Seismic Design and Retrofitting of Structures by using Mass Isolation System with Visco-Elastic Dampers

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ABSTRACT:

This paper presents results of using mass isolation system, MIS, with visco-elastic dampers in seismic design of structures or retrofitting of existing buildings. Herein, MIS consists of two separate frames, a flexible moment resisting frame, which bears main part of structure mass and a relatively rigid braced frame, which carries the remained little mass of the structure and these two frames are connected to each other with visco-elastic dampers. Use of visco-elastic dampers in MIS is here proposed instead of other dampers types, due to their smaller sizes, which make them more applicable specially for retrofitting of existing buildings, and their stiffness, which have very important role on regulating of the flexibility rate of the flexible frame and stability control of the system. Three steel structures with 4, 8, 12 stories are selected and nonlinear dynamic analysis under 7 time-histories acceleration records of the ground strong motions have been carried out for the structures, Drain-2DX software is used for modeling and nonlinear analysis of the structures. From economy point of view, numbers and vertical arrangement of visco-elastic dampers between the two frames of the structures are optimized considering story drift limitations, structures responses and using various mechanical characteristics, stiffness and damping of the dampers. Input energy of earthquakes are obtained and compared with the dissipated energies in the systems. The results show that MIS effectively causes reduction of input energies of earthquakes and visco-elastic dampers dissipate nearly 50% of the input energy and most of structural elements remain at the elastic ranges, which can be inferred that the performance levels of the structures have been significantly improved by using this system.

KEYWORDS: Mass Isolation System, Visco-Elastic Dampers, Nonlinear Dynamic Analysis, Drain 2D-X, Retrofitting.

1. INTRODUCTION

The traditional approach to seismic design has been based upon providing a combination of strength and ductility to resist the imposed loads. For major earthquakes, the structural design engineer relies upon the inherent ductility of conscientiously detailed buildings to prevent catastrophic failure with accepting a certain level of structural and non-structural damage, while the new techniques in the seismic design of structures or retrofitting of the existing buildings are based on changing the dynamic characteristics of the system to receive less earthquake input force and energy and to dissipate the energy with lower damage and deformation in the structural components. Therefore, many new and innovative concepts of structural protection have been advanced and are at various stages of development, one of them is passive energy dissipation method [1-6]. The basic role of passive energy dissipation devices when incorporated into a structure is to absorb or consume a portion of the input energy, thereby reducing energy dissipation demand on primary structural members and minimizing possible structural damage. These energy dissipation devices include: visco-elastic dampers, friction devices and plastically deforming metals. Among the variety of energy-dissipation devices, visco-elastic dampers (VE) are one of the successful devices employed for seismic hazard mitigation application. In the design of structures with VE dampers modifications to the modal damping and stiffness due to addition of VE dampers can be obtained by the modal strain energy method. These visco-elastic type damping devices (passive devices) pose force-displacement relationship which can be approximated by [2]:

$$F(t) = \bar{k}(\omega)x(t) + \bar{c}(\varpi)\dot{x}(t)$$

Where $\bar{k}(\omega)$ and $\bar{c}(\omega)$ are frequency dependent. The force-displacement response of a visco-elastic damper is strongly dependent on ambient temperature, excitation frequency and shear strain amplitude. To simplify the visco-elastic material, the damper is modeled as an elastic spring and dashpot acting in parallel [2]. The force in the damper is the sum of the elastic and the viscous forces, and both the elements are subjected to the same deformation .Chin-Hsiung Loh et al. [2] proposed a design guide line for using visco-elastic dampers for the control of building structures subjected to earthquake loading as well as suspension roof structures subjected to wind loading. Ziaeifar and Tavousi [3] studied on mass participation factor of non-classical mass isolated buildings. Numbers of researches have been carried out on the mass isolation system [3,5], MIS, however, in this study focused on using the visco-elastic type damper and their vertically arrangement optimization.
This study presents the first trial of connecting two flexible and rigid frames with visco-elastic dampers as a mass isolated system, MIS, for passive energy dissipation and mitigation the seismic responses of the compound structure, the vertical arrangement of them are also optimized using drift control and the dynamic modal response methods. Use of visco-elastic dampers in MIS is here proposed instead of other dampers types, due to their smaller sizes, which make them more applicable specially for retrofitting of existing buildings, and their stiffness, which have very important role on regulating of the flexibility rate of the flexible frame and stability control of the system. Three steel structures to cover the short, moderate and relatively tall buildings are selected and nonlinear dynamic analysis under 7 time-histories acceleration records of the ground strong motions have been carried out. Input energies due to the earthquakes have been obtained and compared with the dissipated energies in the systems, and the structures responses with various mechanical characteristics, stiffness and damping of the VE dampers, have been acquired and the results presented.

