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Optimal Design of Viscous and Friction Dampers in Symmetric Reinforced Concrete Buildings

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Abstract **-** In this paper a comparison of the seismic performance of three symmetric in plan reinforced concrete (RC) buildings strengthened with viscous or friction dampers are presented. An overview of the optimal design of each type of dampers is described. Three buildings (a four-storey building, a nine-storey building, and a sixteen-storey building) were subjected to seven (real and artificial) seismic recorded accelerograms. Nonlinear dynamic time history analyses were carried out. The effects of each strengthening solution are presented in terms of the maximum horizontal displacement at the top of each building, the maximum inter-story drift and the maximum acceleration at the top of the building. The outcomes of this comparison show that viscous dampers (VDs) provide a significant reduction for mid-rise buildings, while friction dampers (FDs) increase the performance of all structures under seismic action. Further useful results were observed.

Keywords**:** Viscous damper; Friction damper; Optimal design; Dynamic response

1. Introduction

Passive energy dissipation devices such as viscous dampers (VD) and friction dampers (FD) have widely been used to reduce the dynamic response of civil engineering structures subjected to seismic loads. Their effectiveness is attributed to minimize structural damages as they are able to absorb the structural vibratory energy and to dissipate energy through their hysteresis behavior. For these reasons a lot of buildings and bridges were strengthening with them during the last years [1-6]. Viscous dampers work based on the dissipation of energy by fluid flowing through orifices [7]. Applying the well-developed fluid damping technology to civil structures was relatively straightforward to the extent that, within a short time after the first research projects were completed on the application of fluid dampers to buildings, bridges and panels [8-10]. On the other hand, a typical FD dissipates the external energy through the generated frictional force and stabilizes the structure under the dynamic excitation scenarios [11]. Many researchers proposed friction dampers that focus on the braced frames protection or in the joint connection [12-18].

The aim of this study is to compare the seismic response of three reinforced concrete (RC) buildings, symmetric in plan, with two types of passive energy dissipation systems, the viscous dampers, and the friction dampers. The optimal design was focused on minimize: i) the maximum displacement at the top of the structures, ii) the maximum inter-story drift and iii) the maximum acceleration at the top of the building. Three regular buildings, a four-storey building, a nine-storey building, and a sixteen-storey building, subjected to seven (real and artificial) seismic recorded accelerograms. Nonlinear dynamic time-history analyses were carried out. The effects of each strengthening solution are presented in terms of the maximum horizontal displacement at the top of each building, the maximum inter-story drift and the maximum acceleration at the top of the building. The outcomes of this comparison show that viscous dampers (VDs) provide a significant reduction for mid-rise buildings, while friction dampers (FDs) increase the performance of all structures under seismic action. Further useful results were observed [19].

2. Description of the investigated buildings

The three buildings, which were investigated in this study, are regular in plan and have the same external dimensions, 40.00m in the longitudinal direction and 20.00m in the transversal direction, as shown in Figure 1. The number of the stories is varied with a constant height of each story equal to 3.50m. The first building, mentioned from now on as « Low-rise », consists of 4 stories with the ground floor, the second one, mentioned as « Mid-rise », consists of 9 stories , while the third one, mentioned as « High-rise », consists of 16 stories. The quality of concrete material is C30/37 and the steel rebar's S500B. The selection of static loads is based on the provisions of EC1 [20]

