissipation helps mitigate the damage caused by earthquakes to the structure. The ability of fluid viscous dampers to absorb energy and attenuate the effect of seismic forces helps improve the resilience of structures and limit potential damage during earthquakes.

4.2 Base shear

Fig. 8 (a), (b) and Fig. 9 (a), (b) compare the shear forces at the base for the two cases studied in the X and Y directions. These illustrations demonstrate a reduction in shear forces for the damped structure compared to the one anchored on a fixed base. A detailed analysis of the specific data and values presented in the figures will provide a better understanding of the reduction in shear force achieved through the application of fluid viscous dampers in the X and Y directions.

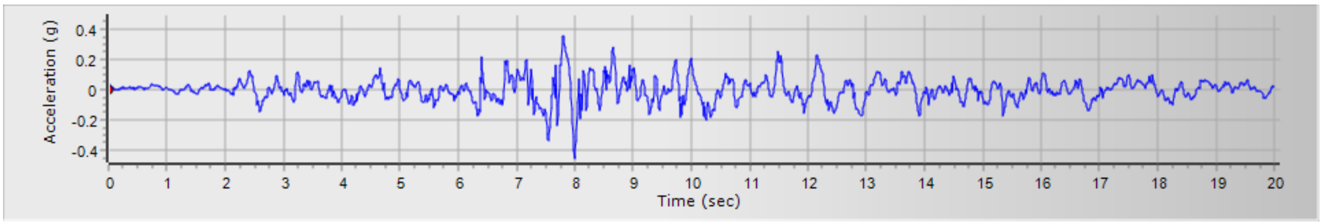


Fig. 6 Time history data for Dar El Beïda (Algeria)

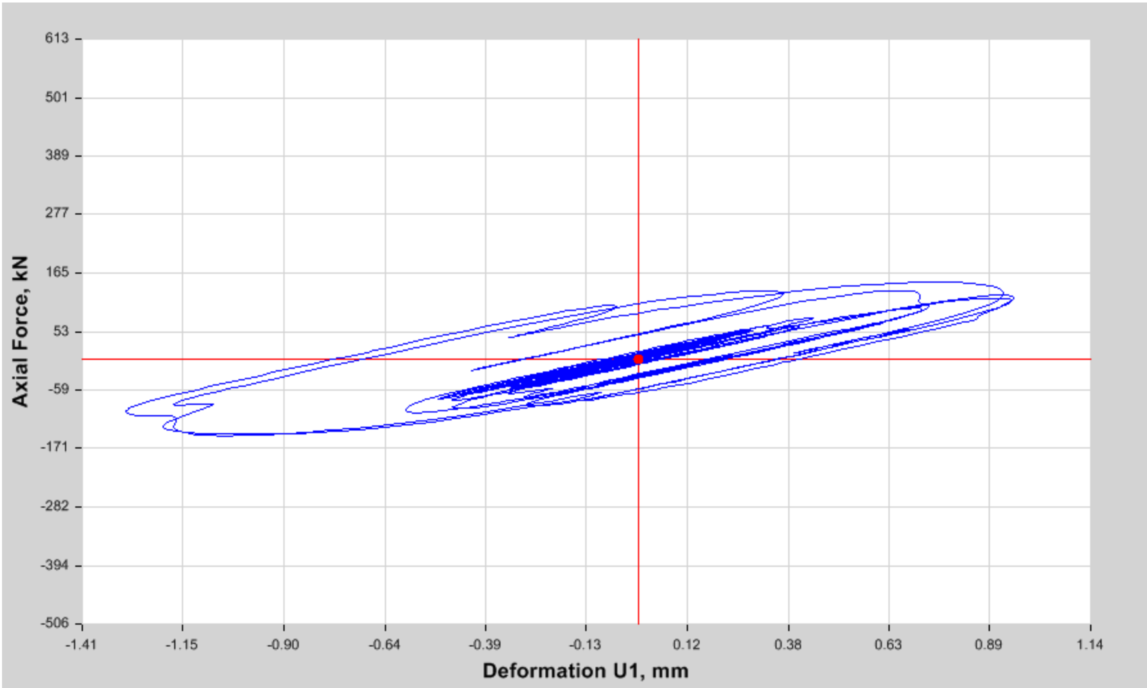
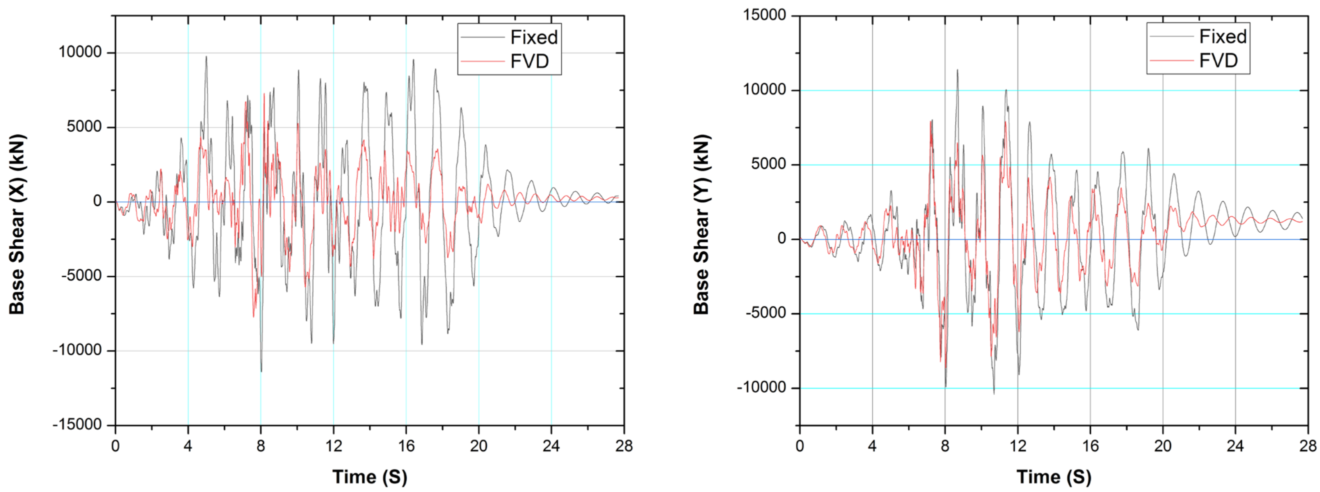


