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STATISTICAL SEISMIC PERFORMANCE ASSESSMENT OF VISCOUS DAMPER IN BENCHMARK BUILDINGS UNDER FAR-FAULT AND NEAR-FAULT EARTHQUAKES

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Abstract

The viscous damper produces a force proportional to the velocity by moving the fluid inside their cylinder and, causes energy dissipation due to the dynamic vibrations by converting mechanical energy into heat. Viscose dampers with their three special features as powerful passive control devices have been widely studied in recent decades. The ability to improve the seismic performance of the structures with significant energy loss, production of out-of-phase damping force relative to displacement, and the increase of the structural damping without making major changes in the stiffness characteristics of the structure are its distinguishing features in comparison with other passive control methods. In this study, the seismic performance of viscous dampers is investigated to control the vibration of three benchmark steel buildings (i.e. 3-, 9-, and 20-story buildings designed for the SAC project) under two sets of recorded near-fault (NF) ground motions possessing forward-directivity (FD) or fling-step (FS) features and compared with the building responses under a suite of far-fault (FF) accelerograms. The results indicate the superior performance of viscous dampers in low-rise buildings and under FF earthquakes, i.e. 59% and 53% reduction in the mean of the maximum roof displacement and velocity, respectively. However, to control the mean of the maximum roof acceleration, the best performance was obtained in the high-rise buildings and under FF earthquakes, showing a maximum of 84% reduction. In general, it can be concluded that the damper has the highest reduction in acceleration response under the FF records, and under the NF records with FD has the least decrease in the velocity response.

Keywords: Passive Control, Viscous Dampers, SAC Benchmark Buildings, Near-Fault Ground Motions, Far-Fault Ground Motions.

1. Introduction

Conventional seismic design establishes the desired performance levels based on a combination of resistance and ductility for the structural elements. In this approach, structural engineers determine the resistance capacity and ductility of the structures to provide the life safety performance of the designed buildings under earthquakes [1]. In parallel and in a different approach, the seismic performance of the structure can be improved by using control strategies under lateral dynamic loads. According to Lu et al. [2], the idea of control was first proposed more than 130 years ago by John Milne, whose idea was to use a seismic isolator as a passive control device to reduce the vibration of structures under earthquake loads.

Viscous fluid dampers are one of the well-developed passive control devices invented to dissipate energy caused by vibration or impact for the first time in military and aerospace sciences [3]. In the last few decades, these dampers have been widely studied and applied to improve the seismic performance of the structures. As a well-recognized design advantage, viscous dampers do not alert the inherent stiffness of the host structure compared to other passive control devices (such as viscoelastic dampers, tuned mass dampers, and seismic isolators) [4], which eliminates the need for an iterative design method based on trial and error. In addition, the ability to dissipate significant energy and improve the seismic performance of the structure, out-of-phase damping force compared to the displacement and elastic force, easy installation, low sensitivity to a wide band of excitation

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frequencies and temperature changes, as well as the need for limited space compared to the amount of displacement and obtainable force are the main advantages of this passive control system [5].

In recent years, investigating the statistical and probabilistic performance of the viscous damper under FF and NF records has received more attention [6]. In 2020, the performance of the viscous damper in a single-degree of freedom system and three shear buildings of 4, 8, and 12 floors has been investigated under a set of NF records with FS features. The results showed the proper performance of the damper in reducing the acceleration of the high-rise building compared to its displacement [7].

About half a century ago and due to the Bolt's opinion, earthquakes were categorized into FF and NF according to the distance from the building site to the active fault, and after the occurrence of destructive NF earthquakes such as Loma Prieta (1989), Northridge (1994), Kobe (1995) and Chi Chi (1999), identifying the areas near the fault became important [8, 9]. Based on the interest of structural engineers, the NF earthquakes can be divided into three categories of records with FD, FS and without pulse characteristics [10].