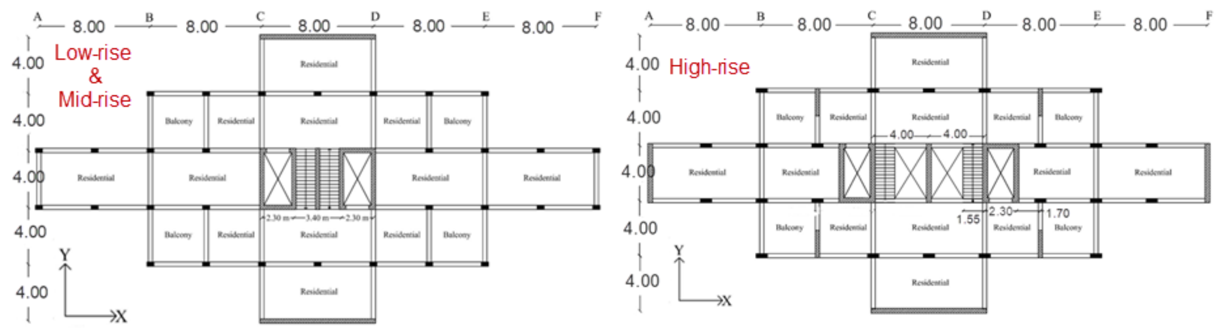


Figure 1. Plan view of the three buildings (units in m).

3. Finite element building's modelling

The beams and the columns were modelled as frame elements with rectangular cross sections, while the walls were modelled as shell elements. The assumption of the rigid floor diaphragm was used. The building is subjected to gravity and lateral loads. Non-linear dynamic time history analyses were performed to account the geometrical and structural non-linearities. N-Link elements have been used for the modelling of the dampers. The damping properties of the nonlinear viscous dampers (VD) were based on the Maxwell model of viscoelasticity [21]. Nonlinear properties (stiffness, damping coefficient, and damping exponent) were specified and modelled in series. For the numerical modelling of friction dampers (FD), fictitious plasticity element having yield force equal to slip load was used. FD and VD were positioned in steel diagonal brace elements. The braces were modelled as frame element.

All building models were studied for seven different real and artificial accelerograms that were compatible to ground type B-dependent Eurocode 8 elastic spectra (seismic zone V according to the French national annex [22]). The selection of the accelerograms was based on the provisions of Eurocode 8 Part 1 [23]. The direct integration, known β-Newmark method, was used. The mass and stiffness proportional damping was chosen and critical damping ratios equal to 5%. Each nonlinear dynamic time history analysis described by bi-directional recorded accelerograms.

4. Optimal design of passive energy dissipation systems

4.1. Viscous Dampers (VDs)

In our study the mathematical model proposed by Seleemah and Constatinou [24] has been used, where the dampers force P(t) is calculated using the equation (1):

$$P(t) = C_d |\dot{u}(t)|^{\alpha}\ sgn[\dot{u}(t)] \tag{1}$$

Where, C_d is the damping coefficient, $\dot{u}(t)$ is the velocity across the damper and α is a coefficient, depends on the piston head design and viscosity properties of fluid.

For earthquake resistance structures, α coefficient has a value ranging from 0.3 to 1.0, in order to provide larger forces and to minimize shocks for high velocities with no degradation of performance. Based to previous researches in our study α value equal to 0.3 has been selected [25]. VD force varies with velocity which is related to structural motion and depends on the structural fundamental period. In this study a parametric study has been done in order to select the correct velocity in accordance with previous studies [26]. In addition, damping coefficient (Cd) is related to the desired effective damping ξ_{eff} attributed to the structure. In the present study, damping coefficient is distributed along the height of the building, based on the proportionality respective of the story shear force (equation 2) and effective damping ξ_{eff} is a sum of the structural inherent damping ratio (ξ_0) and the damping ratio of the viscous dampers (ξ_d) according to recommendations (see equation 3) [26].