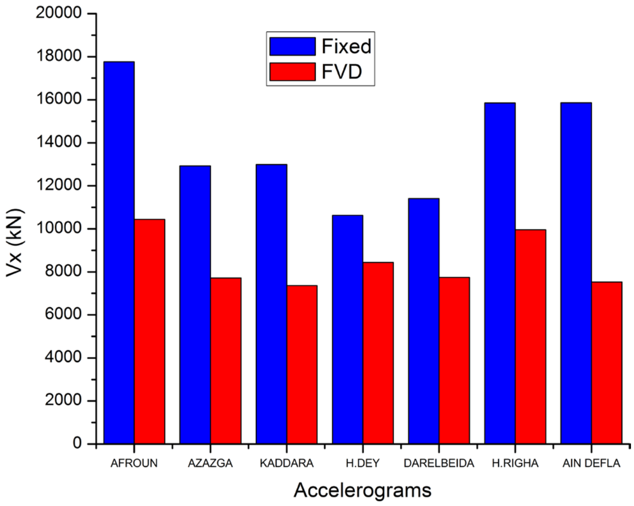
Fig. 7 Hysteresis loops of the damper



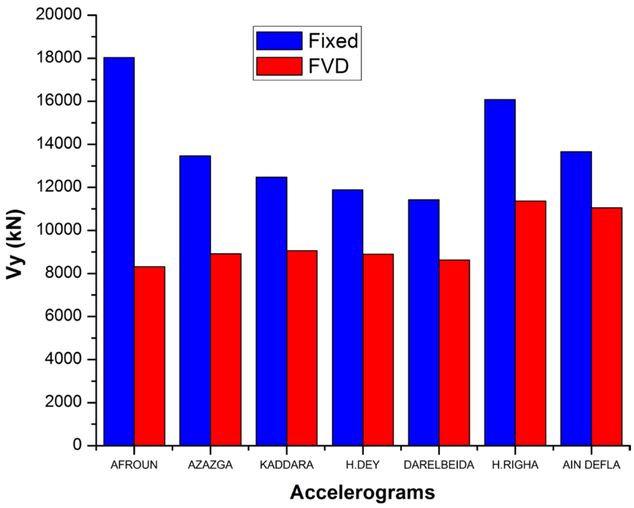
(a) (b)

Fig. 8 Base shear comparison for the two models (fixed-base, FVD isolated) in Dar El-Beïda; (a) in the X direction; (b) in the Y direction

