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Research Article

Evaluating Effects of Viscous Dampers on optimizing Seismic Behavior of Structures

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Abstract

In the present paper, dampers position and optimizing their position at the height of the structure are studied. it investigates about viscous damper systems and their effects on seismic behavior of multistory structures and determines effects of damper system position on structure height using uniform distribution and SSSA methods. In this research, three 4, 8, 12storey steel structure frames were selected as the understudy models. The models were designed and analyzed based on available Codes to represent a sample of available structures. To evaluate effects of specific features of damper system, two 15% and 25% target values were considered for effective damping ratio of the damper system such that the results serve as representative of appropriate spectrum of conventional features of damper system. Following time history analyses on the models created under three earthquake records which were scaled according to spectrum design of Iran 2800 Code-3rd Ed., maximum response of relative displacement of stories was calculated for every position of the obtained damper.

Keywords: *Viscous damper, Time history analysis, Seismic behavior, ETABS, SSSA method*

1. Introduction

Viscous dampers were first used in military and aerospace engineering to absorb the impact produced by the launched missiles or landed airplanes. When the dampers were initially produced for civil applications, it was for more than 35 years that their technology was developed and completed. However, the dampers were used to protect missile silos against shock waves of explosions.

In 1969, viscoelastic damper was used in twin towers of World Trade Center for the first time. The damper was used to lessen wind-resulted vibrations. Mahmoudi was of the first researchers studied effect of different factors on damper in vitro. Thereafter, other researchers, e.g. Soong, Chen, and Shen evaluated damper-equipped structures under earthquake force.

Within last two decades, several measures have been taken to apply modern control systems in earthquake-exposed structures. Inactive control systems constitute major group of the systems lessening seismic vibrations without any need to external energy source and only using structures motion. Some inactive control systems prevent from penetration of earthquake energy to structure through changing its vibration frequency and limiting acceleration transferred to the structure. While in other control systems known as energy dampers, earthquake energy is absorbed once it enters the structure. Based on their laboratory and analytical studies, Mr. Kelli *et al* (1972) introduced the idea of using energy dampers in the structure to control seismic vibrations. In their studies about inactive damping systems in structural engineering, Soong, T.T., *et al* (2007) evaluated dampers role in main frequency time of structures. Markis and Constantinou (1992) suggested a damping system to lessen seismic shocks. SODA (1996) controlled non-linear shock of buildings using a viscous damper. Most researchers focused on optimization of building frame, dampers position, and classifying the complementary dampers in size for structures with viscous dampers (Uetani *et al*, 2003; Main and Krek, 2005). In their studies, Chopra and Lin highlighted viscous dampers applications in asymmetrical one-storey elastic systems. To accelerate viscous dampers configuration in practical and applied engineering, Ou *et al* (2007) developed a simplified computational method to analyze structural reactions with viscous dampers. Recent viscous dampers were also used to strengthen historical and damaged buildings. For instance, Uriz and Whittaker (2001) used viscous dampers to strengthen a steel bending frame

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following Northridge earthquake. Los Angeles hall, a Mediterranean church in Cyprus, and a historical building in Tunes are other examples preserved using viscous dampers. Systematic results suggested that complementary energy damping may intensify excitation energy without increasing base shear and storey acceleration during an earthquake (El. Borgi *et al*, 2005, Chrysostomou *et al*, Youssef, 2001). The study conducted by Carden *et al* (2005) demonstrated that a viscous damper may use an effective hysteretic damping when it covers near-fault grounds and is used for structure isolation.