$$C_{d,i} = \frac{V_i}{\sum V_i} \sum C_j \tag{2}$$

$$\xi_{eff} = \xi_0 + \xi_d = \xi_0 + \frac{\sum \lambda C_j {\phi_{rj}}^{1+\alpha} \cos^{1+\alpha}\theta_j}{2\pi A^{1-\alpha} \omega^{2-\alpha} \sum M_i {\phi_i}^2} \tag{3}$$

$$\lambda = 2^{2+\alpha} \frac{\Gamma^2\left(1+\frac{\alpha}{2}\right)}{\Gamma(1+\alpha)} \tag{4}$$

where A is the amplitude in terms of maximum displacement per fundamental mode, ϕ_{rj} is the relative horizontal displacement of the damper, θ_j is the inclined angle of the damper j, ω is the loading frequency supposed equal to the natural structural frequency, M_i is the vibrating mass of the story i, ϕ_i is the modal displacement at story i, and λ is a parameter calculated by equation 4 [27]. To have an essential damping ratio-repair cost relationship, the range of optimal effective damping is identified as $30\% - 40\%$ to minimize mean economic losses [28]. However, optimal damping amount depends also on building's properties such as the fundamental period of structure. Table 1 shows the selected effective damping and velocities values as well as the calculated damping coefficient.

Table 1. Effective damping and calculated damping coefficient for the three investigated buildings (α=0.3).

Building type	**Direction**	**Fundamental period [s]**	**Suggested velocity [m/s]**	**Suggested effective damping ξ_{eff}**	$\sum C_j$ **[kN·(s/m)$^{\alpha}$]**
Low-rise	Longitudinal	0.156	0.127	30%	71537.07
	Transversal	0.216	0.127	30%	59405.58
Mid-rise	Longitudinal	0.697	0.254	35%	56981.16
	Transversal	0.985	0.254	35%	39325.16
High-rise	Longitudinal	1.983	0.381	40%	12658.71
	Transversal	2.202	0.381	40%	12095.19

It was necessary to ensure that the dampers are located in a configuration that does not introduce eccentricity to the structure, for this raison the most efficient placement would be equivalently with the building's center of mass, along the perimeter of the structures. Different configuration of VD's placement has been studied while two of them are illustrated in the Figure 2. At least two dampers were positioned in each direction and on each side of building's center mass, at every storey. The most suitable configuration has been chosen based on the fundamental period, the top roof displacement and the base shear in longitudinal and transversal directions. As a result, alternative 2 provides the best reduction for the low and mid-rise building and alternative 1 offers the smallest values of displacement for the high-rise building. So, alternative 2 is chosen for the low and mid-rise building and alternative 1 for the high-rise building.

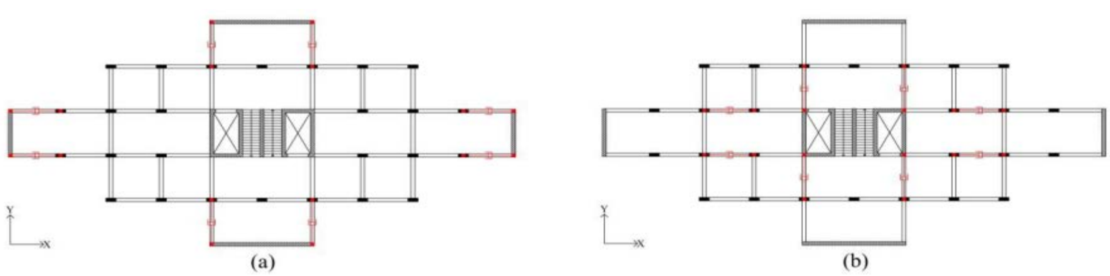


Figure 2. (a) Alternative 1 of dampers placement and (b) Alternative 2 of dampers placement.

4.2. Friction Dampers (FDs)

FD is a displacement-based system which dissipates energy through friction across the surfaces between two solid elements [29]. The simplest model is the Coulomb model of friction, in which the force is equal to $F_t = \mu \cdot F_n$ where F_t and F_n represent the frictional and normal forces respectively, and μ the coefficient of friction. Their hysteresis loops are rectangular showing a great amount of energy dissipated per cycle of motion and the cyclic behavior of FD is strongly nonlinear as shown in Figure 3a. When friction force is overcome, FD adds initial stiffness to the structural system. It is important to note that if no restoring force is provided, permanent structural deformation may exist after an earthquake [2]. As shown in Figure 3b, the response of structure is highly affected by FD slip force and a small variation of FD optimum slip load has minimum effect on structure's response. The selected slip force must be high enough to prevent damper from slipping under small applied lateral loads value and should be low enough to achieve slip before yielding of main structural elements [30, 31].