Fig. 10 illustrates the significant reduction in shear forces at the base for the two configurations in the X and Y directions. In the X direction, the reduction is approximately 40% for the structure equipped with dampers compared to the standard structure. Similarly, in the Y direction, the reduction in shear force is around 31% for a structure with FVDs, compared to a structure on a fixed base. These results demonstrate that the shear forces at the base of the damped structure are significantly lower than those of the structure on a fixed base. The reduction in shear forces



(a)



(b)

Fig. 9 Base shear comparison for the two models (fixed-base, FVD isolated) for different accelerograms; (a) in the X direction; (b) in the Y direction

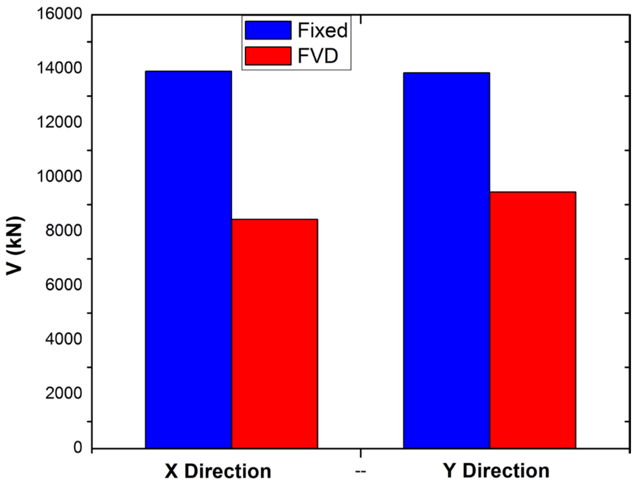


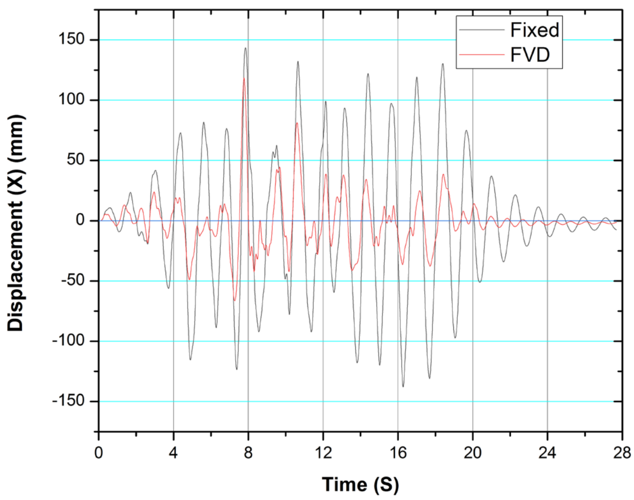
Fig. 10 Average of base shear forces in the X and Y directions

is attributed to the effective attenuation of accelerations transmitted to the superstructure by the implementation of dampers. The study confirms the effectiveness of the FVD system in reducing shear forces at the base.

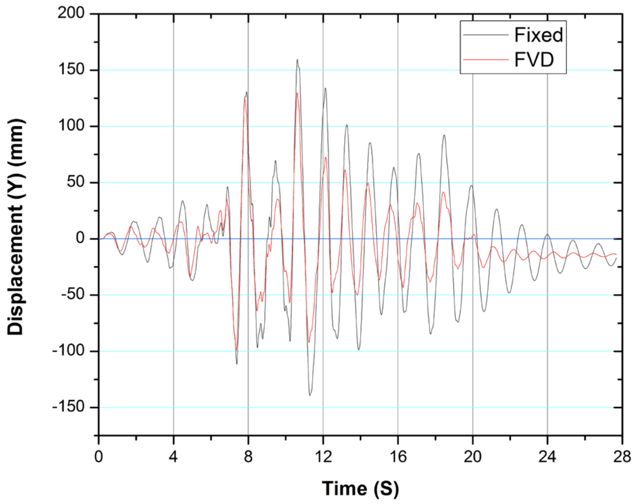
4.3 Displacement

Figs. 11–13 compare the displacements for the two models studied in the X and Y directions. Compared to a fixed base, the displacements of the structure equipped with fluid viscous dampers decrease in Figs. 11–13. This reduction highlights the importance of these dampers in improving the resistance and durability of the structure as well as the safety of the occupants.

