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Effect of Fluid Viscous Damper parameters on the seismic performance

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ABSTRACT

Energy dissipation devices are widely used to enhance the response of structures subjected to dynamic loads caused by wind and earthquake. Especially, viscous dampers are hydraulic devices widely used in structural engineering that dissipate mechanical energy by producing a damping force against the motion. The dampers can mitigate transversal and longitudinal or vertical displacement. It can be set up in different kinds of structures. This study is aimed at comparing the impact of various Fluid viscous damper parameters on the structures under the earthquake. To this aim, a seven-story steel frame structure retrofitted with fluid viscous dampers was considered for analyzing with a variety of parameters. The results showed that installing longitudinal nonlinear Fluid viscous damper can significantly reduce the seismic response by selecting affordable damping parameters, including stiffness, damping coefficient, and velocity exponent. The optimum damping parameters can be calculated accurately by analyzing structure with different damping parameters of nonlinear Fluid viscous damper.

Keywords: **Damper parameters, Damping force, Damping coefficient, Velocity exponent, Seismic performance**

1. INTRODUCTION

One of the most popular passive energy dissipation systems using for civil engineering [1], is the fluid viscous damper (FVD) [2,3] which has obtained popularity recently, because of: 1) the significant energy dissipation and enhancing the seismic performance; 2) The ability to generate forces which are uncorrelated with displacement; 3) the capability of increasing the damping ratio without changing the stiffness characteristics considerably [4–6]. FVDs are effective energy dissipation devices enhancing structural responses to resist the effects of wind and earthquakes. The damping force developed by the FVDs depends on the physical properties of the fluid used in the device [7]. Using FVDs is an effective method for improving the seismic performance of existing and new buildings. FVD provides additional damping without considerably increasing the seismic forces on members in order to reduce the overturning of the structure; so, it can be used as a capable solution to accommodate the requirements of the ever-increasing seismic design for retrofitting existing structures [8].

Several studies have shown that selecting the affordable damping parameters of FVD reduces the seismic response effectively [9–11]. Domenico et al. [12] investigated different combinations of the damping coefficient and velocity exponents. Also, in their subsequent study [13] optimal damping coefficient was determined for a fixed amount of exponent coefficient in order to obtain the best energy dissipation behavior. Wang [14] conducted a sensitivity study that was useful for selecting the values of damping exponent and brace stiffness. Terenzi [15] investigated the relationship between the frequency ratio of the dynamic load applied to the SDOF structure and the damping coefficient for obtaining the optimal velocity exponent and damping coefficient. Martinez-Rodrigo et al. [16] adopted the performance and force index to determine the optimal velocity exponent and damping coefficient. To this aim, the performance index was utilized to assess the behavior of the structure in the case of the maximum floor acceleration and the maximum inter-story drift angle, while the force index was used to quantify the reduction in damping force causing by the nonlinearity of the FVD. Dall'Asta et al. [17] focused on the impact of the uncertainties in the damper properties. Thus, Initial analyses of the variation in the damper properties were carried out to relate the controlled parameters in the experimental tests to the damper constitutive features. In addition, in their subsequent study [18], the effect of the different damper properties on the system response and risk was investigated. He et al. [19] used the method of obtaining the minimum of binary functions in order to calculate the optimal parameters of FVD. Dicleli et al. [20] compared the effect of FVD parameters on the steel chevron braced frames in the case of seismic performance. Zhou et al. [21] determined the amount, mechanical parameters, and placement of the viscous dampers in reinforced concrete structures. Cavaleri et al. [22] presented experimental tests to investigate the damper parameters' dependence on the velocity. Fu et al. [23] studied the properties of viscous and viscoelastic dampers through a parametric process while their expressions were derived as a function of major dimensionless parameters. Lin et al. [24] presented a seismic displacement-based design process for regular and new structures retrofitted with dampers. Subsequently, the passive energy dissipation systems were simulated considering their mechanical properties by the effective viscous damping ratio and stiffness. Sullivan and Lago [25] extended the previous procedure to moment resisting frames equipped with FVD. Domenico et al. [26] presented an overview of the design of FVDs for seismic protection.

This paper presents a structure analysis under a variety of damper parameters for the design of nonlinear FVD to enhance the aseismic performance of the structures. Firstly, the relation among the damper parameters of the FVD under the action of the earthquake is presented in section 2.1. Then, a numerical analysis of seven-story structure with different parameters of dampers is carried out in section 2.2. In section 3, the results of analyses are explained, and a discussion is presented. Finally, in section 4, results are shown that the seismic response of structures can be reduced significantly by installing nonlinear FVD with affordable damping parameters.