In the past few years, application of viscous dampers in available structures has been evaluated by several researchers including Hwang *et al* (2006) studied behaviors of concrete buildings with viscous dampers and light reinforced concrete walls using a shaking table test. The results strongly confirmed knee bracing damper system since it was regarded as an effective installation mechanism when smaller storey experiences relative displacement. According to these successful experiences, viscous damper was used to strengthen microelectronic factories and resulted in completely acceptable functions (Hwang *et al*, 2007). To develop function of moderate and high buildings, modern design instructions have also been offered indicating to a very accurate process used in viscous damping ratio (Hwang *et al*, 2007). In order to strengthen available buildings, non-linear viscous dampers were considered based on displacement in a design (Chang *et al*, 2008). Results of shaking table test indicated to capabilities of viscous dampers in damping of the structure energy. In order to lessen seismic response of the structure by viscous dampers, additionally, researches were managed to control specific subjects within last two decades (kurihara *et al*, 1992). A three-dimensional isolating floor was developed for computerized systems using viscous dampers. According to results, the mentioned three-dimensional isolating floor successfully protects computerized systems of a nuclear power workshop against external vibrations. Asfar and Akour used a viscous damper preventing from self-excited vibrations. Viscous dampers have also been used in non-conventional three-dimensional framed structures with a limited peripheral relative displacement. An optimal design adding viscous dampers to external frames may be useful (Lavan and Levy, 2006). The achievements prove capabilities of the available viscous damper in several fields.

2. Modeling

Table 1 Features of materials used in structural modeling

Mass per unit volum Kg/m2	Min yield stress Kg/cm2	Poisson's ratio	Modulus of elasticity Kg/cm2	Materials
7833	2400	0.3	1.04×10^6	Steel

Features of materials used to analyze and design steel used in structural models are sown in table 1.

Dead loads imposed to the building results from ceilings weight. They are imposed to stories, roof, and external walls as follows. Three-dimensional modeling of roof and stories ceiling, ETABS may calculate weight of joist-slab concrete ceiling. Therefore, it is sufficient to introduce all loads of flooring, foundation, and block as surface to the program. Considering modeling of internal two-dimensional frame of the building, loads computed for roof and stories beams are regarded as uniformly extended dead loads in this thesis. The ceiling system was considered as joist-block system with cement blocks and according to conventional details. Thus, extended dead load of the floor is imposed as 600 kg/m2.

According to Iranian National Building Code, 6th chapter, live load of residential buildings and roof is 200 kg/m2 and 150kg/m2, respectively. In case of three-dimensional modeling of building and ceiling of stories and roof, it is sufficient to superficially impose the mentioned live loads on stories floor and roof. Since the modeling is two-dimensional, however, the mentioned loads should be multiplied at loading length (5m) of corresponding beams of stories or roof and introduced to the program as uniformly extended linear loads imposed to the beams.

Also, lateral loading is calculated using equivalent static analysis method, earthquake coefficient, and parameters required for frame system. For this purpose, the amount of acceleration (A) was considered 0.35, T0=0.1, Ts=0.5, and S=1.5, regarding soil type II, in accordance with Iranian Code (Standard 2800 Iran).

The structures were designed using ETABS software. A series of standard I-shaped profiles were used to model bending frame including beam and column and their designed dimensions will be provided in next pages. The models were analyzed once gravity forces and seismic loads were determined and structural models were prepared. Hypotheses of modeling, analyzing, and designing stages are as follows:

1. Imposing diaphragm rigidity at the modeling stage through relating lateral displacement of all joints of a storey to displacement of the storey centroid
2. Terminal joint areas of beams and columns were regarded as rigid ones since there are big elements with high rigidity at these joint areas. Stiffness coefficient of the joint areas was considered 0.5 at the modeling stage.
3. Secondary P-Δ analyses at models analysis stage
4. Steel structural models were designed for endeavors resulted from following loading combinations.

qu= D.L. + L.L (1)

qu= D.L. + L.L. + E (2)

qu= D.L. – E (3)

qu= D.L. + E (4)

qu= D.L. + L.L. – E (5)

Moreover, ETABS imposes a 33% increase of permissible stress for extraordinary loads combination and it is not required to impose it in loads combination. In addition to combination of the mentioned loads, earthquake-resistant columns should be able to account for axial forces resulting from following loads combination (according to Iranian Code, 2800) [5].