From Fig. 14, it can be seen that the maximum displacement in the X direction decreases by 35% in a structure

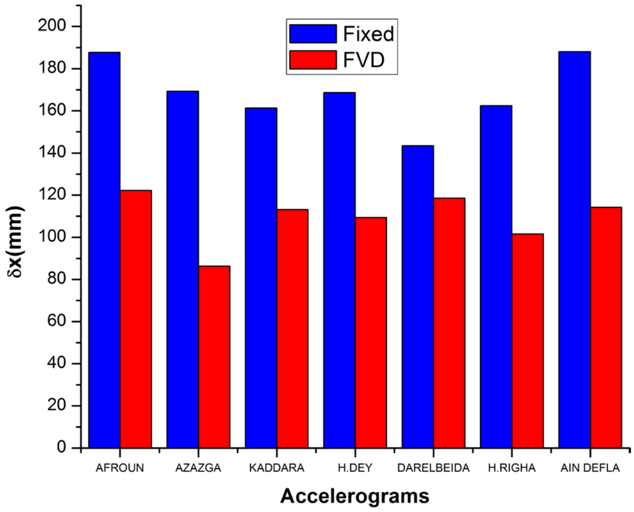


(a)

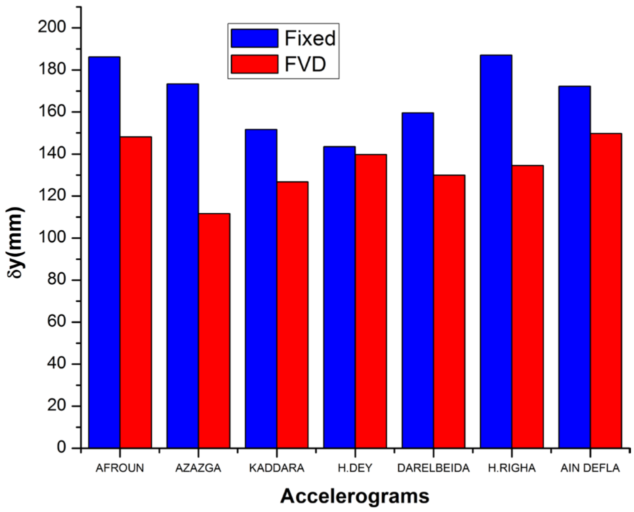


(b)

Fig. 11 Displacement comparison for the two models (fixed-base, FVD isolated) in Dar El-Beïda; (a) in the X direction; (b) in the Y direction

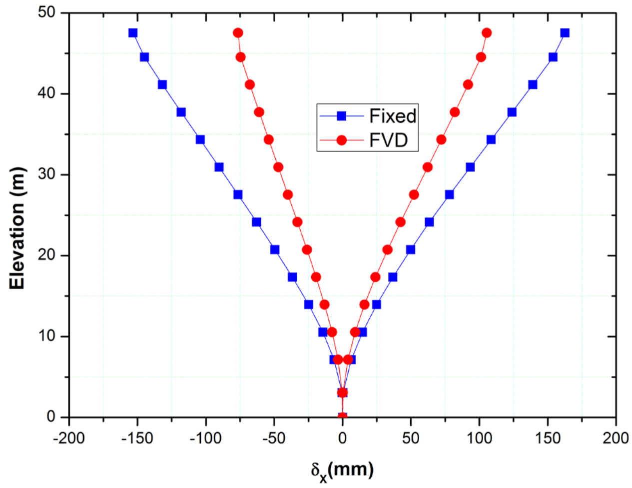


(a)

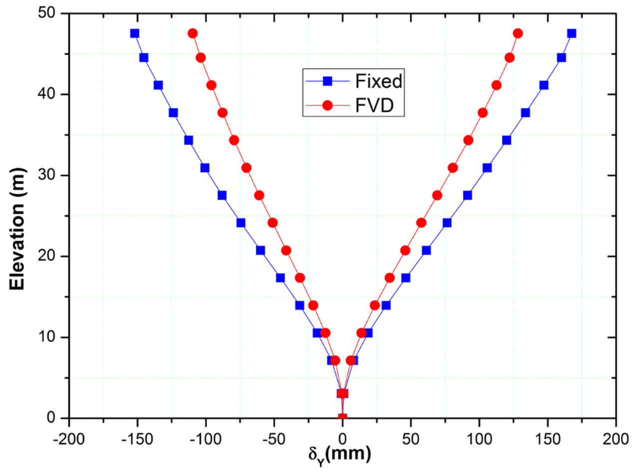


(b)