In this study, the statistical performance assessment of viscous damper on two-dimensional steel frames of 3-, 9- and 20-story benchmark buildings has been investigated under the FF and NF earthquakes. Therefore, three suites of 7 records of FF and NF with FD or FS features have been applied to the benchmark buildings investigating the seismic performance of the controlled buildings with viscous dampers subjected to NF and FF earthquakes. The viscous damping at the height of the building was distributed using inter-story drift proportional distribution determined on the basis of the first mode deformations. In the following, the results of the analysis of the buildings with and without dampers are studied statistically under all types of earthquakes. Finally, the ability of the viscous damper has been investigated to reduce the response of buildings with different heights and under the FF and NF records with different characteristics.

The difference of this article from the previous studies in this field are: (1) in this study, three benchmark buildings with different heights have been modeled to investigate the seismic performance of viscous damper in steel buildings. (2) Six different performance criteria have been compared including the maximum and norm of different responses (i.e., absolute acceleration, velocity, and displacement) which respectively represent the best performance and the mean performance of the damper in the entire length of the record. (3) Statistical seismic performance of the viscous damper has been evaluated under the effect of a suitable number of benchmark natural ground motions (21 records with different characteristics) with reporting not only the mean of responses but also their standard deviation.

2. Viscous Fluid Dampers

Viscous fluid dampers consist of a cylinder and a stainless steel piston with a bronze cap. When the piston rod moves inside the cylinder, the liquid is forced through the orifices built into the cap (piston head), and mechanical energy is consumed by converting it into Heat [11]. As the fluid passes through the orifices, the pressure difference created on the both sides of the damper creates the damper force [12]. Viscous fluid dampers are velocity-dependent devices that dissipate energy by changing the shape of a viscous fluid [13]. The shape, size, configuration, and arrangement of these orifices are the most important factors in the design of viscous dampers, which are the result of experimental tests. Various components of a viscous damper are presented in Fig. 1.

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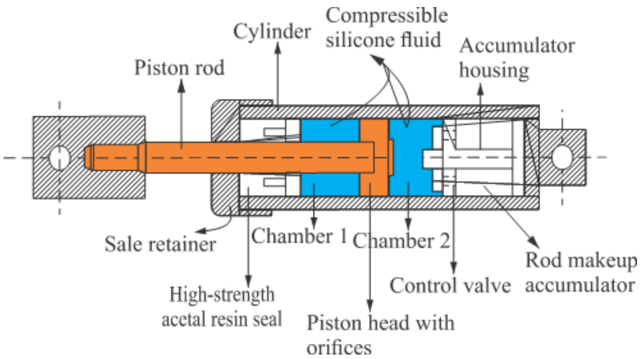

Figure 1. Various components of a viscous damper

3. Verification and numerical study

In this section, first, the verification of modeling and analysis results has been discussed to ensure the accuracy of the obtained results. Then, the benchmark natural ground motions has been presented. Finally, the applied design strategy of the viscous dampers has briefly been reviewed based on the acknowledged literature.

3.1 Verification of benchmark buildings

The benchmark buildings are modeled according to the study of Ohtori et al. [14]. Then a comparison has been made between the frequencies of the buildings based on Ohtori et al.'s article and the frequencies calculated in Table 1. Then, the comparison between the responses under the effect of 50% of the Hachinohe (1968) earthquake is reported in Table 2.

Table 1- Comparing the natural frequencies of the SAC buildings with Ohtori et al. [14]

		frequency (Hz)		
Struc.	Erorr (%)	calculated	Ohtori et al	No.mode
	1.010	0.980	0.990	1
3	0.230	3.050	3.060	2
	4.340	5.577	5.830	3
	0.452	0.442	0.440	1
9	0.508	1.186	1.180	2
	0.880	2.032	2.050	3
	2.700	0.253	0.260	1
20	4.000	0.720	0.750	2
	4.610	1.240	1.300	3

Table 2- Comparing the roof response of the SAC buildings with Ohtori et al. [14]

		Parameter		
Struc.	Erorr (%)	calculated	Ohtori et al	Roof Response
	1.420	0.091	0.090	Disp. (m)
3	0.370	0.535	0.537	Vel. (m/s)