A. Axial pressure

$$q_u = \frac{1.33}{1.7} \text{ (D.L. +0.8 L.L. - 2.8E.)} \quad (6)$$

$$q_u = \frac{1.33}{1.7} \text{ (D.L. +0.8 L.L. + 2.8E.)} \quad (7)$$

B. axial tension

$$q_u = \frac{1.33}{1.7} \text{ (0.85D.L. + 2.8E.)} \quad (8)$$

$$q_u = \frac{1.33}{1.7} \text{ (0.85D.L. - 2.8E.)} \quad (9)$$

Since combination of the mentioned loads is stated according to final strength, Their coefficients are divided to 1.7 in order to use them in permissible stress method.

2.1 Viscous damper

Considering the computed features, the viscous damper was modeled using SAP2000 software with N-link non-linear elements at damper position. SAP2000 software uses parallel and series systems of spring and damper in linear and non-linear analyses, respectively. (figure 1).

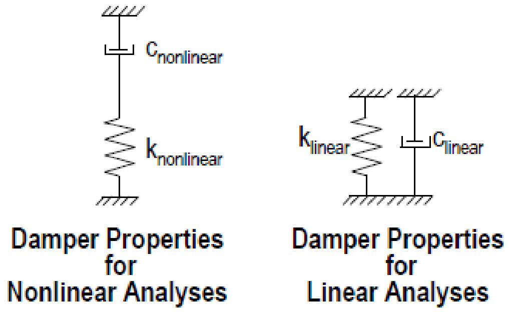

Figure 1 Damper element in SAP2000 software

Since viscous damper system will be modeled as pure stiffness-free damping behavior (stomatal viscous damper), stiffness of damper element will be considered zero in order to reach the pure damping in linear analyses. To eliminate the spring effect, its stiffness should be considered significantly high in non-linear analyses where series model of spring damper is used. In time history analyses where non-linear specifications of damper are used, acceptable results will be achieved if damping coefficient of damper to non-linear spring stiffness ratio is selected one or two degrees smaller than time step of the analysis.

$$\frac{C}{K} \leq 0.01 \times 10^{-2} = 10^{-4} \rightarrow K \geq 10^4 C \quad (10)$$

The article used time step of 0.01s. Therefore, non-linear spring stiffness is considered 10^4 times more than damping coefficient in non-linear element of damper (figure 2). To test the hypothesis, a damper was modeled in the software, its time history was analyzed, and its force-displacement curve was obtained (figure 3). According to the figure, it is evident that the force-displacement curve equals to conventional elliptic curve without any expected stiffness for the viscous damper.

3. Time history analysis

All analyses of the research are of time history analysis type done using SAP2000 software. Three earthquake records were used in time history analyses according to Table 2.

Table 2 Features of the selected earthquakes

Earthquake	station	Distance	PGA(g)
Northridge	SCS05	6.2	0.612
Imperial Valley	H-E06230	1.0	0.439
Manjil	ABBAR-L	40.43	0.505

3.1 Determining dampers position

While preserving reliability, dampers are used to decrease weight and cost of structure. The structure with damper should be designed optimally to justify the cost spent for using damper. As mentioned, practical limitations, durability, size, and position of dampers in structure is the main problem in designing structures with dampers. Accordingly, effect of viscous dampers on seismic behavior of a structure is a function of several parameters including number of dampers, their position in the structure, and physical specifications of damper.

Here, two methods used in determining viscous dampers position in structure height will be discussed: 1) determining two target damping ratios (ξ) as 15% and 25%, equivalent damping coefficient (Ceq) of similar viscous dampers will be determined in all stories- uniform distribution in height, 2) dampers will be placed in the structure height using SSSA method.

3.2 Uniform distribution of dampers in height

Based on improvement instruction recommendations, following formula may be used to calculate effective damping of viscous linear devices:

$$\beta_{eff} = \beta + \frac{T \sum_j C_j \cos^2 \theta_j \phi_{rj}^2}{4\pi \sum_i \left[\frac{W_i}{g}\right] \phi_i^2} \quad (11)$$

Where θj stands for angle of slope of jth device with horizon, Φrj for relative horizontal displacement between two ends of jth device in the first mood, Wi for available weight of ith floor, and Φi for displacement of ith floor at the first mood.

