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A study on the strengthening of buildings by utilizing viscous dampers

Un studiu privind consolidarea clădirilor prin utilizarea amortizoarelor vâscoase

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Abstract

One of the methods that have been considered in recent years for the reinforcement of structures is the use of energy-absorbing systems. A variety of energy-absorbing systems have been developed and introduced, including liquid, viscous dampers. The main purpose of this study is to evaluate the efficiency of viscous dampers in absorbing forces caused by earthquakes and seismic improvement of structures, as well as the feasibility of increasing the floors of an existing structure by using these dampers. For this purpose, three different models with fixed plans and three different numbers of floors as five, nine, and thirteen have selected, and the possibility of increasing one floor to them by using viscous dampers has investigated. The results indicated that by adding a floor to the existing buildings, the stress ratio in some columns and also the relative displacement exceeds the allowable limit; however, viscous dampers can significantly decrease the stresses and displacements and can be used to expand the number of floors of an existing building.

Keywords: viscous dampers, building development, seismic improvement, energy-absorbing systems

1. Introduction

Viscose dampers were first used in the 19th century to counteract the effects of cannonballs on ships. Later, the use of these devices in the aerospace industry for launching missiles. Until the first half of the 20th century, this technology was also used in car factories. The introduction of viscose dampers into the construction industry began with experiments at the University of Buffalo and in the early 1990s [1], and then many scientists and researchers have researched in the field of viscous dampers.

Bhaskararao and Jangid [2] examined the seismic response of adjacent buildings connected to dampers. In this research, the structural response of two adjacent buildings connected to different types of dampers under different earthquake stimuli has studied. The results show that connecting adjacent buildings with different main frequencies with passive dampers can effectively reduce the earthquake responses of both buildings. Shrimali et al. [3] investigated the performance of a variable friction damper (VF). They Considered two connection modes of adjacent 20-story and 10-story frames connected by a friction damper. Their results showed that dampers have a significant effect on the seismic response of two adjacent and identical buildings and reduce the response.

Patel [4] investigated the effect of using viscous dampers in controlling the seismic response generated on adjacent buildings with similar dynamic properties. The results showed that the use of viscous dampers reduces the seismic responses by selecting the appropriate damping coefficient. Separation of the base to prevent the direct transfer of seismic force from the foundation to the structure is one of the important practical measures in improving the seismic performance of structures. Alimohammadi et al. [5] Modeled and analyzed a 4-story steel frame with bending joints in SAP2000 software. The analysis was performed using a nonlinear time history method. Lateral displacement of separator level, lateral displacement of structure, and acceleration of floors in isolated flexural steel frames with different adduction damping ratios have investigated. The results also show that under the influence of earthquakes in the near and far areas, the displacement of the base level is reduced by increasing the additional damping.

Since it is not possible to model a nonlinear viscosity damper in a structure with the behavior of nonlinear materials directly in most software, including Abaqus, Mousavi et al. [6] described the behavior of nonlinear materials. They then examined the responses of the structure under different earthquakes. The results of the analysis showed the addition of mirage viscosity reduces the responses of displacement, acceleration and base shear between 22 to 70% and 20 to 68 and 3 to 65%, respectively. Farahbod and Gharshi [7] investigated the effect of viscose on the seismic performance of high-rise steel buildings with a core system and arm restraint. For this purpose, three buildings of 20, 30, and 40 floors were modeled in three dimensions with an asymmetrical plan and dimensions of 25 × 25 meters and a floor height of 5.3 meters using the finite element software. These models were subjected to nonlinear time history analysis under three distant earthquake records, regardless of wind load, once by changing the bracing position in different classes and again by changing the braking location equipped with viscous dampers in different classes. Examination of these parameters showed that in the case of using mortar viscosity, the average maximum amount of roof displacement is 27% in the 20-storey building, 33% in the 30-storey building, 37% in the 40-storey building, and 13% in the 20-storey building in the 30-storey building. Percentage and in the 40-story building, 21% decreased compared to the state without dampers.

2. Viscous dampers

Viscous dampers were first used in the late mid-19th century to offset the effects of cannon hits on ships. In the first half of the twentieth century, an automobile company extensively increased their endurance and used them for the needs of vehicle suspension systems. During the Cold War, viscous dampers were used to separate silos and rocket launchers, and their use and development for large cannons and warships increased. In the late 1980s, a small variety of these dampers were widely used by military contractors for civilian purposes. A military contractor named Taylor [7] conducted experiments in collaboration with the National Center for Earthquake Engineering at New York University in Buffalo and investigated the adaptability of viscous dampers in building applications to withstand wind and earthquake motion. Since then, viscous dampers have been used in more than 110 large structural applications. Viscous dampers were used in dimensions of 40 cm to 1.4 m. Their output power range is from 44.5 kN to 9 MN. A viscous damper consists of only a few parts. The main part of it is a piston, which has a reciprocating motion. The liquid passes through the holes, and the velocity of the liquid produces force. Figure 1 shows a viscous damper.