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	1.850	4.004	3.930	Acc. (m/s^2)
	1.060	0.188	0.186	Disp. (m)
9	4.420	0.627	0.656	Vel. (m/s)
	5.800	2.750	2.590	Acc. (m/s^2)
	4.700	0.166	0.174	Disp. (m)
20	6.700	0.424	0.451	Vel. (m/s)
	0.110	1.832	1.830	Acc. (m/s^2)

3.2 Benchmark natural ground motions

The response history analysis of the benchmark buildings has been performed under 21 benchmark earthquake records composed of 3 suites of 7 records with various characteristics. This category includes records of NF with FS or FD effect and FF records. The specifications of these records are presented in Table 3. Numbers 1 to 7 are the NF with FS, numbers 8 to 14 are NF records with FD, and numbers 15 to 21 are FF records.

Table 3- Benchmark ground motions

No.	year	Eq.	Station	PGA (g)	No.	year	Eq.	Station	PGA (g)
1	1999	Kocaeli	Yarimca(YPT)	0.23	12	1984	Morgan Hill	Anderson Dam	0.29
2	1999	Chi-Chi	TCU052	0.44	13	1987	Superstition Hills	Parachute Test Site	0.45
3	1999	Chi-Chi	TCU068	0.50	14	1979	Imperial-Valley	Brawley Airport	0.16
4	1999	Chi-Chi	TCU074	0.59	15	1952	Kern County	Taft	0.18
5	1999	Chi-Chi	TCU084	0.98	16	1979	Imperial Valley	Calexico	0.27
6	1999	Chi-Chi	TCU102	0.29	17	1989	Loma Perieta	Presidio	0.10
7	1999	Chi-Chi	TCU128	0.14	18	1994	Northridge	Century CCC	0.26
8	1992	Cape Mendocino	Petrolia	0.66	19	1994	Northridge	Moorpark	0.29
9	1994	Northridge	Olive View	0.84	20	1994	Northridge	Montebello	0.18
10	1992	Erzincan	Erzincan	0.50	21	1971	San Fernando	Castaic	0.27
11	2004	Park field	Fault Zone 1	0.50					

Records are scaled due to the ASCE7-10 regulations. In this method, first, all records are scaled to their maximum value, so that the maximum acceleration of all records reaches the g value. Then, by plotting the response spectrum of 5% damping of the records, the average spectrum for all the records is obtained in such a way that it is not lower than the spectrum of the design for type D soil in the period range of 0.2 to 1.5 T [4]. Notably, in the SAC project, soil type D has been selected [15]. For example, the response spectrum of the records and their average spectrum along with the spectrum of the regulation plan for a 3-story building are presented in Fig. 2.

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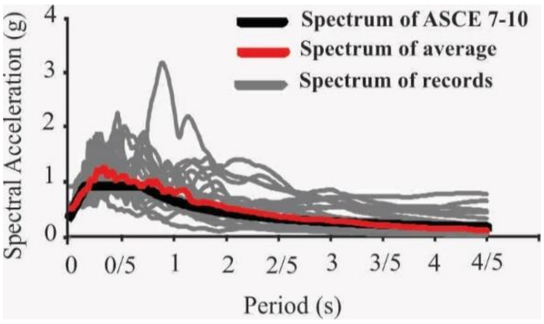

Figure 2. Response spectrum of scaled records for a 3-story building

3.3 Design of viscous dampers

The overall damping required for each building is calculated by Eq. (1) [16]. Then, the calculated total damping should be distributed at the height of the building using a well-approved method. In this study, the first mode shape method [17] has been preferred for the damping distribution through the height of buildings.

$$C = \frac{(\zeta_e - \zeta) \times T_o \times K}{\pi} \tag{1}$$

In Eq. (1), C, ξ_e, and ξ are the damping coefficient of the damper, the target damping ratio and the inherent damping ratio of the structure, respectively. T_o and K are equal to the period of the first mode and the stiffness of the structure, respectively. Inherent damping of SAC project buildings is 2% and target damping for dampers is adopted 20%. The stiffness of the buildings is obtained by the stiffness calibration method. In this method, first, the building is subjected to a lateral load with a triangular distribution, then, the shear and deformation of the floors are calculated, and the stiffness of each floor is extracted from the ratio of the shear of the floors to the relative deformation of the floors, and the stiffness of the whole building is derived from the sum of the stiffness of the floors.