Considering two effective target damping ratios as 15% and 25% for the structure with damper, equivalent

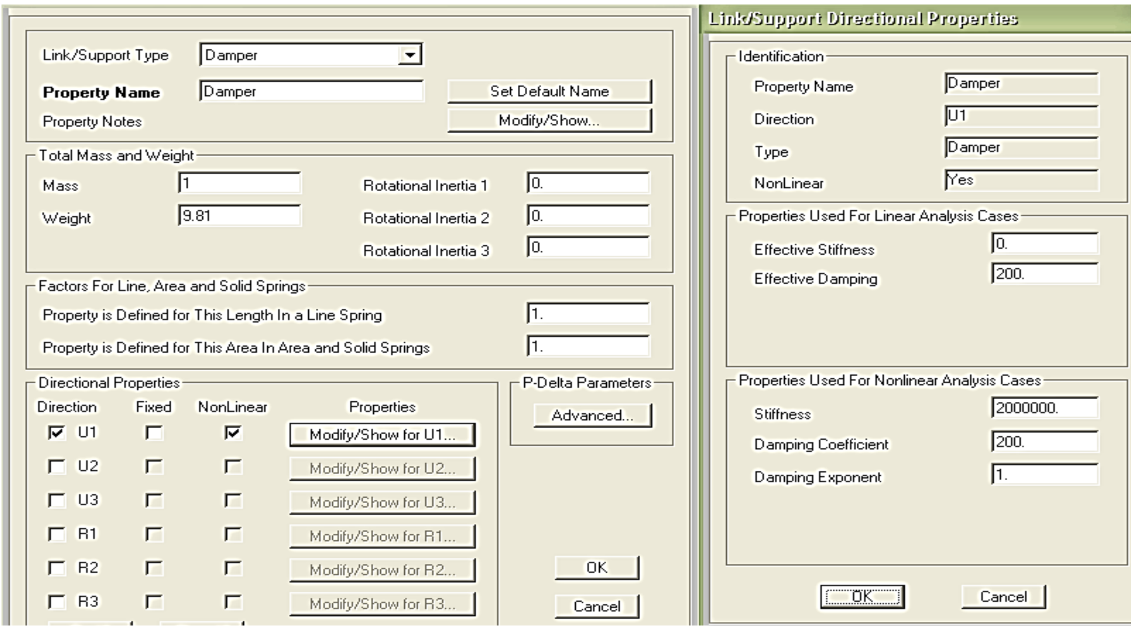

Figure 2 How damper element is modeled in SAP2000 software

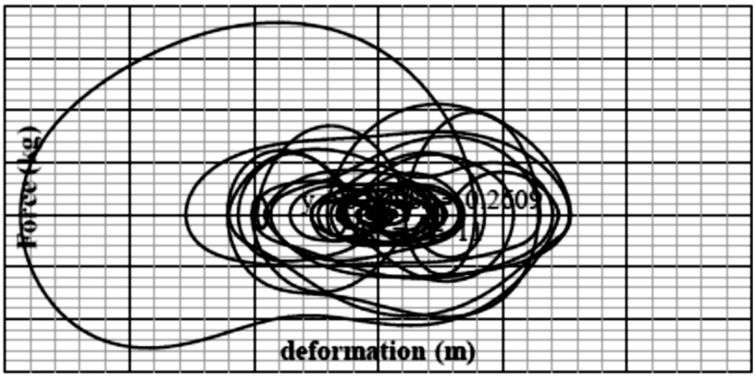

Figure 3 A sample of force-displacement curve of a viscous damper

damping coefficient of dampers are determined using the above formula. Figure 4 refers to shape of first mood of three selected model structures. Since the selected viscous dampers (stomatal) are stiffness-free, adding viscous dampers to the structure will not change mood shape and periods. Assuming 2% of viscous damping (ξ=2%) for the 4,8,12-storey structure, damping coefficient of dampers (C) will be determined as Tables 3 to 5.