Fig. 12 Displacement comparison for the two models (fixed-base, FVD isolated) for different accelerograms; (a) in the X direction; (b) in the Y direction



(a)



(b)

Fig. 13 Average displacement for different levels; (a) in the X direction; (b) in the Y direction

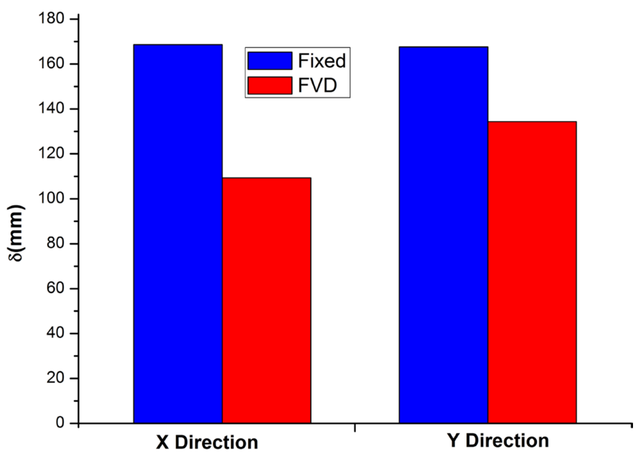


Fig. 14 Average displacement at the top of the structure in the X and Y directions

dampened by FVDs. In the Y direction, the reduction is around 20% for a structure equipped with FVDs. This reveals that fluid viscous dampers are highly effective in reducing displacements at the top of the structure. By dissipating vibrational energy, reducing resonances, and responding quickly to movements, these devices ensure better stability and safety of structures against dynamic forces.

The evaluation of inter-story displacements, also known as drifts, and their distribution throughout the height of the structure is crucial for assessing seismic performance, as it is directly related to structural damage. Fig. 15 (a), (b) represents the inter-story displacements for the isolated structure and the fixed-base structure. In the case of the isolated structure with FVD isolation, the inter-story displacements are significantly reduced. The damped structure behaves more rigidly, with minimal inter-story movements. In contrast, the conventional structure exhibits substantial inter-story displacements, indicating greater vulnerability to seismic forces. When comparing

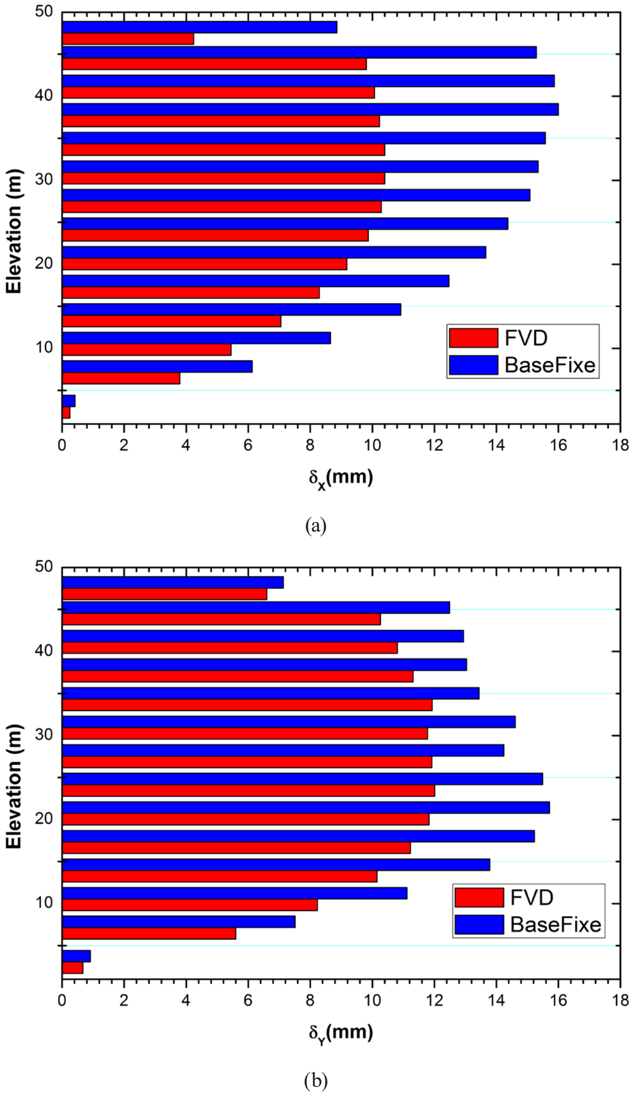


Fig. 15 Drift comparison for the two models (fixed-base, FVD isolated) for different levels; (a) in the X direction; (b) in the Y direction