2. DESCRIPTION OF ANALYTICAL MODELS

In this investigation to reduce mathematical calculation one of the middle frame of each 3D structure has been modeled. In that regard three steel structures with 4, 8 and 12 stories are selected, which each of them consists of two separate steel frames, a flexible frame that bears main part of structure mass and a relatively rigid braced frame, which carries the remained little mass of the structure and these two frames are connected to each other with visco-elastic dampers, Fig.1. The masses in accordance with 2D frames are lumped on connections between beams and columns. It is assumed that the flexible frame mass is 9 times of the rigid frame mass. In the compound structure all stories have the same mass and height equal to 3.5 meters. The material of the structural elements has been modeled with bilinear elasto–plastic behavior and with strain hardening of 1%. Damping model is assumed to be proportional with the stiffness, whereat the coefficient $\beta=c/k$ for the columns and the beams are considered 0.02 and for the braces 0.01, and defining several damping coefficients for the structural members make the compound structures as non – classical systems, the distribution of the lateral resisting stories and the structural elements are preliminarily designed according to UBC97 code [7].

The details of the structural members are given in Table 1, with reference to the code regulations the flexible structure is designed to sustain 25% of the equivalent static base shear in the elastic range, the rigid frame is such designed to have the frequency ten times more than the flexible structure and to sustain 75% of the flexible structure seismic load in addition to its seismic load. The compound structures are obtained by connecting the various visco – elastic dampers at different elevations and numbers.

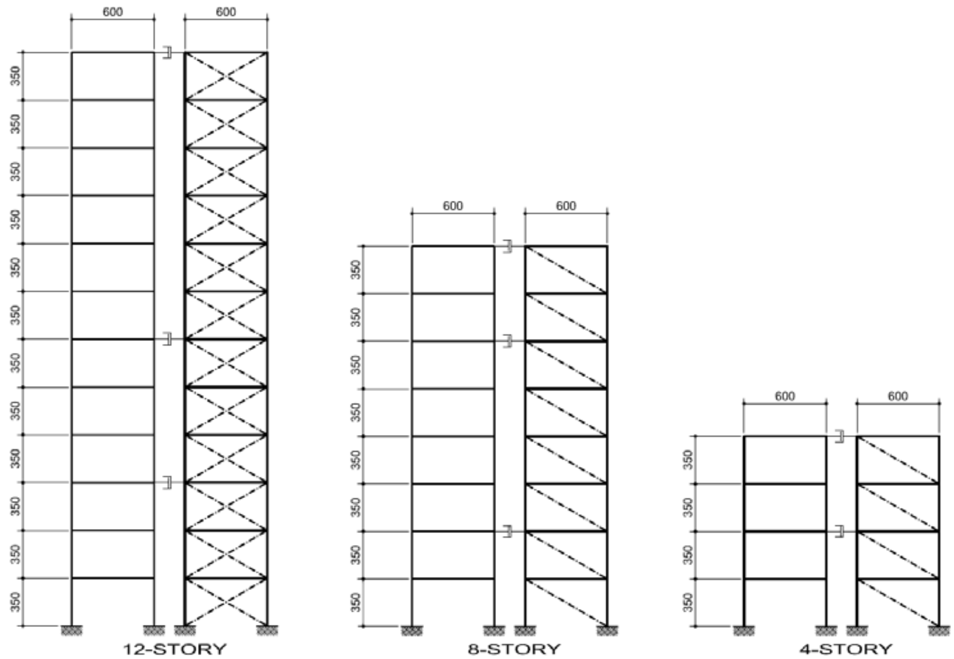

Figure 1. Framing view of 4, 8 and 12 stories of the compound structures in MIS (flexible and rigid frames)