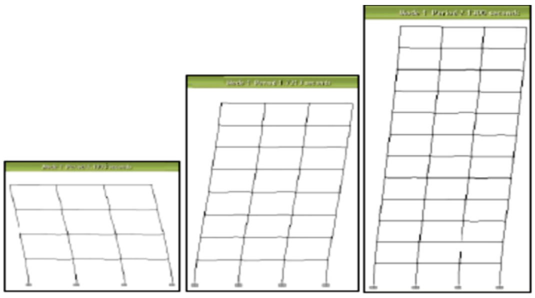

Figure 4 Shape of first mood of three selected model structures

3.3 Determining dampers position using SSSA method

The method presented by L. Garcia (2001) will be dealt with as a simple method to determine optimal position of dampers in structures with multiple degrees of freedom (SSSA). In this method, a general damping coefficient is determined for dampers, number of dampers placed in the structure is specified, and a similar damping coefficient is considered for all dampers. Thus, the dampers are respectively placed at maximum inter-storey relative velocity point and the process continues until all dampers are placed.

Number of dampers may be less or more than that of stories, dampers may be used repetitively in stories, and number of dampers repetition in stories may be limited. Essentially, placing of two dampers in one storey is equal to one damper with double damping capacity. Limiting number of dampers of a storey, therefore, number of dampers with different damping capacity may be controlled. Finally, those dampers leading to the least inter-storey displacement following optimization of the

Table 3 Uniformly determining of damping coefficient of dampers (Ceq: equivalent damping coefficient) at height of a 4-storey structure

φ i= φ	Dr φ= φ rj	m	cosθ	(cosθ)^2*(Dr φ)^2	m*φ^2
1	0.257143	5101.43	0.842271	0.046908661	5101.43
0.742857	0.304762	5202.042	0.842271	0.065890904	2870.678
0.438095	0.266667	5225.013	0.842271	0.050447724	1002.823
0.171429	0.171429	5245.244	0.842271	0.020848294	154.146
				0.184095583	9129.078

Added to structural damping ratio of 2% (ζ)	0.13	0.23
(Θ)	32.61924 degree:	
	0.569313 radian:	
(T1) from the progran	1.1003	

	Damping coefficient of the damper (c)	total damping coefficient (C)
$\xi = 15\%$	73.63 kN.sec/cm	294.5
$\xi = 25\%$	130.3 kN.sec/cm	521.0

Table 4 Uniformly determining of damping coefficient of dampers (Ceq: equivalent damping coefficient) at height of a 8-storey structure

φ	Dr φ	m	cosθ	(cosθ)^2*(Dr φ)^2	m*φ^2
1	0.092105	5104.015	0.842271	0.006018289	5104.015
0.907895	0.118421	5211.541	0.842271	0.009948599	4295.732
0.789474	0.131579	5232.159	0.842271	0.012282221	3261.041
0.657895	0.078185	5258.657	0.842271	0.004336571	2276.081
0.57971	0.113043	5265.061	0.842271	0.00906557	1769.397
0.466667	0.126667	5275.534	0.842271	0.011382268	1148.894
0.34	0.19	5286.549	0.842271	0.025610102	611.125
0.15	0.15	5293.934	0.842271	0.015961975	119.1135
				0.094605596	18585.4

ζ	0.13	0.23
θ	32.61924	
	0.569313	
T1	1.7213	

c	C
186.45	1491.6
329.9	2638.9

dampers position are determined as optimal damper position.

In this study, the same method is used to determine dampers position in structures. Thus, three dampers were selected to be placed in structure. Then, the structure with the least maximum relative displacement of stories was determined as the structure with optimal damper position. Additionally, maximum rate of damper placed in a storey was assumed as that of two dampers in computational operation.