2. MATERIALS AND METHODS

2.1. Parameters of Nonlinear FVD

Figure 1 shows that the FVD contains a cylinder, piston, hydraulic valve, piston rod, and silicone oil [27]. Under the earthquake load, the structure's movement pushes the piston and the cylinder to provide relative displacement. Therefore the reciprocator motion of the piston drives the flow of silicone oil. The fluid generates heat due to the friction between the molecules and the surface of the cylinder; so, the seismic energy may be converted into heat, and consequently, the damping impact may be realized [28,29]. The simplest model of a viscous damper system (e.g., an oil damper) is the viscous type model. The damper force is related to the relative velocity between the two ends with a constant coefficient. Within the practical structural design with oil dampers' utilization, a relief mechanism is commonly used, which changes the constant viscous damping coefficient to a smaller value. Therefore the most damping force is restricted. Moreover, it is accepted that the damper system's stiffness and the surrounding sub assemblage affect the performance of the dampers [30].

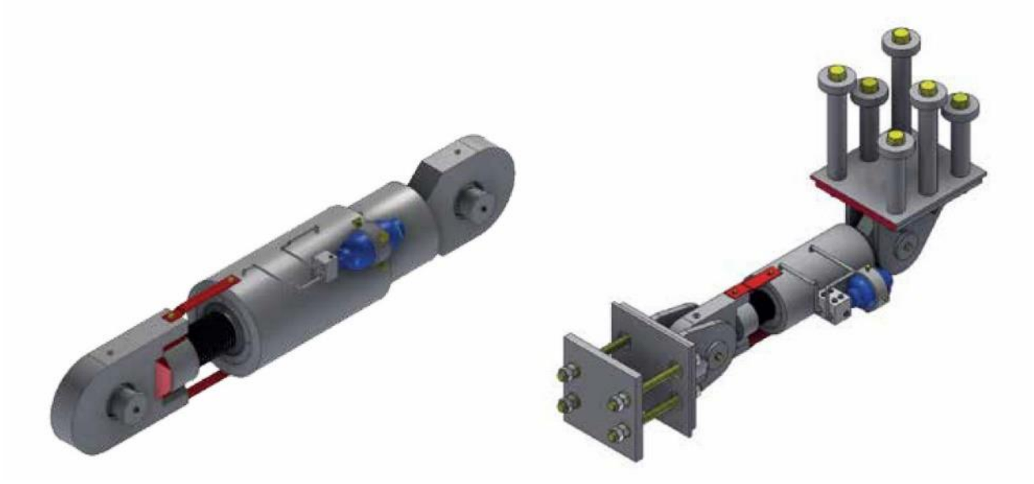


Figure 1. Fluid Viscous Damper

The steps for designing FVDs are as follows: 1) determine the quantity of FVDs, 2) calculation the parameters of FVDs, 3) configure the placement of FVDs. In the second step, the damping ratio, structural deformations, and dampers' connections to other elements should be checked. The force-velocity relationship of the nonlinear dampers is given by:

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

As dampers offer no restoring force the structure itself should resist all static loads. Viscous dampers decrease the structure's response by adding energy dissipation to a structure that considerably reduces the response to any vibration or shock inputs.

Damping Characteristics	$F = CV^{\alpha}$

F: Damping Force, kN
V: Relative Velocity, m/sec
C: Damping Coefficient, kN/(m/sec)α
α: Velocity Exponent

F: Damping force, KN

A pressure differential develops the damping force across the piston head. Therefore, the damping force will increase until the servo valve's pressure reaches a specific value; after that, the damping force becomes constant.

V: Relative Velocity, m/sec

V is the velocity of the piston concerning the cylinder.

C: Damping Coefficient, Kn/ (m/sec)α

C is the damping coefficient that depends on the fluid properties, the piston's diameter, and the orifice areas. Increasing the temperature of fluid leads to the changing of fluid properties. Consequently, it increases the constant *C*. a more stable device can be obtained by using a different material for the cylinder and the piston to counterbalance thermal effects. The damping coefficient cannot be excessively large because it leads to the larger output damping forces beyond the product's scope. On the other hand, the damping coefficient's value ought to create the extra damping ratio to meet the expected value.

α: Velocity Exponent

Velocity exponent is a real positive exponent characterizing the damper's nonlinearity and depends on the form of the piston head. It could be defined in the range between 0.1

and 2. Viscous dampers could be classified based on their value in three categories: Viscous damper with $\alpha = 1$ is called a linear viscous damper, nonlinear FVD for $\alpha < 1$, and ultra-linear viscous damper for $\alpha > 1$. Thus, the velocity exponent defined the nonlinear degree of the FVD [31]. Generally, for the smaller velocity exponent, the additional energy is going to be consumed. To make sure the protection of various structures, we need different velocity exponents. Figure 2 shows the force-velocity diagram of a FVD with different α, while the damping coefficient, the amount of energy dissipation, and the displacement amplitude are constant. It can be seen that a nonlinear FVD with smaller α produces larger damper forces at the ranges with lower velocities.