Figure 1. Viscous dampers

To make structures resistant in front of the lateral loads, there are generally two method, one method is that to use specific structural system with adequate stiffness. In some structures such Special Truss Moment Frames, (STMF), the structure is designed in a way that special segment in the beams can act as a fuse and can fail before failure of whole system. There are various parameters in behavior of this systems; for example, Mousavi et. al. and Alimohammadi et. al. [8], [9] investigated the geometric effects in behavior of these structural systems, the other method is to increase the damping of the structural system utilizing external dampers such as viscose dampers. There are several important advantages to using viscous dampers. The damping force produced by viscous dampers in a structure is inherently non-phase with the maximum response in the structure during a seismic event. It is the highest of the lateral forces. The damping force is the lowest. For this reason, viscous dampers can reduce acceleration class shear and base shear. Viscous dampers could also be combined with shape memory alloy (SMA) wires to take advantage of energy-absorption and superplastic properties of these materials [10]. Viscous dampers have become a sealed device, making them less sensitive to the atmospheric hazards that friction dampers must withstand. Taylor [7] stated that the high quality of products using inelastic seals and polished pistons with a 35-year warranty eliminates the need for regular maintenance. Finally, the performance of the viscous damper is almost heat-independent, and the same viscosity damping equation is valid for all frequency levels, making it easier to model more accurately than the more viscous elastic damper. Due to the low compaction of viscous fluid, starting to work is accompanied by a blow to the viscous damper, and for this reason, viscous dampers act in small structural deformations such as rigid systems. According to Taylor [7], these dampers do not produce any damping at displacements of less than 2 mm. Although in recent years there is some improvement in computational fluid dynamics and standard combined methods for a subsonic flow field, unfortunately, simulating the viscous dampers is still complex to model,[11], [12]. Because their output force is based on their velocity, and the force on the rest of the structure is based on deformation, the assumptions of relative damping may be invalidated.

3. The methodology of the research

In this study, the purpose is to investigate the efficiency of viscous dampers in absorbing earthquake forces and seismic improvement of structures, as well as the feasibility of increasing the floors of an existing structure using these dampers. Accordingly, three models with different numbers of building stories will be studied. In this way, the feasibility of increasing the floors using viscous dampers will be investigated. The specifications of the three models under study are five stories to the six-story building, nine stories to the ten-story building, and thirteen-story to the fourteen-story building for model numbers one, two, and three, respectively. The steps of conducting research in each of the models are as follows:

1) Modeling, analysis, and design of an n-story building by spectral method

2) Modeling, analysis, and design of a 1 + n floor building by spectral method

3) Adding a floor to the designed n-floor building and analyzing the time history and examining changes in displacements and stresses in the n + 1-floor structure

4) Seismic improvement of 1 + n floor structure using viscous dampers

5) Analysis and design of time history of 1 + n floor building by increasing the damping of the structure and determining the appropriate damping percentage

6) Spectral analysis and design of 1 + n floor building with damping obtained from step 5

7) Compare the analysis results of items 1 to 6 by presenting tables and graphs

4. Modeling specifications and input parameters

The general characteristics of the studied sample are given in Table 1. Also, figure 2 shows the typical architectural plan of the floors of the studied building that used in this research that was identical for all the case studies structures.

Table 1. General specifications of the project

Location	Structure type	Building type	Story height	Soil type	Lateral loading type	gravity bearing system type	Floor thickness
Urmia, Iran	concrete	residential	3.2 meter	No III	Medium bending frame in both directions	Beam block roof	0.3 meter

