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SMAR 2024 – 7th International Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures

Comparative analysis of seismic performance enhancement in irregular RC buildings using friction and viscous dampers

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Abstract

The purpose of this study is to demonstrate the impacts of friction dampers (FD) or fluid viscous dampers (FVD) in irregular (in plan and elevation) reinforced concrete (RC) buildings. The buildings (a four-story, a nine-story, and a twenty-story skyscraper) were analyzed using nonlinear dynamic time-history analysis on earthquake-recorded accelerograms, three of which were real while the other four were artificial. For this purpose, 70 nonlinear dynamic analyses were carried out. This paper describes the optimal design of FDs and FVDs, with a focus on minimizing the following parameters: (i) maximum displacement (top of the structures), (ii) building torsion, and (iii) maximum horizontal inter-story drift. Two different placements of the dampers have been studied in each building. The consequences of each strengthening method are shown, and other relevant results were obtained from this creative comparison (optimal design, two passive energy systems, and three different story numbers). The comparable results show that in low-rise structures, FD was more successful than FVD in reducing torsional moment; however, in medium and high-rise buildings, FVD was more effective at improving the seismic performance of the structures.

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Keywords: irregular buildings; plan; elevation; viscous damper; friction damper.

1. Introduction

The behavior of any building is determined by the arrangement of its structural elements. The structural configuration of a structure is mostly determined by its geometry, form, and scale. Dynamic loads, such as earthquakes,

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create inertia forces that concentrate near a structure's center of mass, as presented by Moehle and Alarcon (1986), Chopra and Goel (2004), and Das and Nau (2003). Vertical elements, such as columns and shear walls, resist horizontal inertia forces, resulting in a concentrated force at the center of stiffness. Eccentricity occurs when the center of mass does not align with the center of stiffness of a structure. Eccentricity is caused by uneven structural configurations, leading to torsion in the structure, as mentioned in Cornell and Krawinkler (2000) and De Stefano et al. (2013). It has been shown that irregular constructions are more seismically sensitive than regular structures according to De-la-Colina (2003).

During earthquake events, buildings are damaged owing to irregularities, as plasticity, and damage tends to accumulate near irregularities, resulting in high local ductility demands as presented by Karakostas et al. (2013), and Yaktine et al. (2023). Naeim et al. (2000), and Titirla (2023a) show that new seismic damage mitigation methods by adding passive energy dissipation systems can potentially lessen damage in irregular structures with proper use.

The goal of this study is to show how friction dampers (FD) and fluid viscous dampers (FVD) influence reinforced concrete (RC) structures that are irregular in plan and elevation. The three buildings (a four-story, a nine-story, and a twenty-story skyscraper) were examined utilizing nonlinear dynamic time-history analysis of earthquake accelerograms. This study covers the optimal design of FDs and FVDs, with an emphasis on reducing the following parameters: (i) maximum displacement at the top of the structures, (ii) building torsion, and (iii) maximum horizontal inter-story drift. In every structure, two distinct damper locations have been examined (placement A and B). The outcomes of this study highlight the potential of the dampers to increase the seismic performance and resistance of multistoried structures, as well as the easy processing of selecting appropriate damper characteristics from a wide variety of options. Comparing the buildings, FVDs, and VDs have almost the same capacity for low-rise and mid-rise buildings. At the same time, the Skyscraper leads a huge number of dampers (FVDs or VDs), which would be expensive and the solution of a tuned mass at the top of the Skyscraper could be considered in further study.

2. Investigated buildings

2.1. Structure

Due to architectural reasons, the buildings under examination have irregularities in both plan and elevation, and they are supported by asymmetrically distributed porticos and sails. The initial problem of these buildings is linked to torsional stresses and rotation. The three structures have the same floor designs (Fig. 1), but there are differences in the number of stories and the cross sections of the beams and columns (Table 1). The first is a four-story building, the second is a nine-story one, and the third is a twenty-story skyscraper. Fig. 1a shows the lower floor plan (floors 1 to 3 of the low-rise building, floors 1 to 7 of the mid-rise building, and floors 1 to 14 of the high-rise building), while Fig. 1b shows the upper floor plan (4th floor of the low-rise building, floors 8 to 9 of the mid-rise building, and floors 15 to 20 of the high-rise building). The concrete material belongs to category C35/45 and the steel rebars are S500B.