The schematic arrangement of dampers at the height of the examined frame is presented in Figure (3). For information on the complete sections of the buildings, refer to the article by Ohtori et al. [14].

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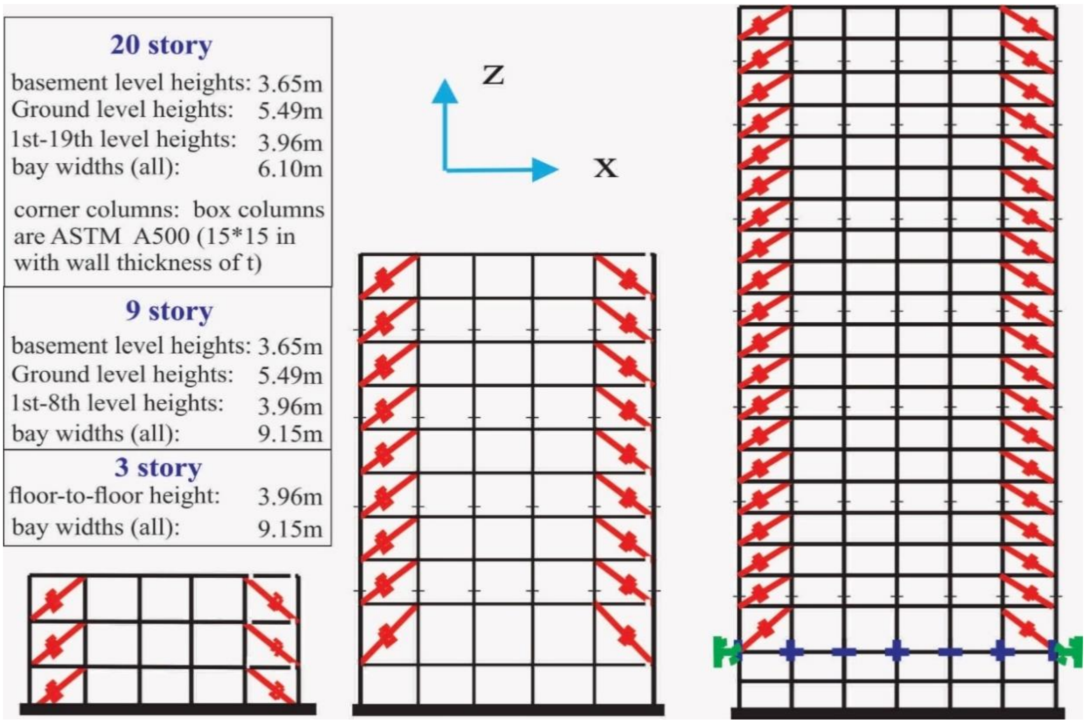

Figure 3. Viscose damper configurations in 3-, 9- and 20-story buildings

In the following, the distribution of viscous dampers at the height of the buildings based on the first mode shape method is briefly described in a simple flowchart in Fig. 4.