Table 1. Details of the structural elements for 4, 8 and 12 stories of compound structures

	4-Story	Flexible Frame	Rigid Frame
1St	Beam	HE280-AA	HE200-B
	Columns	HE280-A	HE600-B
2St	Beam	HE280-AA	HE200-B
	Columns	HE280-A	HE450-A
3St	Beam	HE280-AA	HE200-B
	Columns	HE240-A	HE450-A
4St	Beam	HE280-AA	HE200-B
	Columns	HE240-A	HE450-A

	8-Story	Flexible Frame	Rigid Frame
1St	Beam	HE340-A	HE260-A
	Columns	HE400-A	HE550-A
2St	Beam	HE340-A	HE260-A
	Columns	HE400-A	HE340-A
3St	Beam	HE340-A	HE260-A
	Columns	HE400-A	HE340-A
4St	Beam	HE340-A	HE260-A
	Columns	HE400-A	HE300-A
5St	Beam	HE320-A	HE260-A
	Columns	HE360-A	HE300-A
6St	Beam	HE320-A	HE260-A
	Columns	HE360-A	HE300-A
7St	Beam	HE320-A	HE260-A
	Columns	HE360-A	HE300-A
8St	Beam	HE320-A	HE260-A
	Columns	HE360-A	HE300-A

	12-Story	Flexible Frame	Rigid Frame
1St	Beam	HE360-A	HE300-A
	Columns	HE500-B	HE650-B
2St	Beam	HE360-A	HE300-A
	Columns	HE500-B	HE650-B
3St	Beam	HE360-A	HE300-A
	Columns	HE500-B	HE650-B
4St	Beam	HE360-A	HE300-A
	Columns	HE500-B	HE650-B
5St	Beam	HE340-A	HE300-A
	Columns	HE400-B	HE650-B
6St	Beam	HE340-A	HE300-A
	Columns	HE400-B	HE650-B
7St	Beam	HE340-A	HE220-A
	Columns	HE400-B	HE650-B
8St	Beam	HE320-A	HE220-A
	Columns	HE340-A	HE450-B
9St	Beam	HE320-A	HE220-A
	Columns	HE340-A	HE450-B
10St	Beam	HE320-A	HE200-A
	Columns	HE340-A	HE450-B
11St	Beam	HE320-A	HE200-A
	Columns	HE340-A	HE450-B
12St	Beam	HE320-A	HE200-A
	Columns	HE340-A	HE450-B

3. METHOD OF ANALYSIS

Drain – 2DX (version -93) software has been used for modeling and non-linear analysis of the structures. The compound model used in this research has the capability to be analyzed directly in time domain. Here, the models have been analyzed by using direct time integration method. Thus, seven different earthquakes records on the alluvium sites are selected as representatives of the ground strong motions; they are represented in Table 2. First, the fundamental periods, damping and modal effective mass of the compound structures with having different vertical arrangement of the visco-elastic dampers have been verified, and the damping ratio and the stiffness coefficients of dampers have been changed from soft to very rigid conditions, Table 3. Then, ratio of dissipated energy by the dampers to total system energy and the remaining energy in the structural elements are obtained and verified. Furthermore, some of the responses such as the base shear, the structural elements forces and the stories drifts under the records have been calculated.

As it is mentioned earlier, the connections of two flexible and rigid frames have been provided with use of the visco-elastic dampers. For customizing the solutions, several methods concerning arrangement, numbers, damping and stiffness coefficients of the dampers have been utilized as the following:

1- *Drift Method*: With regard to the analysis and design of structure, usually unifying the structural relative displacement of stories causes to have better optimum function of the structure and ultimate use of the structural elements capacities, hence, dampers arrangement to uniform the structural relative displacement for connecting two flexible and rigid frames have been used. In this method, for first try, the roof stories of two frames are connected to each other and the compound structure is analyzed, then the next damper is placed on the maximum relative displacement of the flexible structure and this process is continued till the minimum number of the dampers required for having the acceptable stories drifts and the structural elements forces obtained.