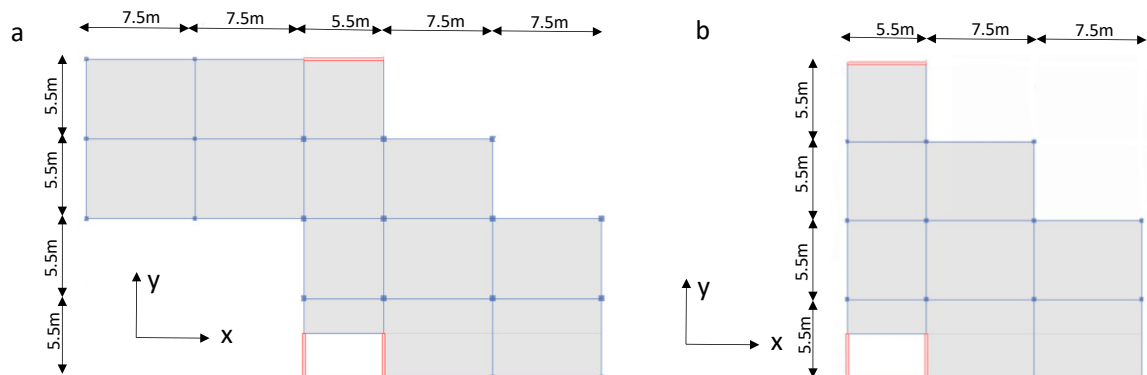


Fig. 1. (a) lower floor plan; (b) upper floor plan of the buildings.

Table 1. Dimensions of the structural elements in the buildings under investigation.

Structural elements	Low-rise	Mid-rise	High-rise
Cross-section of the beams	30x60 (cm)	35x60 (cm)	40x70 (cm)
Floor thickness	20 (cm)	25 (cm)	30 (cm)
Cross-section of the columns (lower floors)	30x30 (cm)	40x40 (cm)	50x50 (cm)
Cross-section of the columns (upper floors)	Fl. 1-3: 40x40 (cm)	Fl. 1-7: 50x50 (cm)	Fl. 1-14: 60x60 (cm)
	Fl. 4: 30x30 (cm)	Fl. 8-9: 40x40 (cm)	Fl. 15-20: 50x50 (cm)

Several requirements must be satisfied for the structure to be regular in plan according to Eurocode 8, one of which is that the vertical parts in the structure must be distributed roughly symmetrically in both horizontal directions. This requirement is not met in these buildings, so they are irregular in plan. In addition, in framed structures, the setback at any level must not be more than 20% of the preceding plan dimension in the setback's direction, and the ratio between the actual story resistance and the resistance needed by the analysis should not differ disproportionately across adjacent stories. This ratio is 44% in the investigated buildings, so they are also irregular in elevation.

2.2. Finite elements modeling

Walls were modeled as shell components and beams and columns were modeled as frame elements with a suitable rectangular cross-section (Table 1). Gravity and lateral loads were considered following EC1 regulations. At the foundational level, the building is fixed and each story contains a model of a stiff floor diaphragm. Non-linear link components represented FVD and FD. The dampers were fastened to steel diagonal bracing which were modelled as frame elements.

This study utilized an efficient mathematical model (linear or nonlinear) presented by Seleemah and Constatinou (1997) to calculate the force of the FVDs. The model is based on the damping coefficient (C_d), displacement across the damper (u_t), and coefficient (α) based on the piston head design and fluid viscosity. We chose an α value of 0.3 for our investigation. The damping parameters of nonlinear viscous dampers were calculated using the Maxwell model of viscoelasticity.

The numerical modeling of friction dampers (FD) was simple since its hysteretic loop is rectangular, similar to a perfectly elastoplastic material. They were modeled using an N-Link plastic element with a yield force equal to the slip load.

The optimal design of the dampers has been contacted following the process of previous work by Mrad et al. (2021), and Titirla (2023b) with an emphasis on reducing the following parameters: (i) maximum displacement at the top of the structures, (ii) building torsion, and (iii) maximum horizontal inter-story drift. International regulations stipulate that a minimum of two devices must be utilized in each direction and distributed symmetrically to prevent eccentricity and torsion. They also need to be put on every floor. To optimize the dampers' efficacy, many arrangements have been looked at, and two of them are presented in the following illustrations (Fig. 2 and Fig. 3).