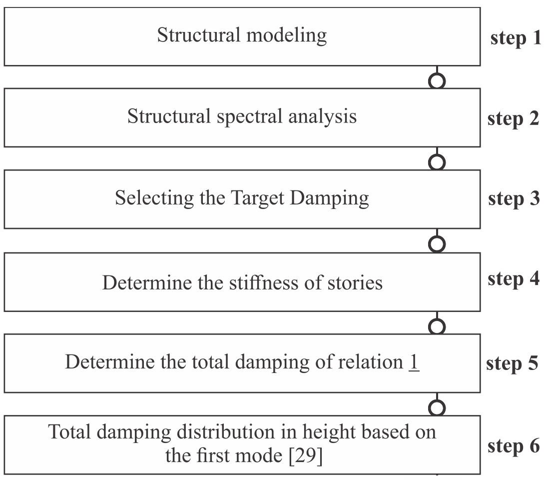

Figure 4. Viscous damper design flowchart

4. Seismic performance assessment and comparison

In this section, the response history results of the uncontrolled and controlled buildings are obtained under the benchmark earthquakes and compared based on the maximum and norm of responses. As an example, the 40 seconds of the response history of all three benchmark buildings is presented in Fig. 5

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under one of the records. Notably, after 25 seconds from the start of the excitation time, the displacement response has decreased by 50, 60, and 75%, for 3-, 9- and 20-story buildings, respectively.

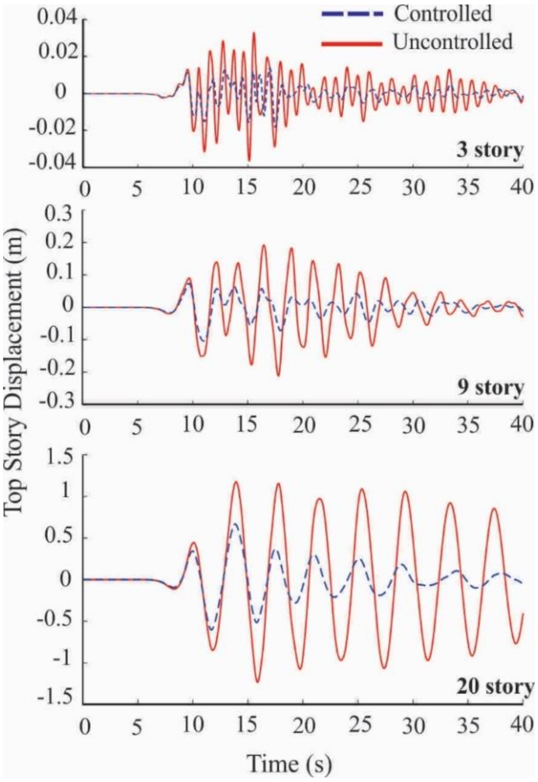

Figure 5. Response history of the roof displacement in 3-, 9- and 20-story buildings under record number 1

4.1 Comparing maximum and norm of responses

In the previous section, the performance of the viscous damper was shown under a specific record and qualitatively during the excitation time. In this section, the maximum and norm of different responses of the building, including displacement, velocity, and absolute acceleration of the building roof are calculated and compared for both uncontrolled and controlled buildings under 3 categories of records. The results for 3-, 9-, and 20-story buildings are presented in Figs. 6-8, respectively. In all figures, the responses of the controlled buildings are normalized to the responses of the uncontrolled ones. The maximum and norm of displacement, velocity, and acceleration responses of the buildings are plotted in the subplot of a-c for each figure, respectively under all records (3 suites of 7 records). The red, green, and blue colors show the responses under NF records with FS, FD, and FF records, respectively. Also, in the subplot of d-e of the figures, the mean and standard deviation of each response under 7 records are presented in column diagrams and the value of these criteria is reported over each column.

In Fig. 6 (d-f), results show that for the 3-story building, the mean of maximum reduction for roof displacement, velocity and acceleration is 59%, 53% and 63%, respectively under FF records. Also, the minimum reduction in the mean of maximum response for displacement, velocity, and acceleration responses was obtained by 48%, 50%, and 52%, respectively under NF records with FD. Therefore, the effect of viscous damper in reducing the acceleration response was the highest under the FF records in reducing the velocity response was the least under NF records with FD.