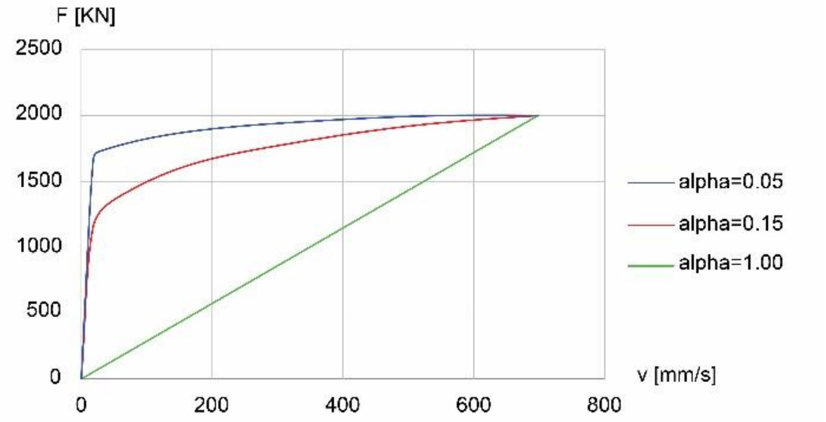


Figure 2. Typical response Force / Velocity diagram (alpha variable from 1.00 to 0.05) [32]

Figure 3 depicts the typical force-displacement diagram with different values of α. It can be seen that the shape of the curve at α=1 is like an ellipse and the shape of the curve at α=0.05 is closer to a rectangle.

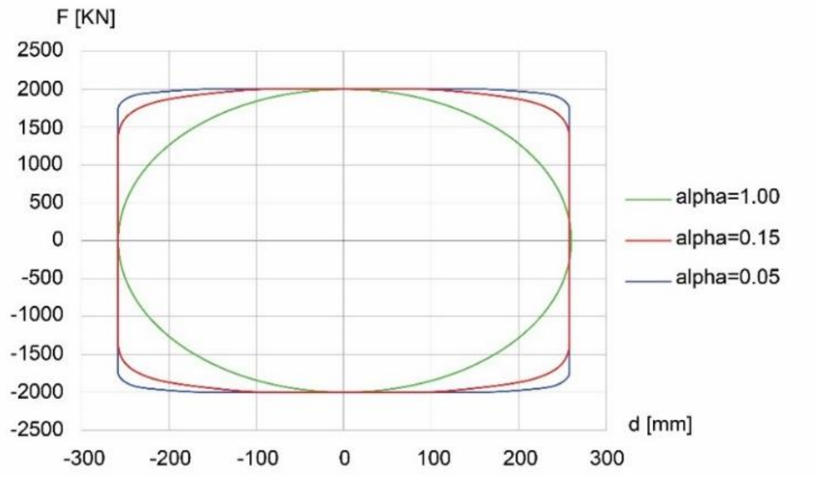


Figure 3. Typical response Force / Displacement diagram (alpha variable from 1.00 to 0.05) [33]

These parameters affect the performance of FVDs for seismic protection of buildings [22]. Selecting appropriate design parameters such as velocity exponent α and damping coefficient C is essential for designing FVDs to obtain the optimal damping performance [34]. These parameters can be estimated by monotonic tests and considering constant velocity. The perfect behavior of such a damper is shown in Figure 4 in the force-velocity plane.

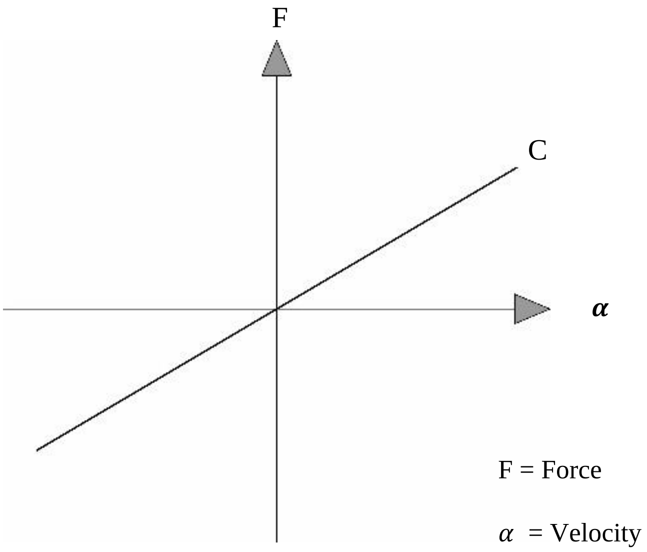


Figure 4. The idealized behavior of a damper [35]

2.2. Numerical example

In this model, a seven-story frame was analyzed, which was retrofitted by the viscous dampers. The mentioned structure was an unsymmetrical steel frame. The height of the building was considered about 21 meters. Seven dampers were installed on the left side of the structure along the X-direction. Damper element is used to simulate the FVD. The ground acceleration recorded from the El Centro earthquake was used for analyzing. As shown in Figure 5, the two ends of the damper essentially have equivalent displacements and velocities due to the special installation type.