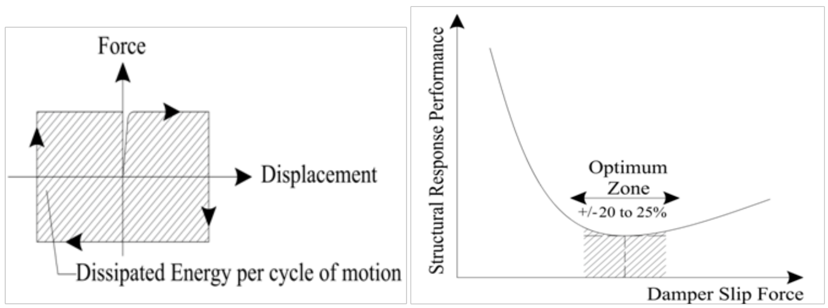


Figure 3. (a) Hysteresis loop of a friction damper, (b) Optimal slip force effect on structural response.

A simple method used in the present study consists of taking a portion from the applied shear force, so the load at each story is estimated by the equation (5):

$$F_{t,optimal} = \frac{1}{3}[V_i \, / \, n_i] \tag{5}$$

where $F_{t,optimal}$ is the optimal slip force or frictional force, V_i is the shear load and and n_i the number of damper per direction in storey i. The same two alternatives, as in the optimal design of VDs, were studied in the optimal design of the FDs (see Figure 2). Table 2 summarizes and compares the results and the authors selected the configuration number 1 due to the followings criteria: the significant reduction obtained in the longitudinal direction in terms of displacement and base shear.

Table 2. Responses of the three investigated buildings for the two alternatives of FDs placement.

Parameters	Direction	Low-rise		Mid-rise		High-rise	
		Altern.1	Altern.2	Altern.1	Altern.2	Altern.1	Altern.2
Fundamental period	Longitudinal	0.158	0.158	0.707	0.708	2.016	2.016
[s]	Transversal	0.218	0.218	0.998	0.999	2.239	2.239
Top roof	Longitudinal	0.228	0.290	1.682	1.775	6.915	7.787
displacement [cm]	Transversal	0.126	0.057	1.124	0.298	4.349	2.672
Base shear	Longitudinal	6971.2	7296.2	14030.2	14639.4	12373.0	13950.1
[kN]	Transversal	1525.1	2000.0	3100.0	3500.0	3494.58	4000.0

5. Results and discussion

5.1. Top displacement

Figure 4 illustrates the horizontal displacement at the top of each building in the longitudinal and transversal direction for the seven investigated accelerograms. The percentage of reduction of the responses for the low-rise building equipped with friction dampers or viscous dampers was compared with the structure without dampers (Figure 4 a, b). By evaluating the mean value of percentage reduction in both directions which is equal to 91.11% and 30.82% with viscous dampers, 71.44% and 76.87 % with friction dampers, it can be seen that friction dampers perform better than the two other types in the response reduction of the low-rise building. According to the results of the mid-rise buildings (Figure 4 c, d), it can be seen that utilizing viscous dampers reduces the displacement the most in both horizontal directions which go beyond 91.46%. Maximum displacement values with friction dampers presented an 87.26% and 79.25% reduction respectively in longitudinal and transversal direction. Both systems seem to perform well under all earthquake records for the mid-rise building. On the other hand, the percentage of reduction for the high-rise building equipped with friction dampers reaches a maximum of 90.36% in the longitudinal direction and a maximum of 69.50% in the transversal direction, which is considered high (Figure 4 e, f). Viscous dampers provide as well high values of reduction reaching a maximum of 91.89% and 76.96% in both horizontal directions, respectively.