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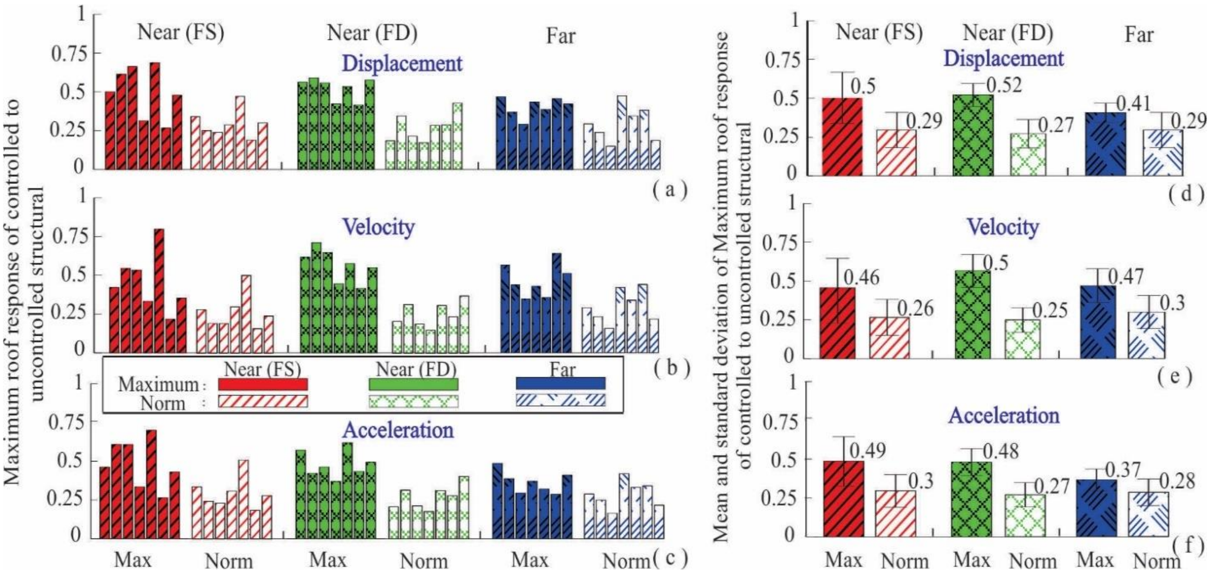

Figure 6. The maximum and the norm of response for 3-story building under 21 benchmark records

In Fig. 7, the performance of the viscous damper is presented in the control of the 9-story building. Vividly, the effect of the damper in reducing the acceleration response is obvious compared to reducing the displacement and velocity responses. According to Fig. 7 (d-f), the maximum reduction of the mean response for the roof displacement, velocity, and acceleration were 52%, 53%, and 75%, respectively under the FF records. Additionally, the minimum reduction in the mean response for displacement, velocity and acceleration responses was obtained by 46%, 44%, and 64% under the NF records with FD.

Remarkably, in the 9-story building, there is a slight difference between the performance of the building under FF and NF records in the reduction of the displacement and velocity responses. However, a noticeable reduction could be obtained in the reduction of the acceleration response, especially under the FF records.