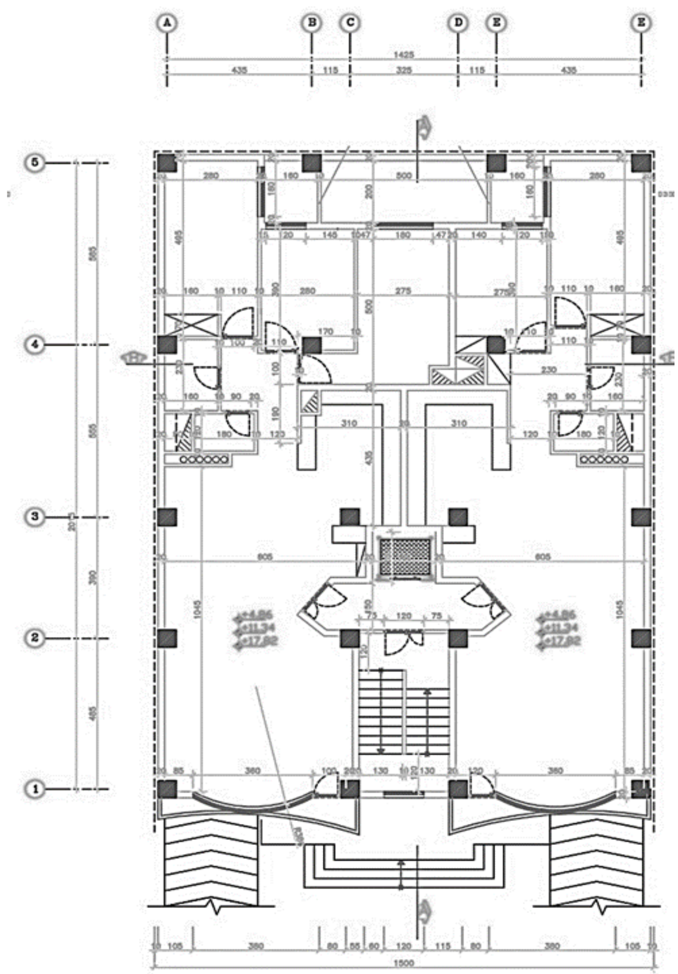


Figure 2. Architectural plan of floors

The concrete material and steel material specifications and design parameters used in this study are described in Table 2.

Table 2. The concrete material and steel material specifications

Concrete material		Steel material	
Unit weight (kg/m^3)	2500	Unit weight (kg/m^3)	7850
Elastic modulus (kg/cm^2)	265180	Elastic modulus (kg/cm^2)	2 E6
Poisson's ratio	0.15	Yield tension (kg/cm^2)	4000
Compressive strength of concrete (Mpa)	25	Ultimate strength (kg/cm^2)	6000

In this research, ETABS software has used to model and design the sample building, as well as Excel software, to analyze the results of structural analysis and to present the graphs. Table 3 shows the loads used in modeling.

Table 3. Summary of the loads on the floors

Location	Dead load (kg/m^2)	Live load (kg/m^2)	Walls load (kg/m^2)
Roof	455	150	-
floors	402	200	100

In general, to earthquakes design of buildings, the base section obtained from the equivalent static method must be calculated. For this purpose, according to the characteristics of the building and its structural system, earthquake coefficients in the two main directions of the building should be determined according to the relevant design codes which 2800 standard code used in this study. Also, spectral dynamic analysis and time history methods have used to perform structural analysis and design the models. It should be noted that the use of dynamic methods firstly increases the accuracy of the design and makes the distribution of forces in the structure more rational. Secondly, in regular structures or some irregular buildings, it can lead to being designed to be lighter (due to the reduction in the amount of base cut compared to static analysis. By performing modal analysis, the specifications of different modes of the structure are calculated by the ETABS software. In the spectral analysis method, each vibration mode of the structure is practically like an independent structure. In the modal analysis method, structural responses such as internal forces of members, displacements, shear of the floors, and the reaction of supports are obtained for each mode separately. However, it should be noted that because the vibration alternation times of different modes are different from each other, the maximum structural responses for different modes do not occur simultaneously. Therefore, it is not possible to determine the response of the whole structure. There are two main methods for combining the effects of modes, which are: the square root total method (SRSS) and the complete square combination method (CQC). Of the two methods, the CQC method is more accurate and can be used in all structures.

5. Results of analysis

As mentioned in section 2, model number one is a five-story building, and the possibility of increasing it by one floor using viscous dampers was investigated in this study. Model number two and three are a nine-story building, and thirteen-story building respectively and the possibility of increasing it by one floor using viscous dampers were investigated in this study. The method of calculation was the same for all these three models mentioned in this section, as below.

After modeling and analyzing the five-story building and also determining and applying the correlation coefficient according, the design of the five-story building was done, and the sections of beams and columns of the structure were obtained. The structure was designed in such a way that the stress ratio in the beams and columns, as well as the relative displacement of the floors, reached its allowable value by making trial and error in the dimensions of the beam and column sections. In addition to the stress ratio in the members of the structure, the relative displacement of these elements is also very important in making trial and error to further optimize the design schemes [13], [14]. Because the lateral load-bearing system of the structure is flexural in both directions, the relative displacements are often controlling to the stresses, and the dimensions of the sections should be increased to allow them. In order to compare the maximum amount of floor displacements in different structures, the displacements in the floors are extracted from the results of software analysis.