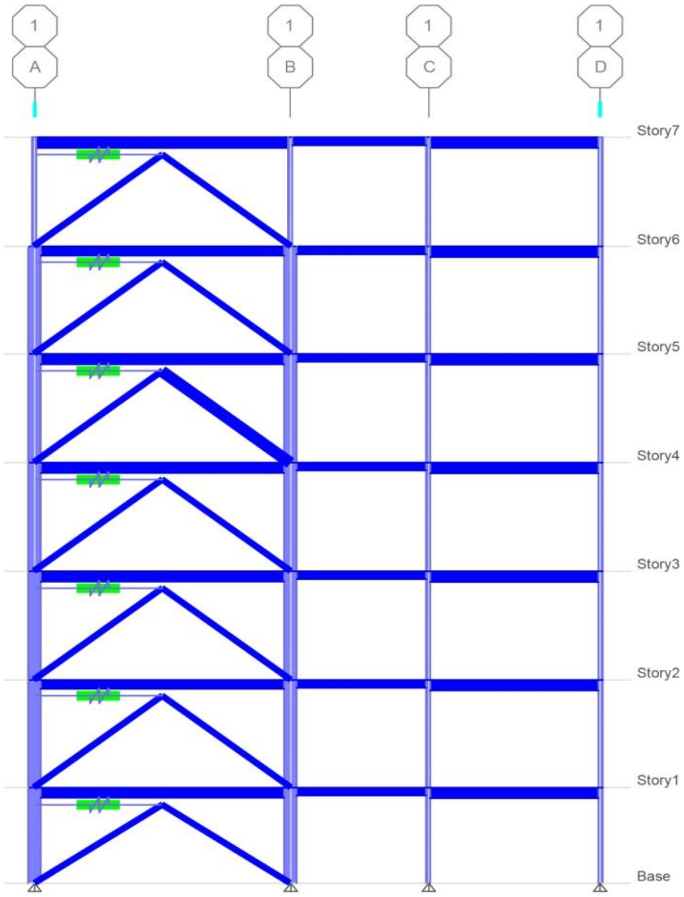


Figure 5. Model of structure

Different values for the parameters, as shown in Table 1, were used for analyzing within the 12 Conditions. The action applied to the structure was earthquake acceleration that was provided from El Centro Earthquake data input. The nonlinear time-history analysis method was used to analyze the relationships among the internal forces, displacements, and damping parameters.

Table 1. Viscous dampers properties

	Stiffness kN/m	**Damping Coefficient** kN*(s/m)	**Damping Exponent**
Case 1	10000	500	0.9
	10000	1000	0.9
	10000	2000	0.9
Case 2	10000	1000	0.3
	10000	1000	0.6
	10000	1000	0.9
Case 3	10000	500	0.9
	10000	1000	0.6
	10000	1500	0.3
Case 4	2000	2000	0.9
	5000	2000	0.9
	10000	2000	0.9

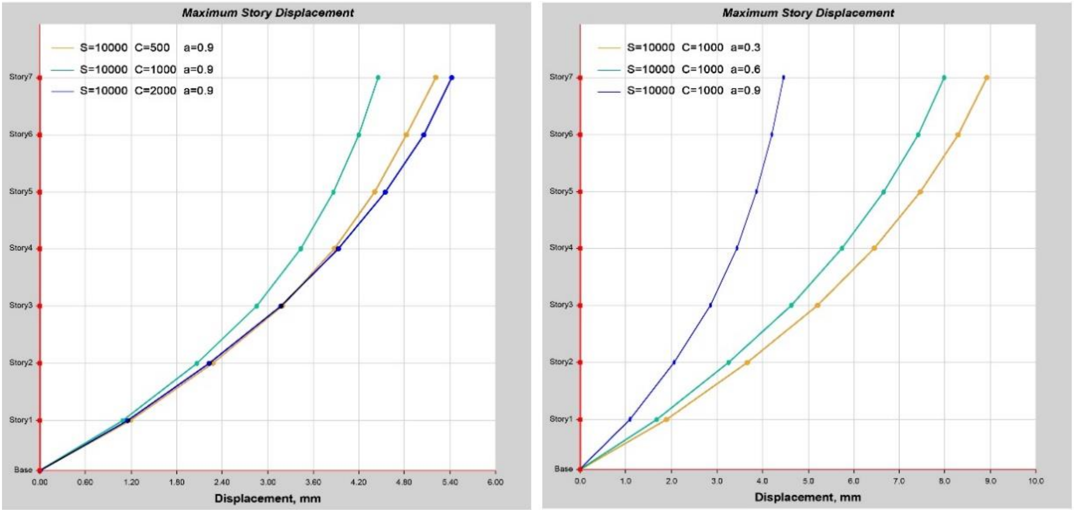
The main aspects of comparison between structures modeled with different viscous dampers parameters have been explained under four subtitles:

- Story displacement
- Story drift
- Story shear
- Hysteresis loops

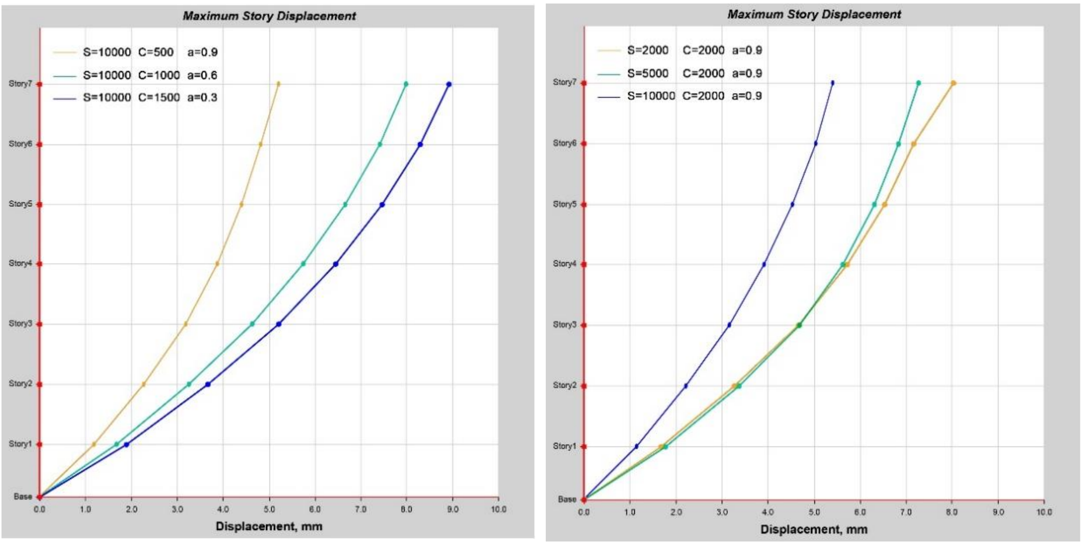
3. RESULTS AND DISCUSSION

3.1. The effect of various parameters on displacement

After adding FVDs, the structural response was computed. Floor displacements were plotted in Figure 6, which showed the comparison of the impact of various parameters of a viscous damper on displacement. It has been observed that by increasing the damping coefficient, the response was enhanced. As can be seen in Figure 6 (a) damping coefficient equal to 1000 kN×(s/m) was the best choice for reduction of story displacement subjected to earthquake load. It was determined that, by adding more powerful dampers to the structure, its response level at each floor was reduced gradually. Also, it has been ascertained that increasing the damping exponent had an effective role in comparison with two other options. The optimal damper parameters for the displacement were observed in case 1 and 2, which the damper parameters were as follows: S= 10000 kN/m, C= 1000 kN×(s/m), and α= 0.9.