To evaluate results of the method, total damping coefficient used in this method was selected equal to total damping coefficient calculated in dampers uniform distribution method for 15% and 25% of damping ratio. Considering three structural model, three earthquake records, two damping coefficients, and three dampers placed in the structure, 54 computational operations were done to determine optimal position of dampers in the selected structures. Relative displacement profiles of stories was selected for three dampers, demonstrated in diagram, and only results of Northbridge earthquake were briefly presented for 4,8,12-storey structures while damping ratio is 15% and 25%.

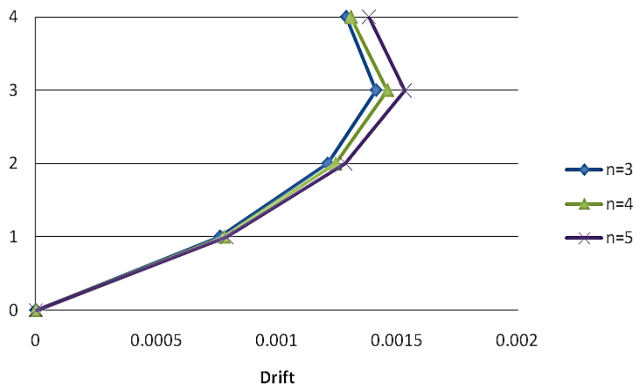

Figure 5 Relative displacement profile of stories, a 4-storey structure, Northbridge earthquake, damping ratio of 15%

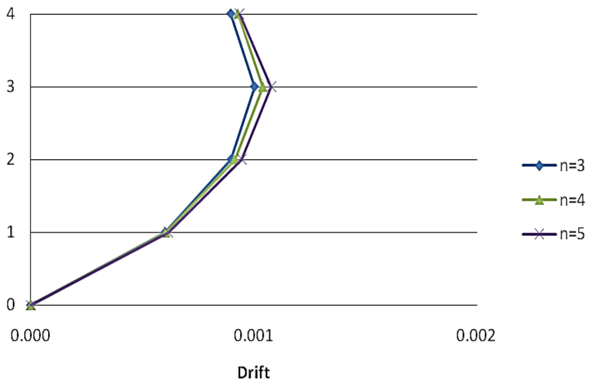

Figure 6 Relative displacement profile of stories, a 4-storey structure, Northbridge earthquake, damping ratio of 25%

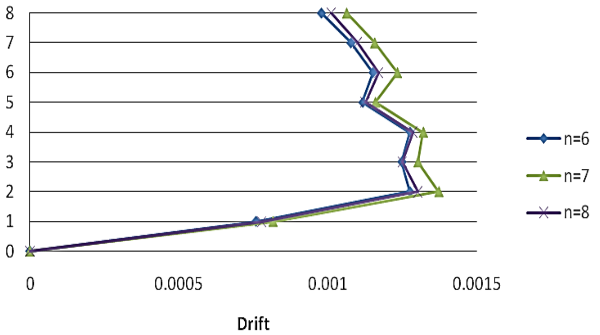

Figure 7 Relative displacement profile of stories, a 8-storey structure, Northbridge earthquake, damping ratio of 15%

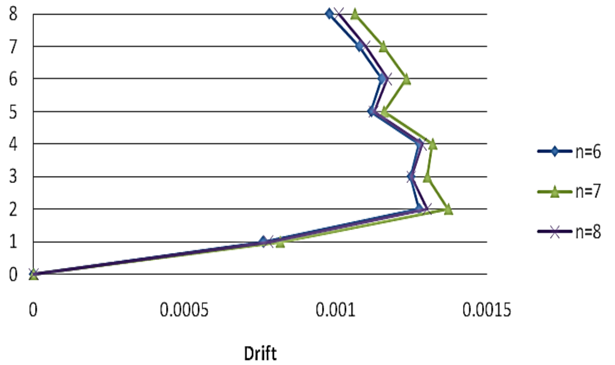

Figure 8 Relative displacement profile of stories, a 8-storey structure, Northbridge earthquake, damping ratio of 25%