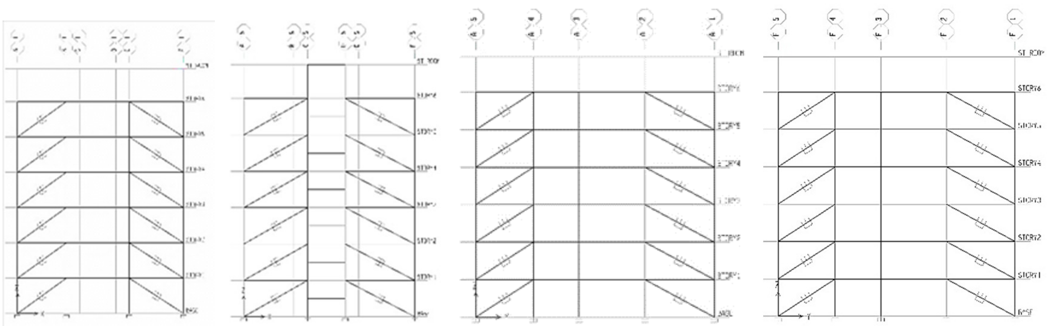
After analyzing and designing the five-story building in the previous stage, one floor was added to the existing five-story building, and the six-story structure was analyzed dynamically by time history and under scaled accelerometers. After performing the analysis, the values of stress ratio in columns and structural displacements were investigated. After modeling and analyzing the six-story building in ETABS software and also determining and applying the correlation coefficient according to the method, the design of the six-story building was done, and the sections of beams and columns of the structure were obtained. In order to design a six-story building, by making trial and error in the dimensions of the sections of beams and columns and controlling the amount of stress in the sections, the optimal possible dimensions for the six-story concrete structure was reached. To improve the seismicity of the 5 + 1-story building and to allow relative stresses and relative displacements, viscous dampers have used. Meanwhile, in this stage, to perform analysis and design, the method of dynamic analysis of time history has used. Then, the damping coefficient, stiffness of the dampers, and the type of dampers are done. Finally, the changes in the stress ratio of the columns and the number of displacements after adding a viscous damper to the structure are examined.

5.1. Calculation of damping coefficient and hardness of dampers

The damping ratio created in the structure by the damper can be calculated using Equation 1:

$$\zeta_d = \frac{T \sum C_j \varphi_{rj}^2 cos^2\theta_j}{4\pi \sum m_i \varphi_i^2} \quad (1)$$

In the above relation T, the period of the main mode of the structure, C_j, the attenuation coefficient of floor j, φ_rj, the relative horizontal displacement of the two ends of the damper due to deformation of the structure in the first deformation mode, θ_j The displacement of floor i is due to the deformation of the structure in the first mode of displacement. In the following, each of these parameters is calculated, and finally, the damping coefficient is calculated. Dampers are located in the side openings of frames 1, 5, A, and F. The location of the dampers can be seen in Figure 3.



a) b) c) d)

Figure 3. Location of dampers in the 1 + 5 floor building for a) frame 1, b) frame 5, c) frame A, d) frame F

Table 4, the damping coefficient of type 1 dampers is calculated using Equation 1 with a damping ratio of 15%.

Table 4. Calculation of damping coefficient of type 1 dampers with a damping ratio of 15%

Story	Modal Disp (φ_i)	Modal Drift (φ_{rj})	m_i (kg)	cos θ_j	$m_i\varphi_i^2$	$\varphi_{rj}^2 cos^2\theta_j$	C $\frac{kg-sec}{m}$
6	0.0039	0.0006	26336.432	0.477	0.4005771	8.19104E-08	2593523
5	0.0033	0.0008	26136.015	0.477	0.2846212	1.45619E-07	
4	0.0025	0.0007	27814.154	0.477	0.1738385	1.11489E-07	
3	0.0018	0.0008	29805.101	0.477	0.0965685	1.45619E-07	
2	0.001	0.0006	30133.991	0.477	0.030134	8.19104E-08	
1	0.0004	0.0004	31469.846	0.477	0.0050352	3.64046E-08	
sum	-	-	-	-	0.9907745	6.02952E-07	

The stiffness of the dampers is obtained from Equation (2)

$$\tau = \frac{C}{K_{nonlinear}} \qquad (2)$$

In this regard, C is the same damping coefficient calculated in the previous section. The parameter τ is equal to the ratio of the damping coefficient to the stiffness of the damper. If the stiffness is set so that this parameter is obtained between 0.01 to 0.001 inverse of the natural frequency of the structure, it will be appropriate. Therefore, the value of parameter τ was considered to be 0.01 inverse of the natural frequency of the structure. The natural frequency of the structure can also be calculated from Equation (3).

$$\omega_n = \frac{2\pi}{T} \qquad (3)$$

In this regard, T is the main periodicity of the structure. Table 5 shows the hardness of dampers.