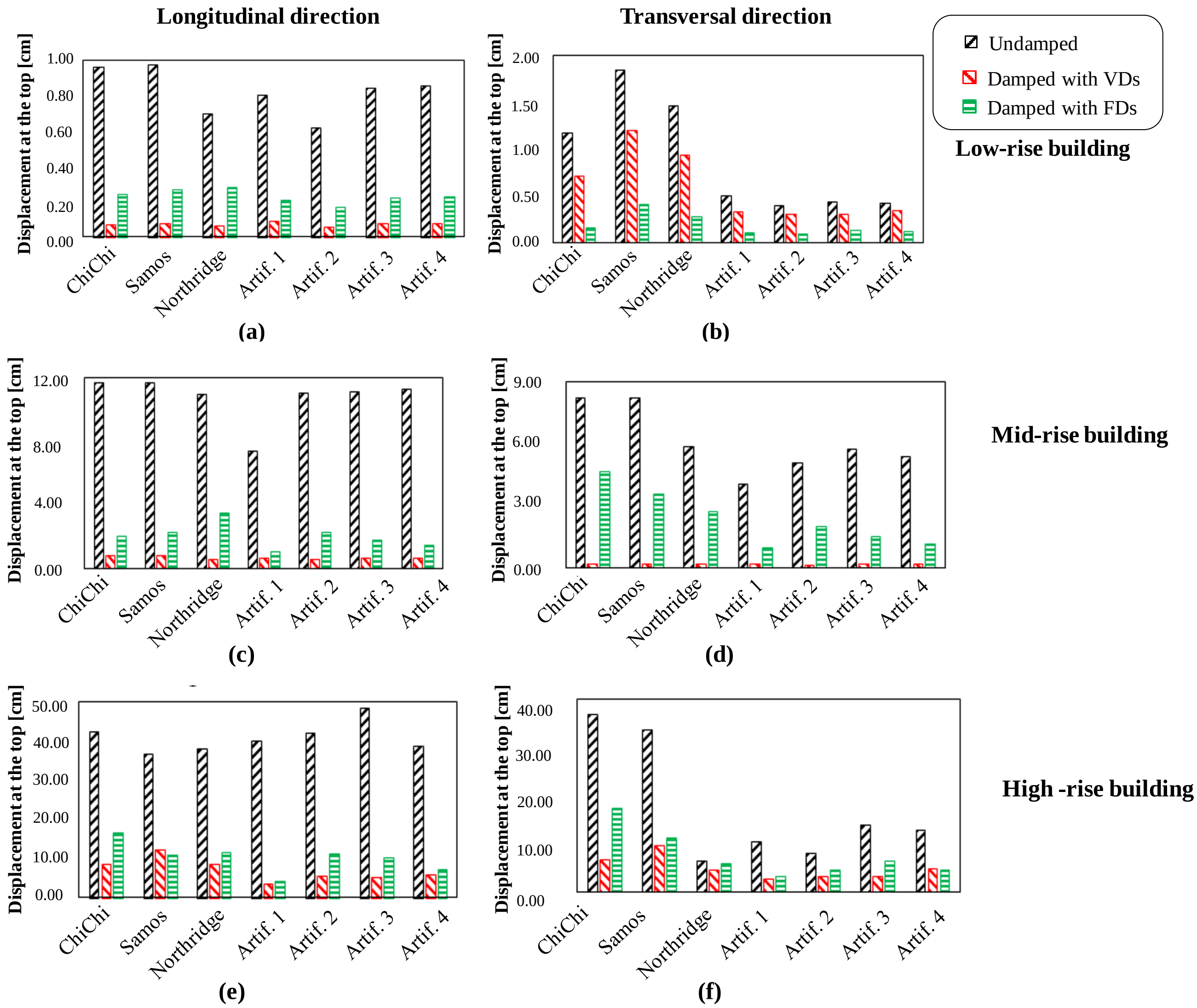


Figure 4. Horizontal displacement at the top of (a) (b) the low-rise building, (c) (d) the mid-rise building and (e) (f) the high-rise building for all the accelerograms.