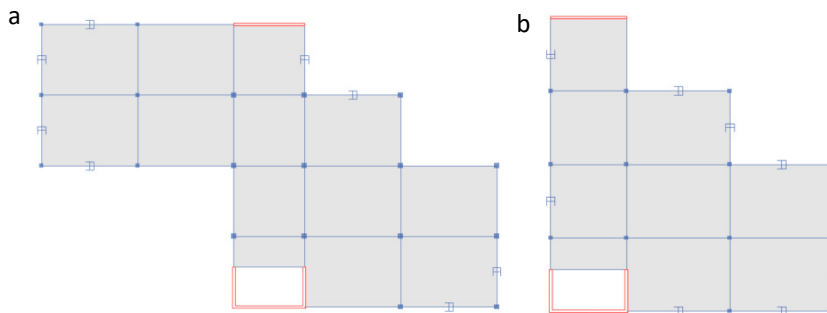


Fig. 2. Dampers placement A in the (a) lower floor plan; and (b) upper floor plan of the buildings.

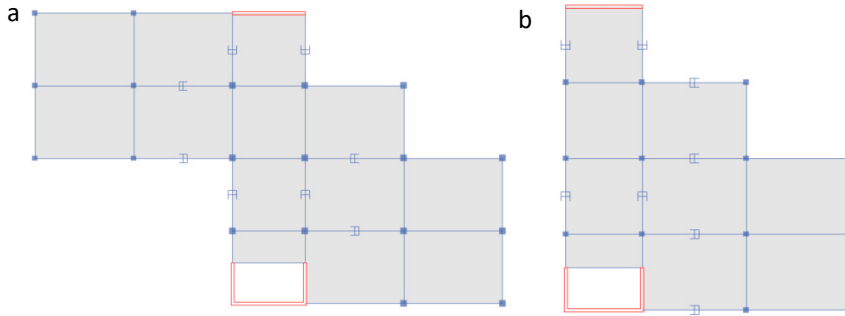


Fig. 3. Dampers placement B in the (a) lower floor plan; and (b) upper floor plan of the buildings.

Seven accelerograms, both simulated and real, that were compatible with ground type B—seismic zone II according to the French National Annex of 1998—were analyzed for the three buildings. The chosen accelerograms from the word database adhere to the guidelines in Eurocode 8 Part 1. Table 2 shows the selected, effective damping and velocity values, as well as the calculated damping coefficient obtained by the optimal design of the FVDs for placement number A, while Table 3 presents the values of the selected slip force of the FDs for placement number A.

Table 2. Effective damping and calculated damping coefficient of VD_s ($\alpha = 0.3$).

Building	Direction	Velocity (m/s)	Suggested effective damping ξ_{eff}	$\sum C_i$ ($kN \left(\frac{s}{m}\right)$)
Low-rise	x-x	0.125	30 %	110930
	y-y	0.125	30 %	73949
Mid-rise	x-x	0.25	35 %	100700
	y-y	0.25	35 %	100860
High-rise	x-x	0.38	40%	147762
	y-y	0.38	40 %	132117

Table 3. Selected slip force of FD_s,

Building	Direction	$F_{slip} = 1400$ kN	$F_{slip} = 900$ kN	$F_{slip} = 450$ kN
Low-rise	x-x	1-2 floor dampers	3rd-floor dampers	4th-floor dampers
	y-y	1-2 floor dampers	3rd-floor dampers	4th-floor dampers
Mid-rise	x-x	1-4 floor dampers	5-7 floor dampers	8-9 floor dampers
	y-y	1-5 floor dampers	6-7 floor dampers	8-9 floor dampers
High-rise	x-x	1-12 floor dampers	13-18 floor dampers	19-20 floor dampers
	y-y	1-11 floor dampers	12-18 floor dampers	19-20 floor dampers

3. Results

Fig. 4 presents the reduction of horizontal displacement at the top of each building compared with the initial undamped building, in x-x and y-y directions, the eccentricity, and the rotation for the three buildings.