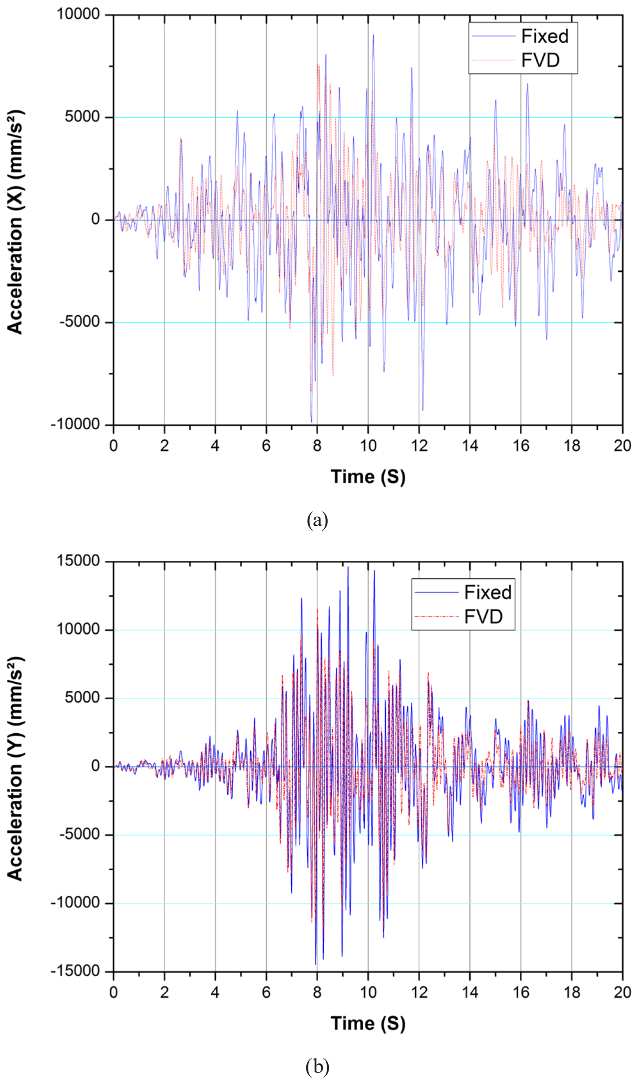


Fig. 16 Acceleration comparison for the two models (fixed-base, FVD isolated) in Dar El-Beïda; (a) in the X direction; (b) in the Y direction

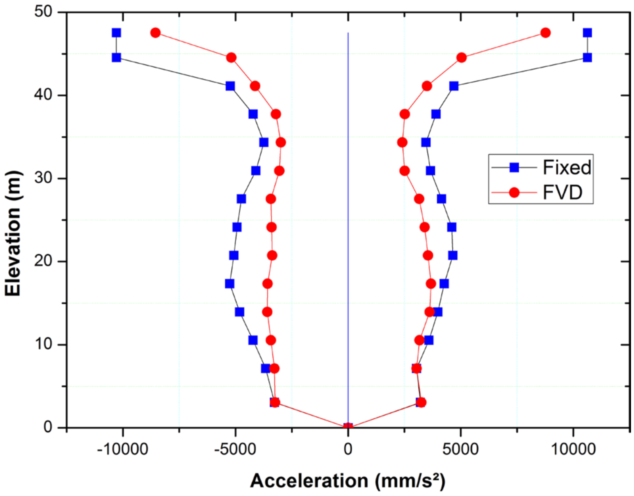
the FVD-isolated structure to the fixed-base structure, a remarkable reduction in inter-story displacements is observed. This reduction highlights the effectiveness of the isolation system in mitigating structural damage and limiting the extent of inter-story movements.

It is essential to note that controlling inter-story displacements is crucial for maintaining the integrity and proper functioning of a structure during seismic events. By minimizing the displacement between floors, the isolated structure can better withstand seismic forces and reduce the risk of damage or collapse.