(a) Case 1 (b) Case 2

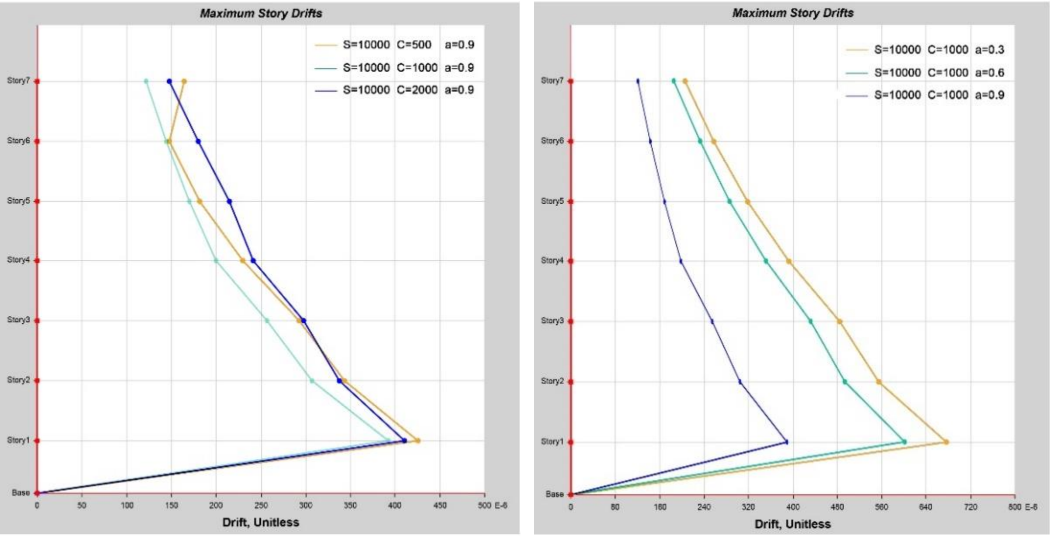


(c) Case 3 (d) Case 4

Figure 6. Story displacement response of the structure

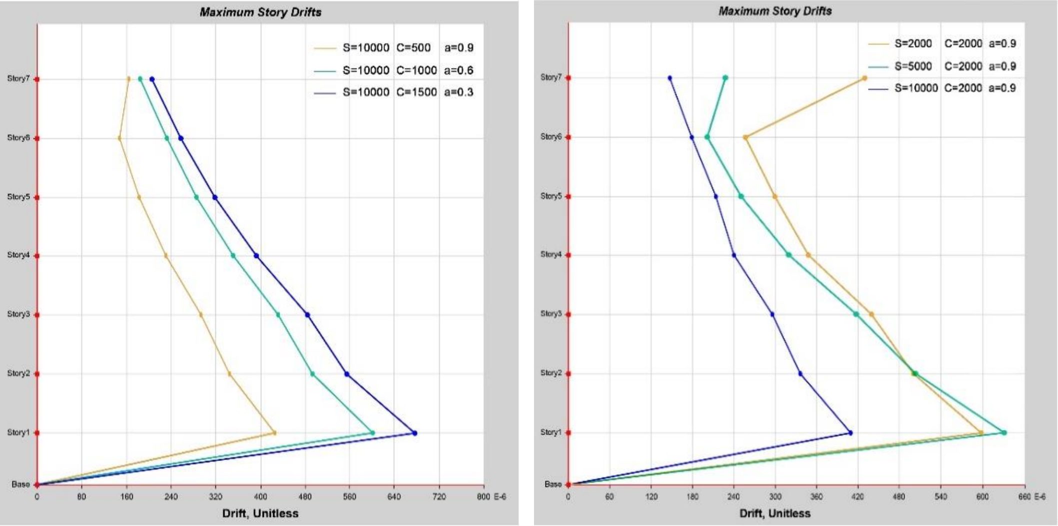
3.2. The effect of various parameters on drift

Story drift was calculated and compared for all cases and concluded that more powerful viscous dampers reduced drifts more practically, as shown in Figure 7. In case 1, it has been determined that optimum reduction in drifts accrued when the damping coefficient was about 1000 kN×(s/m). In case 2, it was discovered that drift effectively was going to be diminished by increasing the damping exponent. Case 3, showed that the damping exponent had more impact on drift reduction than the damping coefficient. Case 4, demonstrated increasing stiffness had a sensible result for decreasing drift. The final optimum damper parameters for the drift may be determined in cases 1 and 2 that the damper parameters were as follows: S= 10000 kN/m, C= 1000 kN×(s/m), and α= 0.9.