In low-rise structures, both systems show a reduction in total displacements. The FVD provides more ideal responses, with average difference margin values of 63.2% and 73.9% for the directions x-x and y-y, respectively, while the FD provides values of 47.2% and 59.2%. In terms of rotation, which is the main problem of the irregular buildings, we notice initial response margins of 20% with FD and 7% with FVD, respectively. This makes the use of

FDs more effective than FVDs and is consistent with the enhancement of symmetric buildings with the use of FDs in low-rise buildings provided by Mrad et al. (2022).

The FVD provides a more ideal response than the FD for mid-rise buildings, in terms of displacement with average difference margin values of 49.7% and 58.7% for the X and Y directions, respectively. This result highlighted previous findings by Yaktine et al. (2023). A reduction of torsion at the base with average values of 21.7% and 32.7% respectively with the use of FDs and FVDs.

As with low-rise and mid-rise buildings, it is noticed that both dampers greatly minimize the maximum horizontal displacement for high-rise buildings. But compared to the FDs, which provide values of 29.9% and 17.4% for the x-x and y-y directions, respectively, the FVDs provide a more appropriate response, with average difference margin values of 59% and 40.4%.

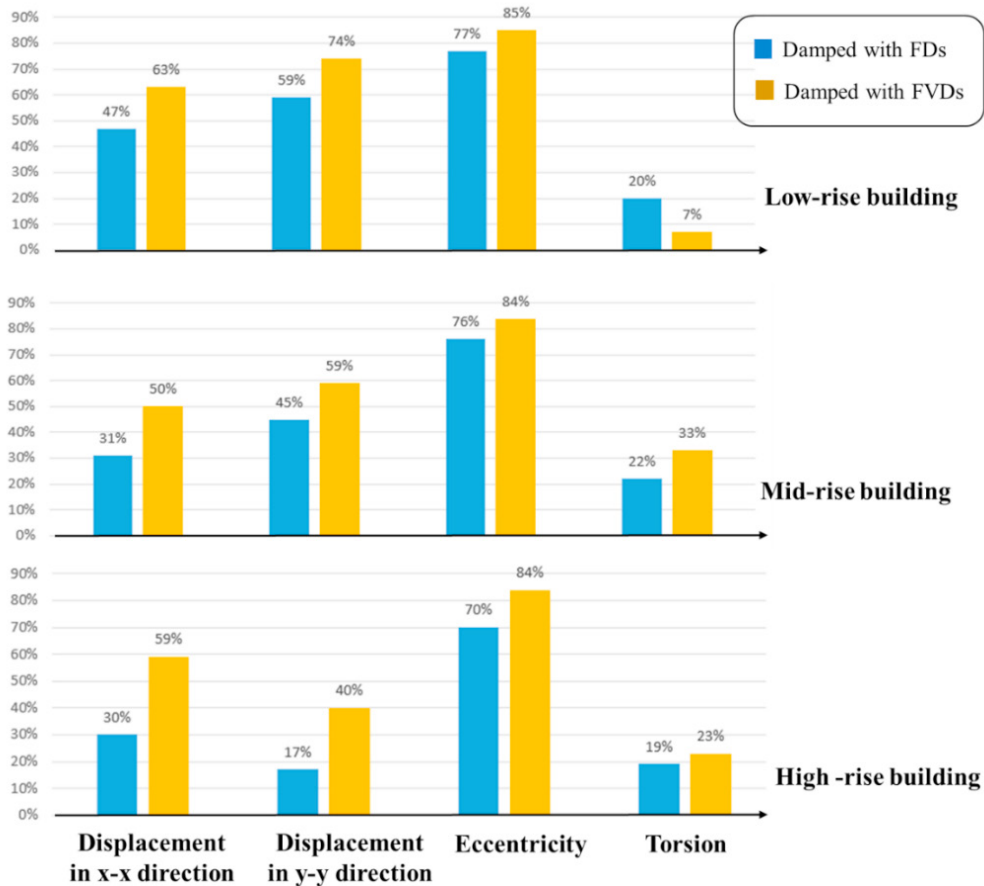


Fig. 4. Reduction of horizontal displacement at the top of each building and rotation for all buildings.