2- *Mode Shape Method*: in the drift method the structural relative displacements control depends on the lateral loads function and distribution, thus to reduce this dependency and to consider only the structures natural behaviors, the mode shape method has been utilized. In this method, the dampers locations and numbers have been such arranged and designed to control the modal responses. The required number of modes is selected to cover more than 90% of total structural effective mass. For first try, the roof stories of two frames are connected and the compound structure is analyzed, then the next damper is placed on the maximum modal displacement response of the flexible structure and continued till finding the last damper location.

3- *Last Level Method*: In this method, it is intended to control the maximum displacements. Consequently, the dampers have been applied at the upper levels, the dampers placement starts at the roof level and continues from top to the down sequentially till the minimum number of dampers acquired.

Table 2. Selected ground motions recorded on alluvium sites

Station	*Geology*	*Earthquake Date*	*Magnitude*	*Epicentral Distance (km)*	*Component*	*PGA (g)*
El Centro-Irrigation Distinct	Alluvium	Imperial Valley 1940	6.3 (ML)	8	S90W, S00E	0.21, 0.318
Taft-Lincoln School Tunnel	Alluvium	Kern County, July 21, 1952	7.7 (MS)	56	308, 218	0.15, 0.18
Figueroa 445 Figueroa St.	Alluvium	San Fernando February 9, 1971	6.5 (ML)	41	N52E, S38W	0.14, 0.12
Los Angeles-Baldwin Hill	Alluvium	Whitter_Narrows, October 1, 1989	6.5 (ML)	27	360	0.13

Table 3. Selected dampers

Damper's No.	1	2	3	4	5
K (N/mm)	5.00E+01	5.00E+02	5.00E+03	5.00E+05	5.00E+08
C (N.S/mm)	For each damper is considered β=c/k=5, 10, 15, 20, 25, 30				

4. ANALYTICAL RESULTS

Sample dynamic characteristics such as the effective masses, damping ratios and periods of the compound structures with three dampers, which alternatively connected in even stories of the systems are given in Table 4. Results show the mass participation of the first mode of the compound structure is approximately 70% for all of the structures. Damping ratio of the systems depends on the amount of damper damping and the stiffness of the system, therefore in the upper modes the damping ratios increase due to stiffness of the system increment. As shown, the fundamental periods of the systems can be altered by changing the dampers stiffness, which implies that the VE dampers can have effective role in the dynamic response of the system.

Table 4. Results for compound structure with specified damper at even stories

	K (2-4-…)	β=c/k	T (sec)	ξ	m_{eff}
4-story	K=5E+01	10	1.745	126.6%	72.6%
	K=5E+02	10	1.379	927.2%	73.6%
	K=5E+03	10	0.765	1576.0%	76.3%
8-Story	K=5E+01	10	2.194	70.7%	70.4%
	K=5E+02	10	1.643	854.4%	71.9%
	K=5E+03	10	0.923	1402.2%	73.2%
12-Story	K=5E+01	10	2.983	176.2%	66.6%
	K=5E+02	10	2.000	790.9%	69.2%
	K=5E+03	10	1.241	601.1%	68.0%

Input energy here means the remaining seismic energy in the structural elements. Increasing of system stiffness causes increase of the input energy, and since the number of the dampers affects on the system stiffness, they have been such designed to not only deduct the input energy but also to control the first mode period of the system and to have minimum plastic hinges occurrence probability in the structural elements. The input energies versus the VE dampers stiffness with different arrangements based on the described methodology are presented under Elecentro seismic record for 8 and 12 stories structures in figures 2, 3 and 4. It is inferred that by using the softest damper here with stiffness of *k=0.5 E+1 N/mm* the responses are not properly within the acceptance criteria, thus the results of this damper are relinquished. It can be observed from Fig.2 that in the 8 stories compound structure with dampers stiffness *k=5 E + 2 N/mm*, input energy for three dampers is less than input energy for four dampers based on the Last Level Method, while this structure with the same dampers stiffness have the best condition with four dampers in accordance with the Mode Shape Method, Fig.3, in addition, as shown in Fig.4 three dampers has resulted minimum input energy to this structure with Drift Method. In the Last Level Method the best levels for dampers locations have been 6, 7 and 8, and in the Mode Shape Method the dampers are used at 8 and 7 stories that two dampers at the 8 story and two at the 7 story, which means one damper has two times equivalent stiffness and damping, and in the Drift Method two dampers have been placed at the 8 story and one of them at the second story.