5.2. Interstory drift

The inter-story drift index is defined as interstory displacement, $\delta_{s,i}$ divided by story height, *hi*. The relationship between interstory drift index and the global drift index δ_t/h_t depends on the extent of inelasticity in the structure, the type of plastic hinge mechanism, and the importance of higher mode effects. The continuous line presents the performances in the longitudinal direction while the dashed one in the transversal direction. From this comparison (Figure 5) it is clear that in terms of interstory drift, viscous dampers (VDs) provide a significant reduction for mid-rise buildings, while friction dampers (FDs) increase the performance of all structures under seismic action.

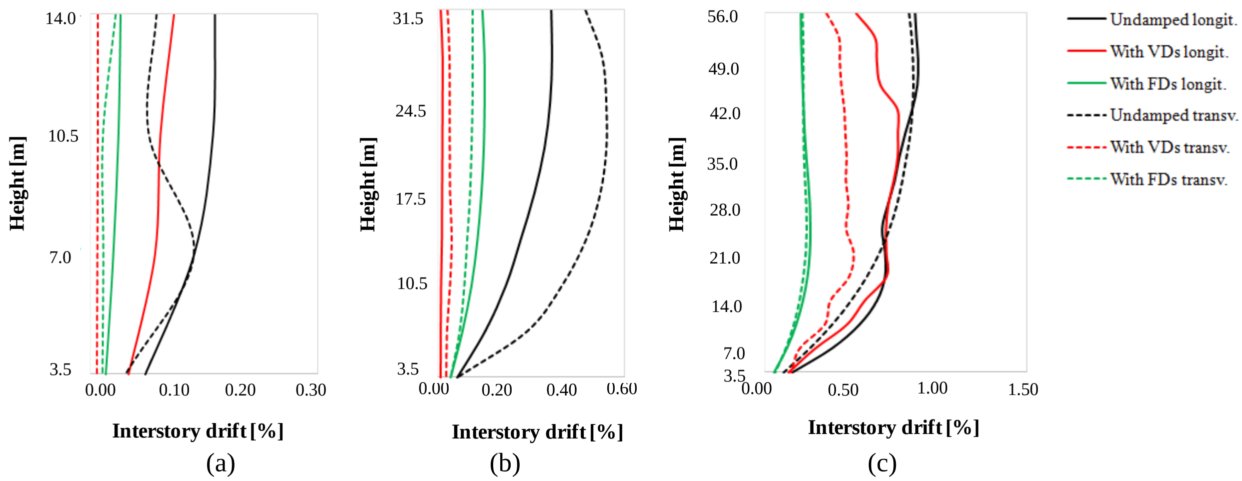
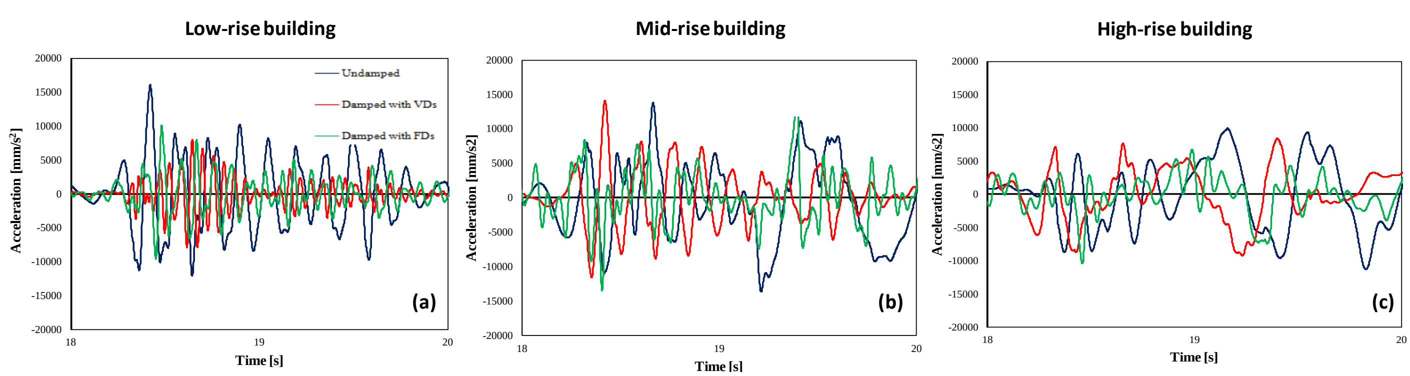