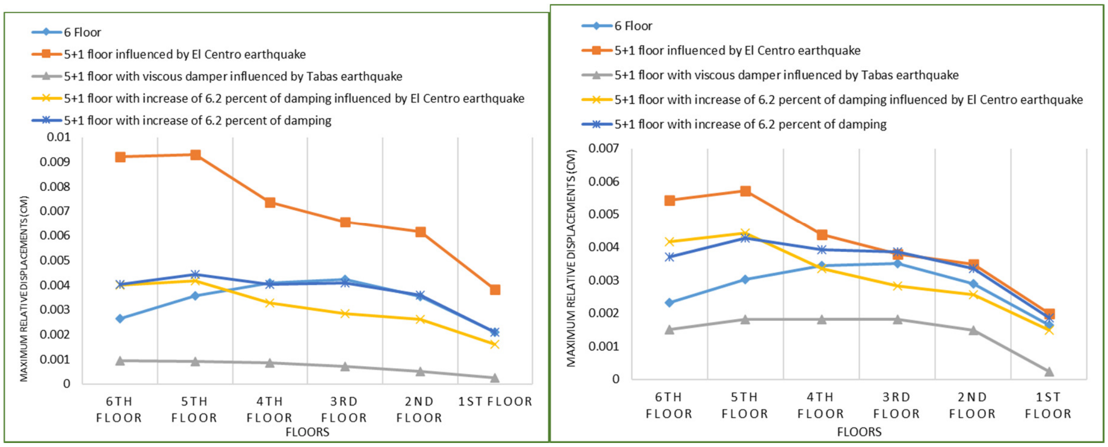
Table 5. Calculate the hardness of dampers

تیپ	T(s)	ω_n	τ	C $\frac{kg-sec}{m}$	K (kg/m)
1	1.1943	5.261	0.0019	2593523	1365012105
2	1.1943	5.261	0.0019	1972206	1038003158
3	1.1943	5.261	0.0019	1706759	898294211
4	1.1943	5.261	0.0019	2398631	1262437368
5	1.1943	5.261	0.0019	2740886	1442571579

After obtaining the optimal damping of 15% in the previous stage, in this stage, the 5 + 1-storey building has been analyzed and designed by the spectral method with damping of 6.2%. With increasing the damping of the structure by 6.2% in the structure of 5+1 floors, it was observed that the stress in the columns that exceeded the strength of the member reached the amount of resistant stress. This trend repeated for all three models. In analytical models Rayleigh method is utilized to define damping matrix. This method is one of the common methods of defining the damping matrix in structural engineering; for example, Mousavi et. al. and Alimohammadi et. al. [5], [15] used this method for defining the damping matrix in double layer braced barrel vaults in assessing the progressive collapse probability in theses space frame systems,

5.2. model number one

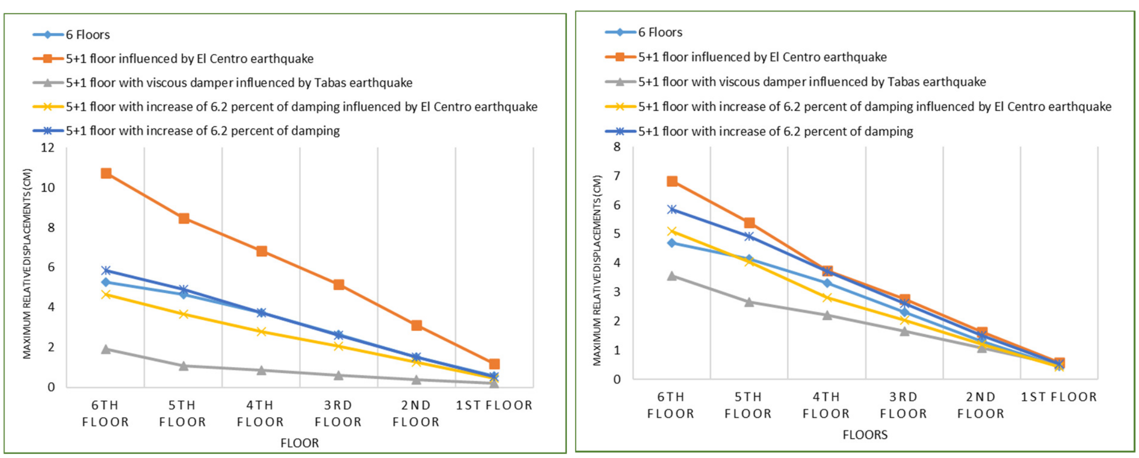
Figure 4-a shows the diagram of the relative displacements of the classes in the x-direction in different cases of model number one. In the chronological analysis, only the results of the most critical earthquake acceleration are given. Figure 4-b shows the diagram of the relative displacements of the classes in the y-direction in different cases.



a) b)

Figure 4. a) Diagram of the relative displacement of the floors in the x-direction, b) the relative displacements of the classes in the y-direction in different cases in different cases in model number 1

Figure 5-a shows the diagram of the maximum displacement of the floors in the x-direction, and figure 5-b shows the maximum displacement of the floors in the y-direction in different cases of model number one.