Fig. 5 presents the reduction of rotation of each building compared to damped with the FDs and the FVDs, with the initial undamped building under the accelerograms of the Samos earthquake. The results show that as the floor number increases (height), the story rotation increases, and maximum floor rotation occurs at the highest stories. With the use of FDs and FVDs, we can notice a reduction of rotation of more than 50%. Reduction of the torsion leads to the adding the dampers located near the corners of the building. This change improves the performance of all the multi-story buildings because the torsion occurs in the third mode of vibration.

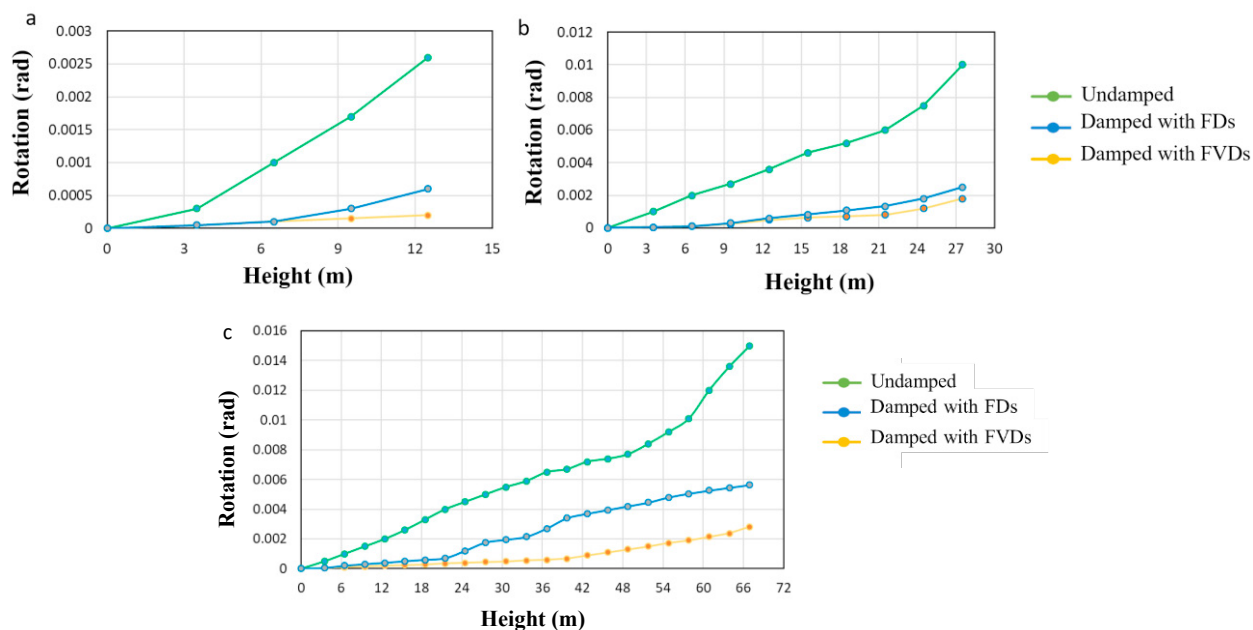


Fig. 5. Comparison of rotation in each floor for the initial undamped, the damped with FDs, and the damped with FVDs for the (a) low-rise, (b) mid-rise, and (c) high-rise buildings under the acceleration of Samos.

4. Conclusions

Valente and Milani (2018) and Requena-García-Cruz et al. (2019) have examined the best-chosen way to reinforce an engineering construction, considering several different variables. In this work, we address the impact of VD or FVD instead of attempting to determine the optimal solution for irregularities in plan and elevation-reinforced concrete structures. Three buildings were examined using nonlinear dynamic time-history analyses under earthquake-recorded accelerograms. With a focus on lowering the following parameters—i) maximum displacement at the top of the structures, ii) building torsion, and iii) maximum horizontal inter-story drift—this study addresses the best design of FDs and FVDs. Two different damper sites (placements A and B) have been inspected in each building. The study's findings demonstrate how dampers may improve multistory buildings' seismic resistance and performance. They also demonstrate how simple it is to choose the right damper characteristics from a large range of available possibilities. When comparing the buildings, the capacities of FVDs and VDs for low-rise and mid-rise structures are about equal. Simultaneously, the Skyscanner leads a large number of dampers (FVDs or VDs), which would be costly. For this reason, more research may look at the possibility of using a tuned mass at the top of the Skyscanner.

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