Figure 5. Maximum interstory drift for (a) low-rise, (b) mid-rise and, (c) high-rise building in the longitudinal and transversal direction.

5.3. Maximum acceleration at the top of the building

The following diagram's show the comparison of the acceleration at the top of the buildings for the earthquake Samos in the longitudinal (Figure 6 a, b, c) and transversal direction (Figure 6 d, e, f). For the longitudinal direction the time history results from 18-20sec are presented, while for the transversal direction from 14sec to 26sec. Blue line shows the results of undamped buildings, red line of the damped strengthened with VDs while green line of the damped strengthened with FDs. The comparison of the maximum acceleration at the top of the building validates the general conclusion of this study.



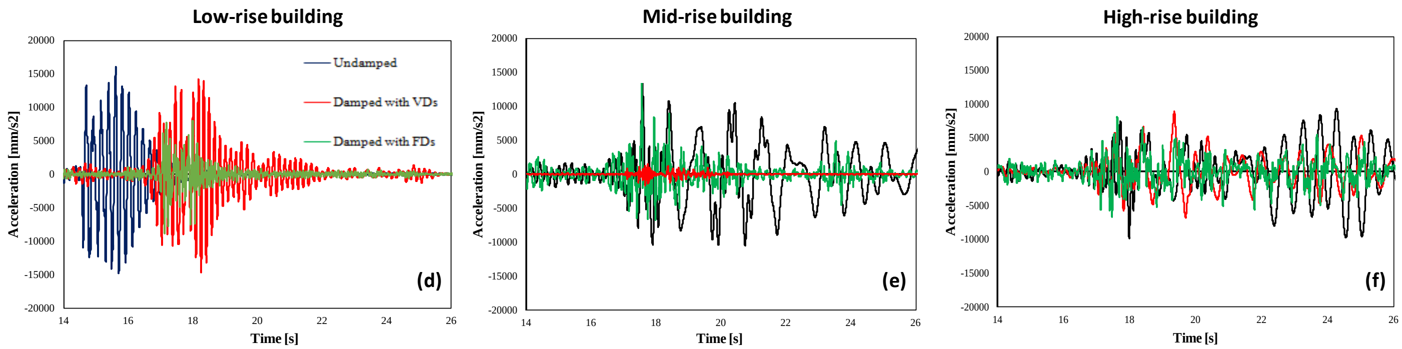


Figure 6. Maximum acceleration at the top of the building

6. Conclusions

In this paper a comparison of the seismic performance of three symmetric in plan reinforced concrete (RC) buildings strengthening with viscous or friction dampers are presented. An overview of the optimal design of Viscous and Friction dampers is described. The three buildings (a four-storey building, a nine-storey building, and a sixteen-storey building) were subjected to seven (real and artificial) seismic recorded accelerograms. Nonlinear dynamic time history analyses were carried out. The effects of each strengthening solution are presented in terms of the maximum horizontal displacement at the top of each building, the maximum inter-story drift and the maximum acceleration at the top of the building. The outcomes of this comparison show that viscous dampers (VDs) seem to perform well under all earthquake records for the mid-rise building, while friction dampers (FDs) increase the performance of all structures under seismic action.

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