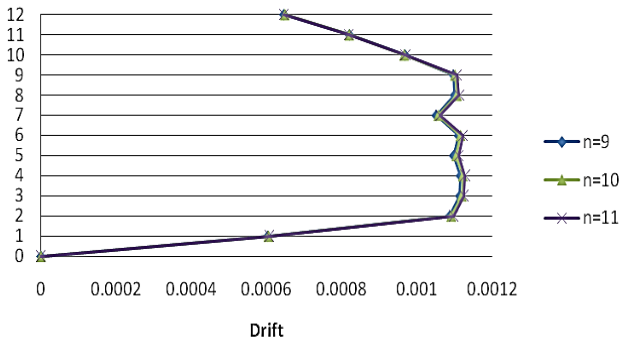

Figure 9 Relative displacement profile of stories, a 12-storey structure, Northbridge earthquake, damping ratio of 15%

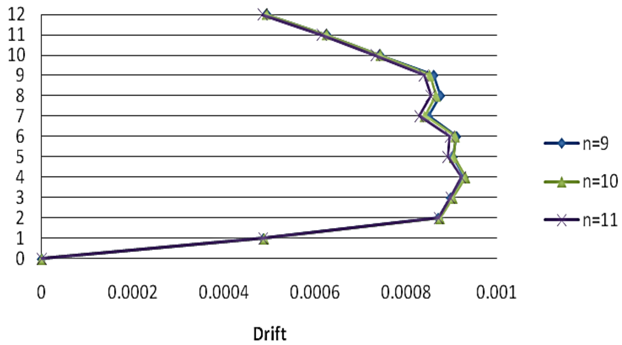

Figure 10 Relative displacement profile of stories, a 12-storey structure, Northbridge earthquake, damping ratio of 25%

3.4 Time history analyses

Earthquake-based damages of different buildings generally results from two main factors, i.e. relative displacement of building stories to each other and acceleration developed at the building floors. On the other hand, dampers are used as devices to decrease earthquake force and better distribute of lateral forces between the structures supports. As mentioned, the present research uses time history analysis method and relative displacement profile of stories to evaluate structural models and compare evaluated structural models, respectively. Results of structural models under time history analyses are presented. In this investigation, only general results of analyses are presented for damping ratio of 15%.

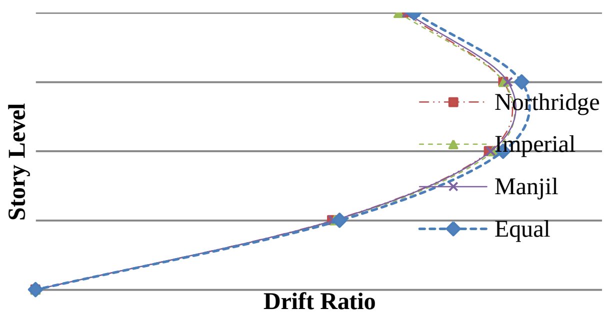

Figure 11 Relative displacement profile of stories, a 4-storey building, Northbridge earthquake, damping ratio of 15%

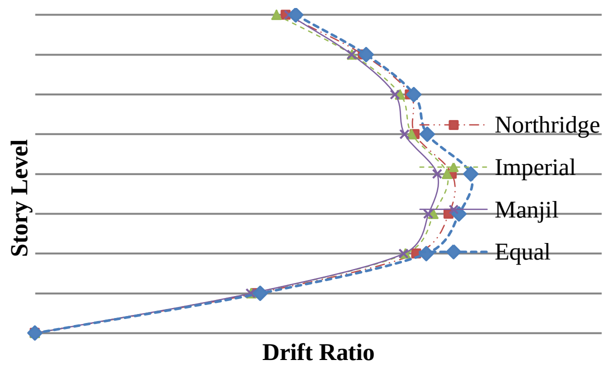

Figure 12 Relative displacement profile of stories, an 8-storey building, Northbridge earthquake, damping ratio of 15%