(a) Case 1

(b) Case 2



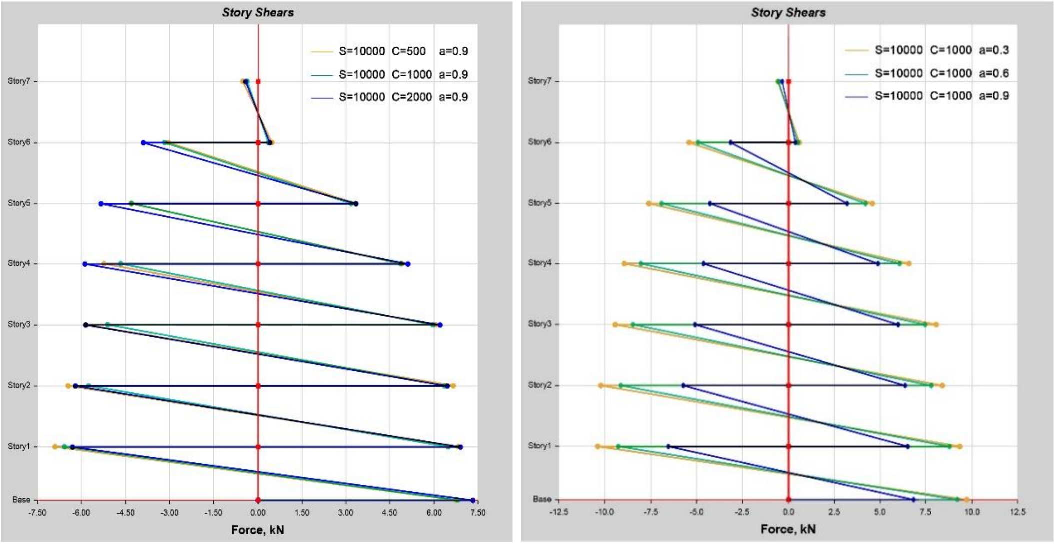
(c) Case 3

(d) Case 4

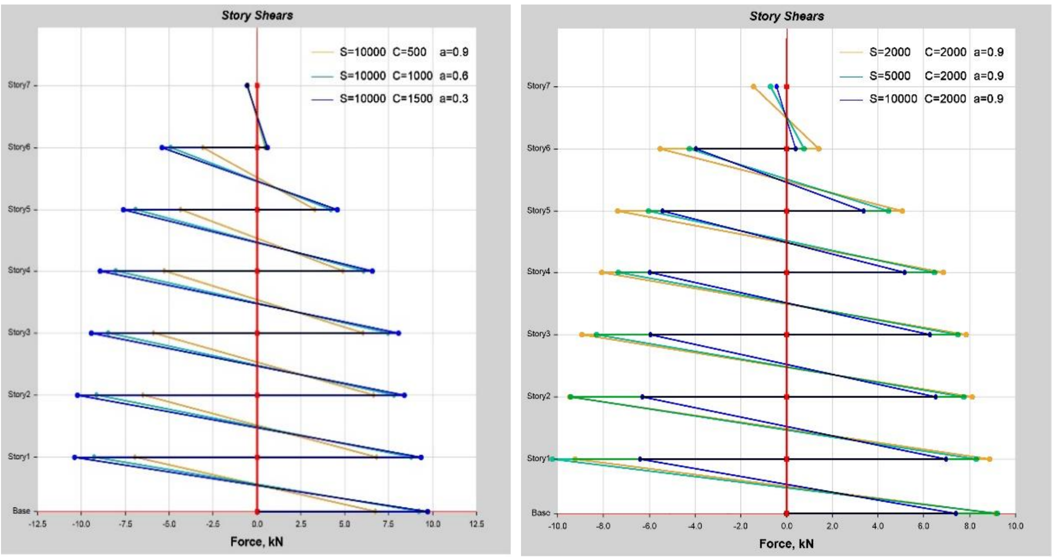
Figure 7. The story drifts response of the structure

3.3. The effect of various parameters on shear force

After analyzing, results have shown that dampers' efficiency on story shears was smaller on the upper stories than that within the lower stories. Figure 8 demonstrated the results of these analyses. Case 1 depicted that increasing the damping coefficient had no significant effect on story shears. Case 2 showed that increasing damping Exponent reduced story shears effectively. Case 3 demonstrated that increasing the damping coefficient decreased story shears considerably. In case 4, Assumed that all the dampers had a similar value of damping constant, but different stiffness. It has been ascertained that stiffness reduces shear force effectively. The final optimal damper parameters for the base shear force may be ascertained in case 3 that the damper parameters were as follows: S= 10000 kN/m, C= 500 kN×(s/m), and α= 0.9.