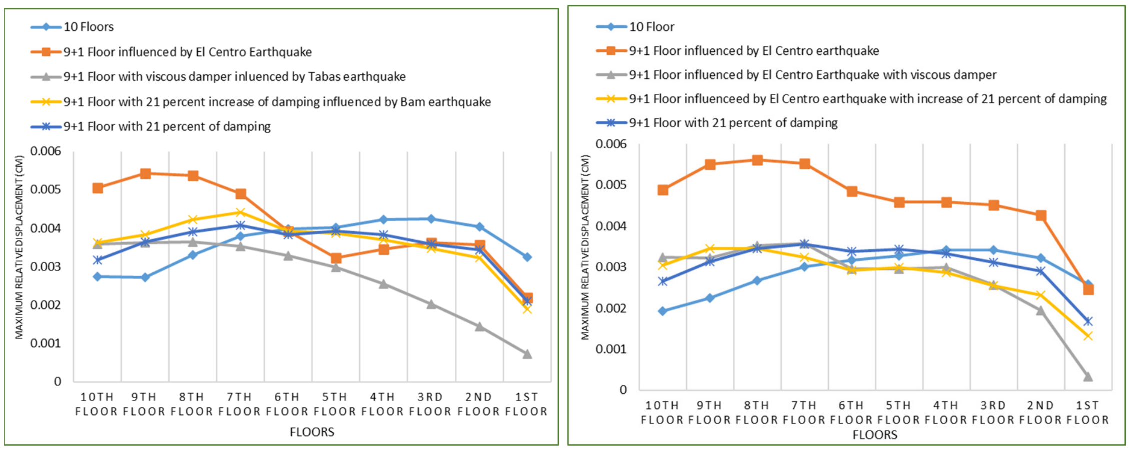
a) b)

Figure 5. a) Diagram of the maximum displacement of floors in the x-direction, b) the maximum displacement of the floors in the y-direction in different cases in model number one

Carefully in these diagrams, it can be seen that the displacements in the 5 + 1-floor building with dampers are less than other cases, which indicates the very favorable effect of these dampers on the behavior of the structure.

5.3. model number two

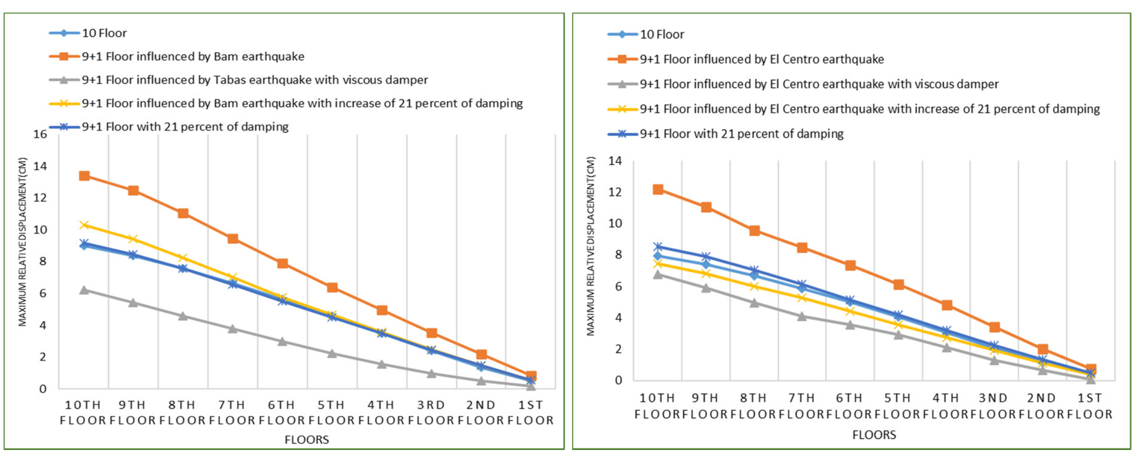
Model number two studied in this research is a nine-story building and the possibility of adding one story to it using viscous dampers. Figure 6-a shows a diagram of the relative displacements of the classes in the x-direction, and figure 6-b shows the relative displacements of the classes in the y-direction in different cases of model number two. In the chronological analysis, only the results of the most critical earthquake acceleration are given.



a) b)

Figure 5. a) Diagram of relative displacement of classes in the x-direction, b) relative displacement of classes in the y-direction in different cases in model number two.

Figure 6-a shows the diagram of the maximum displacement of the floors in the x-direction, and figure 6-b shows the maximum displacement of the floors in the y-direction in different cases of model number two.