Table 6 Maximum relative displacement of stories, a 4-storey building, damping ratio of 15%

ζ=15%	No damper	Equal (%)	Damper arrangement under Northridge earthquake (%)	Damper arrangement under Imperial earthquake (%)	Damper arrangement under Manjil earthquake (%)
Northridge	0.03025	57.4	59.0	59.0	58.7
Imperial	0.02746	27.8	34.1	34.5	32.7
Manjil	0.02982	58.0	61.6	61.3	61.2

Table 7 Maximum relative displacement of stories, an 8-storey building, damping ratio of 15%

ζ=15%	No damper	Equal (%)	Damper arrangement under Northridge earthquake (%)	Damper arrangement under Imperial earthquake (%)	Damper arrangement under Manjil earthquake (%)
Northridge	0.03367	54.3	56.3	56.8	57.9
Imperial	0.02562	28.5	31.0	33.1	34.4
Manjil	0.02570	34.1	37.2	39.2	40.7

Table 8 Maximum relative displacement of stories, a 12-storey building, damping ratio of 15%

ζ=15%	No damper	Equal (%)	Damper arrangement under Northridge earthquake (%)	Damper arrangement under Imperial earthquake (%)	Damper arrangement under Manjil earthquake (%)
Northridge	0.02592	52.00	51.82	53.34	51.58
Imperial	0.02642	39.28	39.43	41.74	41.46
Manjil	0.02313	41.31	41.60	44.08	43.58

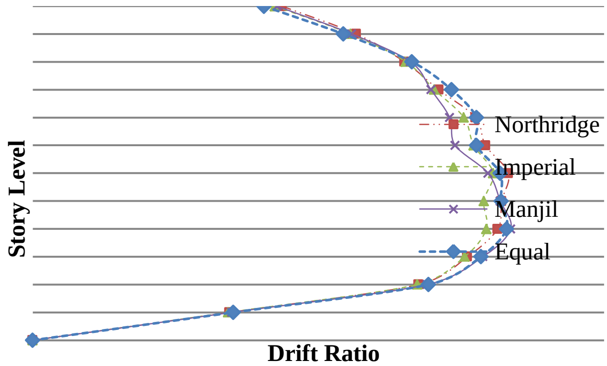

Figure 13 Relative displacement profile of stories, a 12-storey building, Northbridge earthquake, damping ratio of 15%

4. Conclusion

Concentrating on dampers position and optimizing their position in the structure height, the paper studies viscous damper systems and their effect on multistory structures behavior. To evaluate effects of damper system position on structure height, its position was determined using uniform distribution and SSSA methods. In this study, three 4, 8, 12-storey steel structure frames were selected as the understudy models. The models were designed and analyzed based on available Codes to represent a sample of available structures.

To evaluate effects of specific features of damper system, two 15% and 25% target values were considered for effective damping ratio of the damper system such that the results serve as representative of appropriate spectrum of conventional features of damper system. Following time history analyses on the models created using three earthquake records which were scaled according to spectrum design of Iran 2800 Code -3rd Ed., maximum response of relative displacement of stories was calculated for every position of the obtained damper. General results of the research are as follows:

- Damper system significantly affects dynamic features of structure. The higher the damping ratio of the damper system, the lower the seismic response.
- In comparison with the uniform distribution method, using SSSA method to place dampers at a height with fixed damping coefficient of all dampers, higher effective damping ratio is obtained for both methods.
- In comparison with the uniform distribution method, using SSSA method to place dampers at height, more decrease of relative displacement of stories is seen. In a 12-storey structure and generally at higher stories of structure, however, maximum relative displacement of some stories in a structure obtained with SSSA

method is more than that of the uniform distribution method.

- In SSSA method with less number of dampers, higher effective damping ratio is created in structure in most cases. Generally, the method leads to better results than the uniform distribution method.
- Although SSSA method offer better results than uniform distribution one in height, the method practically requires high computational operation than the latter one.
- Results of SSSA method highly depends on earthquake record and damping ratio of the selected target in time history analyses.

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