(a) Case 1 (b) Case 2

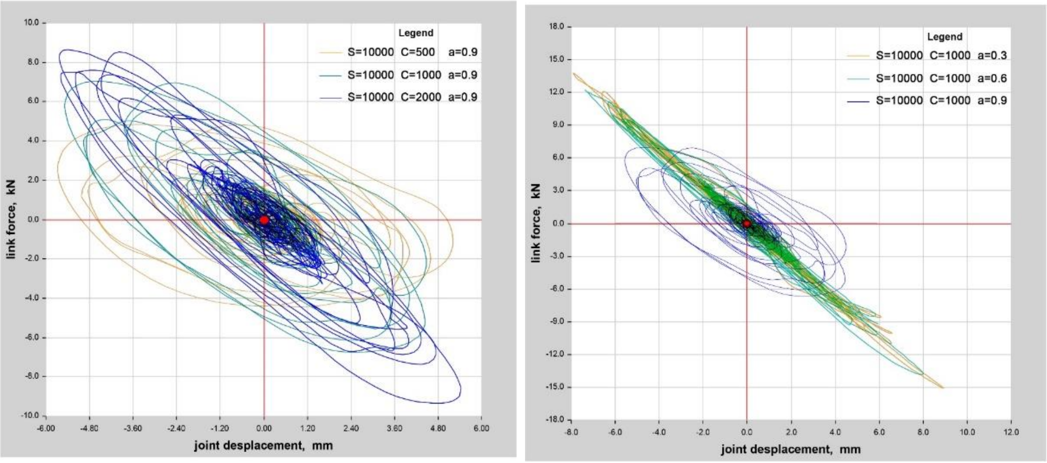


(c) Case 3 (d) Case 4

Figure 8. Story shears response of the structure

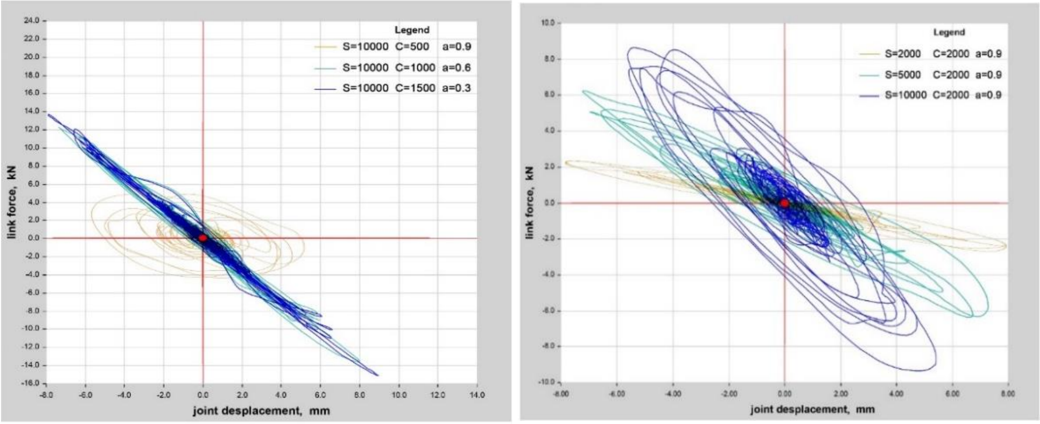
3.3. Joint Displacement Vs Link force

The hysteresis loops (joint displacement-Link force) of the viscous dampers with different parameters which illustrate the effect of viscous dampers on the absorption and loss of inputs energy to structures have been shown in Figure 9. As can be seen, in structures with more powerful viscous dampers, the amount of energy absorption and dissipation increased while the amount of force and displacement decreased. The maximum damping force was found to be approximately 14 kN corresponding to the practical velocity of the damper. The saturated hysteresis loops demonstrated that part of the energy was effectively dissipated. Figure 9 (c) showed that α had a more effective role in absorbing energy than *C*.



(a) Case 1

(b) Case 2



(c) Case 3

(d) Case 4

Figure 9. Hysteresis loop of the viscous damper

3.4. Discussion

This section discusses the variability of the FVDs parameters by comparing the current study results with previous studies. Three representative design parameters of FVD investigated in this paper, including stiffness, damping coefficient, And damping exponent. As known from previous studies, nonlinear FVDs are suitable for retrofitting the buildings against the earthquake. The smaller value of α increases energy dissipation and simultaneously leads to a reduction of the uncoupling between dissipative and elastic forces. It means that a nonlinear damper in comparison with the linear damper allows lower force levels while the same amount of energy dissipation has to be achieved. Considering the inverse relationship between C and α, a larger C has to be selected with a smaller α to obtain a certain amount of force. The results of other studies are as follows: experimental test and numerical studies that have been carried out by Symans and Constantinou [36] showed that a nonlinear damper with α=0.5 dissipated 11% more energy in compere with a linear one and 31% more than a nonlinear damper with α=2. Moreover, it presented a smaller peak damper force in comparison with two other cases. Analysis of a six-story steel structure retrofitting with nonlinear dampers by Martinez-Rodrigo and Romero [16] demonstrated that a nonlinear damper's peak force is about 35% lower than a linear damper while they have equal energy consumption. He et al. [19] achieved the optimal value of α and C equals to 0.4~0.5 and 10000 kN×(s/m), respectively. It should be mentioned that using smaller α values is more effective when the expected damper velocities are less than 1 m/s [20]. By comparing the present study results and other mentioned research, It can be concluded that the optimal value of α based on the damper forces and structural performance is slightly smaller than 1.

In terms of damping constant C, in most cases, C's value selection relies on trials and experiences. In addition, the value of *C* is proportional to story stiffness [37]. Stiffness is another parameter that has an essential effect on the behavior of the damper. FVDs also provide additional stiffness and strength besides the energy dissipation. Mostly, the higher stiffness leads to larger energy dissipation.

As a result, choosing the proper value for *C* and *α* is an essential matter in the design process. It should be noted that the larger amount of *C* and *α* will not guarantee the lager mitigation of the effects due to the earthquake.

4. CONCLUSION

In this study, a seven-story structure was analyzed under the El Centro earthquake. A simulation, including the unsymmetrical steel frame retrofitted with the fluid viscous dampers, was carried out to investigate various parameters' effects. The FVDs was installed in a steel structure for finding the optimal damping parameters that have a significant effect on the mitigation of seismic responses.

The following conclusions can be obtained:

- The optimal values of damping parameters can be found explicitly by the structural analysis that is beneficial for the design of nonlinear Fluid viscous damper installed in the structure.
- The optimum design of damper parameters is possible by analyzing the effect of the damping coefficient on the structure's response and choosing appropriate damper properties for the desired type of the structure based on the impact of damper devices to diminish the seismic load.
- It was observed that for time history analysis, the structure's response, such as the story drift and story displacement, reduced more by changing damper parameters compared to the shear force.
- After the simulation analysis in 12 conditions, the reasonable damping parameters can be preliminarily determined. For the nonlinear fluid viscous damper of the analyzed structure in this study, the seismic response can be effectively reduced when the velocity index α is in the range of 0.6-0.9, and the damping coefficient *C* is about 500-1000 kN×(s/m).
- In the case of stiffness, usually larger energy dissipation can be obtained by higher stiffness. In this study, the optimal value for the stiffness was obtained equal to 10000 kN/m.

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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