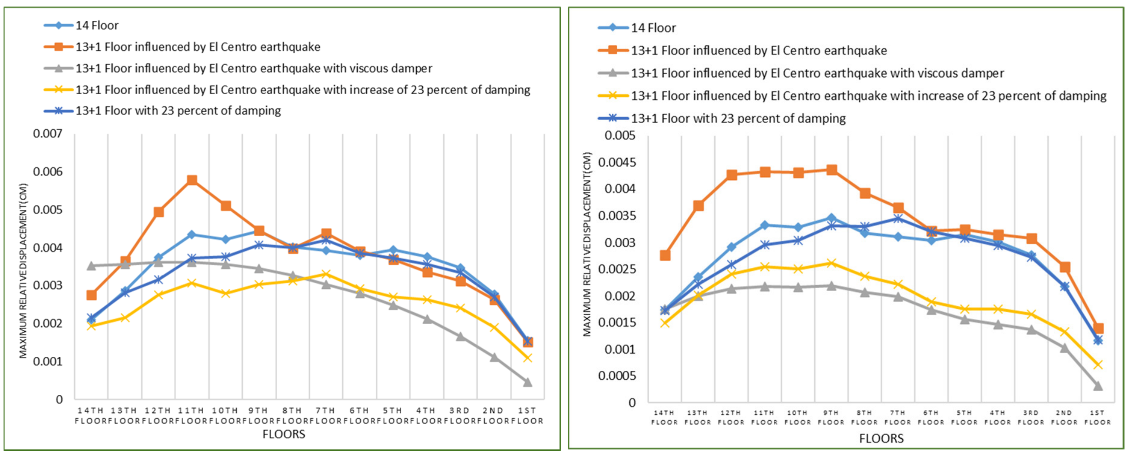
a) b)

Figure 6. a) Diagram of the maximum displacement of floors in the x-direction, b) the maximum displacement of the floors in the y-direction in different cases in model number two

Carefully in these diagrams, it can be seen that the displacements in the 9 + 1 story building with dampers are less than other cases, which indicates the very favorable effect of these dampers on the behavior of the structure.

5.4. model number three

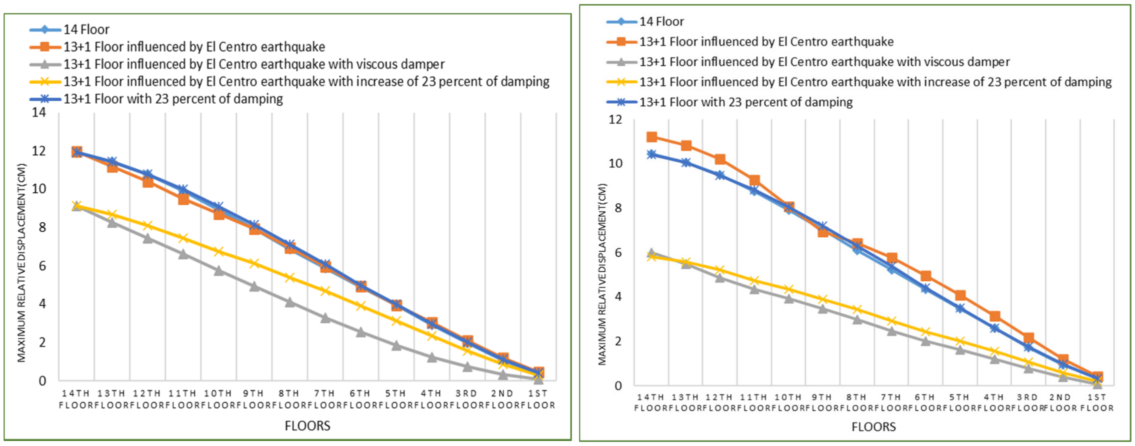
Model number three studied in this research is a thirteen-story building and the possibility of adding one story to it using viscous dampers. Figure 7-a shows a diagram of the relative displacements of classes in the x-direction, and figure 7-b shows the relative displacements of the classes in the y-direction in different cases of model three. In the chronological analysis, only the results of the most critical earthquake acceleration are given.



a) b)

Figure 7. a) Diagram of relative displacement of classes in the x-direction, b) relative displacement of classes in the y-direction in different cases in model three

Figure 8-a shows the diagram of the maximum displacement of the floors in the x-direction, and figure 8-b shows the maximum displacement of the floors in the y-direction in different cases of model three.



a) b)

Figure 8. a) Diagram of the maximum displacement of floors in the x-direction, b) the maximum displacement of the floors in the y-direction in different cases in model number three

Carefully in these diagrams, it can be seen that the displacements in the 13 + 1 story building with dampers are less than other cases, which indicates the very favorable effect of these dampers on the behavior of the structure.

6. Conclusions

In this study, the feasibility of developing the number of floors of a building with a concrete structure was investigated. Thus, three models with a different number of floors were designed. After adding one floor to them, the number of relative displacements and the ratio of stresses in the members of the structure were corrected using viscous dampers. After conducting these studies and analyzing the different responses of the structure and according to the results given in the fourth chapter of the dissertation, summarize these results could be mentioned as below.