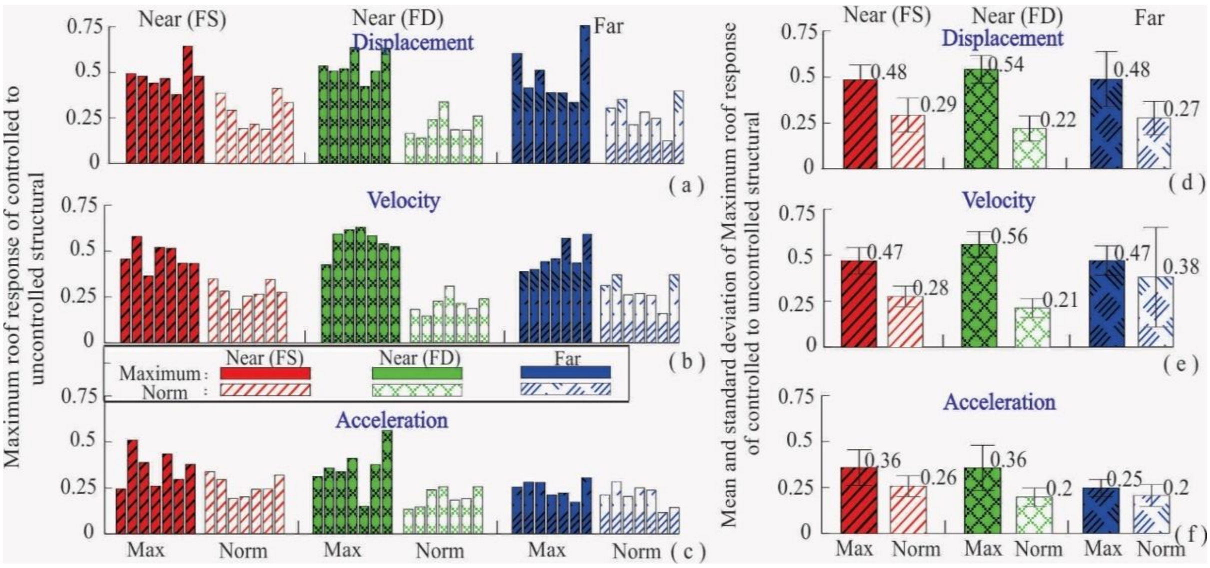

Figure 7. The maximum and the norm of response for 9-story building under 21 benchmark records

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In Fig. 8, for the 20-story building as well as the 9-story building, due to the reduction of 46%, 44%, and 84% respectively for the response of displacement, velocity, and acceleration under the FF records, it can be attributed to the role of improved control in reducing the acceleration response of the building. He pointed to two other answers. Also, the minimum reduction in the mean of maximum response has been obtained for the roof displacement, velocity, and acceleration to the amount of 35%, 42%, and 65%, respectively under the NF records with FS.

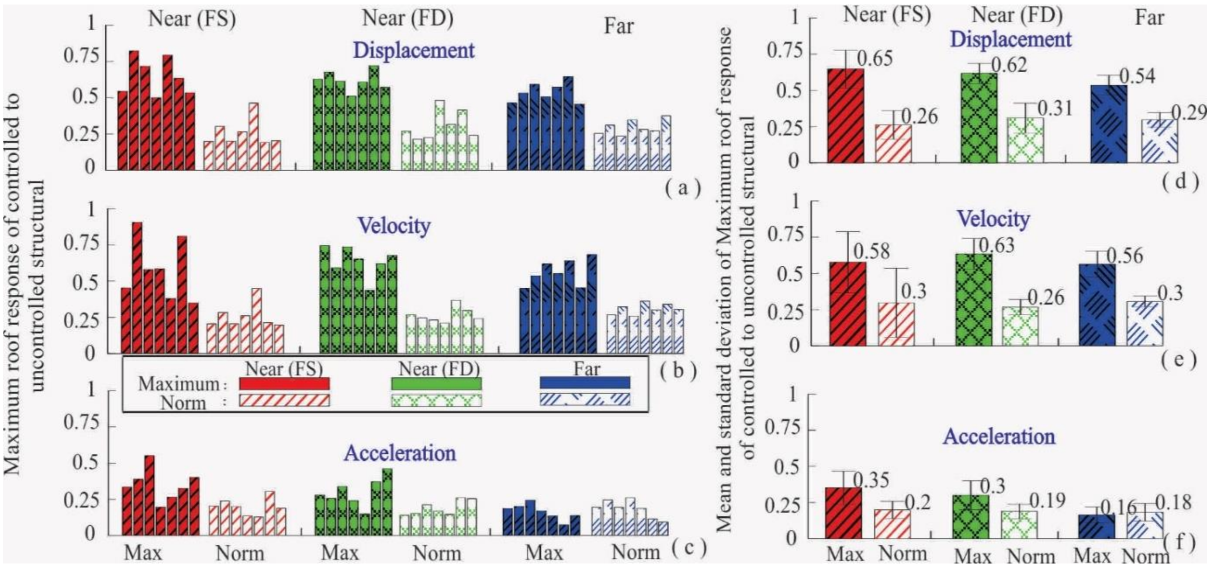

Figure 8. The maximum and the norm of response for 20-story building under 21 benchmark records

In general, regarding the mean of maximum response reduction, the viscous damper has the greatest effect in reducing acceleration under the FF records, and the least effect is almost in reducing the velocity response under NF records with FD.