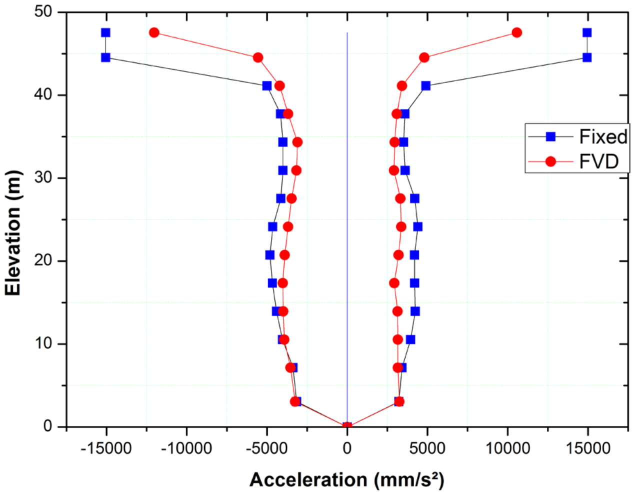
4.4 Acceleration

Acceleration refers to the rate of change in velocity over time, and during seismic events, it reflects the shaking or ground movements experienced during an earthquake. Fig. 16 (a), (b) compares the acceleration at the top of the structure between the two configurations in the X and Y directions. It is evident from these figures that the structure isolated with FVDs experiences lower acceleration compared to a structure with a fixed base. This underscores the effectiveness of the isolation system in mitigating seismic forces transmitted to the superstructure.

Fig. 17 (a), (b) illustrates a notable reduction in accelerations recorded in the X direction, showing a decrease of 49% for the FVD-isolated system compared to the fixed-base structure. Similarly, in the Y direction, accelerations demonstrate a 64% reduction for the FVD-isolated system compared to the fixed-base setup. These findings underscore the effectiveness of the FVD isolation system in lowering structural acceleration responses during seismic events. By significantly reducing these accelerations, the isolation system enhances occupant safety and minimizes the potential for structural damage.



(a)



(b)

Fig. 17 Acceleration comparison for the two models (fixed-base, FVD isolated) for different levels; (a) in the X direction; (b) in the Y direction

5 Conclusions

To address the effects of earthquakes and strengthen structures, it is essential to adopt seismic design principles to minimize potential damage caused by these events. This involves incorporating a seismic protection system, notably by using isolation devices such as seismic dampers. This approach, which absorbs and dissipates seismic energy, is one of the most effective methods for mitigating the effects of seismic shocks by reducing relative displacements, accelerations, and forces exerted at the base.

In this study, the impact of energy dissipators on the dynamic response of a residential building type G+12 with a basement was examined. Relevant data on isolation systems are presented, and the design principles and calculation methodology of fluid viscous devices (FVD) in accordance with the Taylor Devices manual 2024 are detailed.

The structure chosen as a case study was designed according to Algerian codes and the modeling phase, conducted using Etabs and SeismoSoft softwares, considered two models:

1. a fixed-base model representing unprotected structures, and
2. a model dampened by FVDs.

Here are the key findings:

- The base shear force decreases after the introduction of fluid viscous dampers by 40% in the X direction and 31% in the Y direction. This reduction occurs because the dampers absorb and dissipate kinetic energy from dynamic loads, converting it into heat and thereby reducing the amplitude of vibrations transmitted to the building's base.
- The inter-story displacements of the structure equipped with fluid viscous dampers decrease compared to the structure without damping in both the X and Y directions. This means that the relative movement between floors is reduced, enhancing the building's overall stability and reducing the risk of structural damage during dynamic events.
- The displacements of the floors of the structure equipped with FVDs decrease compared to the structure without dampers by 35% in the X direction and 20% in the Y direction. This reduction in floor displacements indicates that the building experiences less sway and movement, contributing to improved occupant comfort and structural integrity during dynamic loading conditions.
- Acceleration decreases after adding fluid viscous dampers by 49% in the X direction and 64% in the Y direction. The significant reduction in acceleration levels suggests that the dampers are highly effective in minimizing the forces acting on the building during dynamic events, leading to a smoother and safer response.

The findings underscore the critical role of fluid viscous dampers in improving the resilience and performance of tall buildings subjected to dynamic stresses.

While our study focused on FVDs' effectiveness in enhancing dynamic response, we recognize the value of structural damage analysis for a complete understanding of structural resilience. Damage analysis methods are crucial for assessing damage from dynamic events. Future research will benefit from incorporating damage analysis to evaluate how FVDs not only mitigate immediate impacts but also contribute to the long-term safety and durability of high-rise structures, leading to more robust design and maintenance strategies.

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