1. Adding a floor to the existing building caused the stress in some columns to exceed the resistant stress and also caused the relative displacement of the floors to exceed the allowable value.

2. The addition of dampers to the developed building caused the stress in the columns to be less than the amount of resistive stress in the member.

3. The addition of dampers to the developed building caused the relative displacement of the floors to be less than the allowable value.

4. After examining the number of stresses and relative displacements of floors in the three models in the conditions of increasing the damping of the structure, it was shown

that in 6, 10, and 14 story buildings with increasing the damping by 6.2, 21 and 23, respectively. Percentage, stresses, and relative displacements reached their allowable values.

5. The results showed that in different modes of the models, different earthquakes became more critical, but among the earthquakes applied to the structure, the El Centro earthquake, in most cases, creates more critical conditions.

Conflict of interest

The corresponding author states that there is no conflict of interest.

References

[1] Oscar M. Ramirez, "Development and evaluation of simplified procedures for analysis and design of buildings with passive energy dissipation systems," *Rep. No . NCEER-00-0010*, p. State University of New York at Buffalo, Buffalo, 2000.

[2] A. V. Bhaskararao and R. S. Jangid, "Seismic response of adjacent buildings connected with friction dampers," *Bulletin of Earthquake Engineering*, vol. 4, no. 1. Springer, pp. 43–64, Feb-2006.

[3] M. K. Shrimali and S. D. Bharti, "Earthquake Performance Of Coupled Building By VF Damper," *14th World Conf. Earthq. Eng.*, vol. 2, 2008.

[4] C. C. Patel and R. S. Jangid, "Seismic response of dynamically similar adjacent structures connected with viscous dampers," *IES J. Part A Civ. Struct. Eng.*, vol. 3, no. 1, pp. 1–13, Feb. 2010.

[5] H. Alimohammadi and M. Lotfollahi Yaghin, "Study on the Effect of the Concentric Brace and Lightweight Shear Steel Wall on Seismic Behavior of Lightweight Steel Structures," *Int. Res. J. Eng. Technol.*, vol. 6, no. 8, pp. 1358–1362, 2019.

[6] S. Mousavi, A. Keramat, and B. Shekasteband, "Investigation of the Effect of Geometric Parameters on Behavior of Special Truss Moment Frames," *Int. Res. J. Eng. Technol.*, vol. 6, no. 7, pp. 1566–1573, 2019.

[7] R. J. McNamara and D. P. Taylor, "Fluid viscous dampers for high-rise buildings," *Struct. Des. Tall Spec. Build.*, vol. 12, no. 2, pp. 145–154, Jun. 2003.

[8] S. Mousavi, A. Keramat, and B. Shekasteband, "Investigation of the Effect of Geometric Parameters on Behavior of Special Truss Moment Frames," *Artic. Int. J. Eng. Technol.*, 2019.

[9] H. Alimohammadi and B. Izadi Babokani, "Finite element electrodynamics modeling of a layered piezoelectric composite shell with different materials by using numerical software," *ISSS J. Micro Smart Syst.*, 2020.

[10] B. Farahi, M. R. Esfahani, and J. Sabzi, “Experimental Investigation on the Behavior of Reinforced Concrete Beams Retrofitted with NSM-SMA/FRP,” *Amirkabir J. Civ. Eng.*, vol. 51, no. 4, pp. 421–426, 2020.

[11] M. K. Moayyedi and M. Najaf beygi, “A high fidelity cost efficient tensorial method based on combined POD-HOSVD reduced order model of flow field,” *Eur. J. Comput. Mech.*, vol. 27, no. 4, pp. 342–366, Jul. 2018.

[12] H. Alimohammadi, K. Yashmi Dastjerdi, and M. Lotfollahi Yaghin, “The study of progressive collapse in dual systems,” *Civ. Environ. Eng.*, vol. 16, p. https://doi.org/10.2478/cee-2020-0009, 2020.

[13] A. Morovatdar, M. Palassi, and R. S. Ashtiani, “Effect of pipe characteristics in umbrella arch method on controlling tunneling-induced settlements in soft grounds,” *J. Rock Mech. Geotech. Eng.*, Jul. 2020.

[14] S. Satvati, A. Nahvi, B. Cetin, J. C. Ashlock, C. T. Jahren, and H. Ceylan, “Performance-Based Economic Analysis to Find the Sustainable Aggregate Option for a Granular Roadway,” *Transp. Geotech.*, p. 100410, Jul. 2020.

[15] S. Mousavi, R. Najafpour, and M. Sheidaii, “Investigating the effect of restraints’ configuration on resistance of double layer braced barrel vaults to Progressive collapse,” *Int. Acad. Inst. Sci. Technol.*, vol. 6, no. 1, pp. 26–38, 2019.