In Table 3, the mean and standard deviation of the maximum and norm of different responses are presented for all three benchmark buildings under 3 suites of ground motions with different characteristics. In general, all responses have decreased between 30% and 85%, where absolute acceleration experienced the greatest reduction while displacement and velocity experience the least and almost similar reduction. Notably, the maximum and minimum reduction is obtained in the 20-story building related to the mean of the maximum of the roof acceleration and displacement, respectively. Additionally, the damper almost showed the predominant performance under the FF records, while the inferior performance has almost been obtained under the NF records with negligible difference between records with FD or FS.

Table 3- The mean and standard deviation of the maximum and norm of responses for 3-, 9- and 20-story buildings

		Performance Ceriteria											
ζ = %2		Displacement				Velocity				Acceleration			
		Max		Norm		Max		Norm		Max		Norm	
Strct.	Eq. Ch.	Mean	S.d	Mean	S.d	Mean	S.d	Mean	S.d	Mean	S.d	Mean	S.d
3	FS	0.50	0.17	0.29	0.09	0.46	0.19	0.26	0.11	0.49	0.16	0.30	0.10
	FD	0.52	0.07	0.27	0.09	0.50	0.11	0.25	0.08	0.48	0.09	0.27	0.08
	Far	0.41	0.06	0.29	0.11	0.47	0.11	0.30	0.11	0.37	0.07	0.28	0.09

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9	FS	0.48	0.08	0.29	0.09	0.47	0.07	0.28	0.06	0.36	0.12	0.26	0.06
	FD	0.54	0.07	0.22	0.07	0.56	0.08	0.21	0.05	0.36	0.12	0.20	0.05
	Far	0.48	0.15	0.27	0.09	0.47	0.07	0.38	0.27	0.25	0.11	0.20	0.06
20	FS	0.65	0.13	0.26	0.10	0.58	0.21	0.30	0.24	0.35	0.11	0.20	0.06
	FD	0.62	0.07	0.31	0.10	0.63	0.10	0.26	0.05	0.30	0.10	0.19	0.05
	Far	0.54	0.07	0.29	0.05	0.56	0.09	0.30	0.04	0.16	0.05	0.18	0.06

5. Conclusion

In this study, the performance of viscous dampers to control the seismic vibration of steel benchmark buildings i.e., short-, mid-, and high-rise buildings were investigated under natural ground motions with different characteristics. Generally, the mean of the norm of responses experienced more reduction than the mean of the maximum of responses. Remarkably, in terms of the mean of the norm of responses (through the whole earthquake time), the maximum reduction is related to the acceleration response, and its values for the 3-, 9-, and 20-story buildings are 73%, 80%, and 82%, respectively, and under FF earthquakes. Also, in terms of the mean of the maximum of responses, the minimum percentage of reduction is related to the velocity response, which values are 50%, 44%, and 37%, respectively, and under NF earthquakes with FD. However, in terms of the mean of norm responses, it is possible to see a maximum decrease in the velocity response to 75% in a 3-story building and under NF earthquakes with FD, and in 9 and 20-story buildings to a maximum decrease in the acceleration response to values of 80% and 82% under the FF earthquakes. Therefore, the viscous damper has a commendable performance in all buildings and under all earthquake records. However, the performance of the viscous damper in reducing the velocity or displacement responses in short-rise buildings and under FF records outperforms the mid-rise buildings, and in mid-rise buildings, it is far better than high-rise buildings. In contrast, in reducing the acceleration responses, the viscous damper has a profound effect on high-rise buildings.

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