It can be concluded from the figures 2, 3 and 4 for the 12 stories structure that use of three dampers is adequate to minimize the input energy and the seismic response mitigation in all three methods of the damper arrangement, whereat, in the Last Level Method and the Mode Shape Method the dampers have been installed at the 10, 11, 12 stories, and in the Drift Method placed at the 3, 6, 12 stories.

Therefore, the taken steps for the damper selection and design can be expressed as follows:
At the first stage, suitable stiffness for dampers corresponds to the minimum imposed input energy to the structural elements were derived, and in the second stage, the dampers numbers for each method of arrangement have been optimized, then at the final stage, the best method of arrangement for connecting of two flexible and rigid frames is selected with considering the minimum input energy and the structural responses. As samples, the used three optimization methods with several different stiffness and damping coefficients of the dampers under Elcentro record and average results of the seven records have been verified and shown in figures 5, 6.

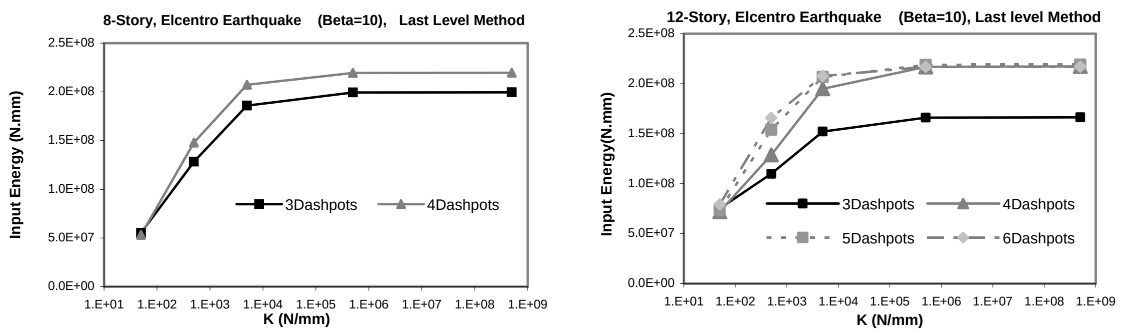

Figure 2. Input energy versus VE dampers stiffness, and number of dampers for Last level Method

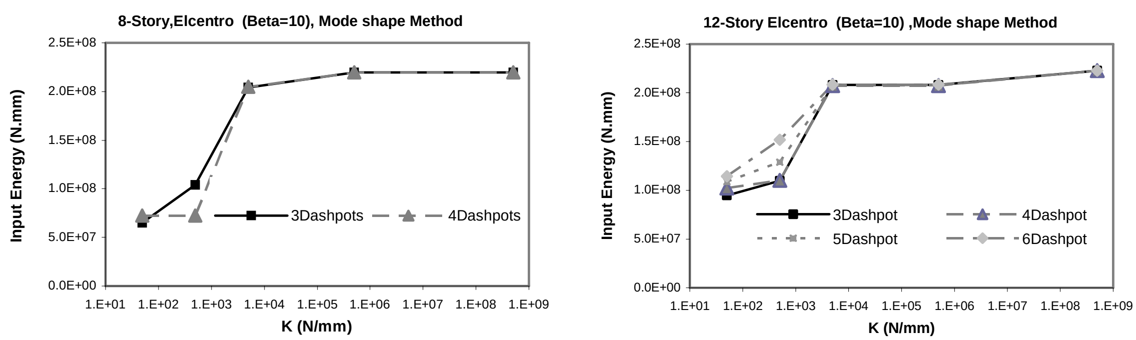

Figure 3. Input energy versus VE dampers stiffness, and number of dampers for Mode Shape Method

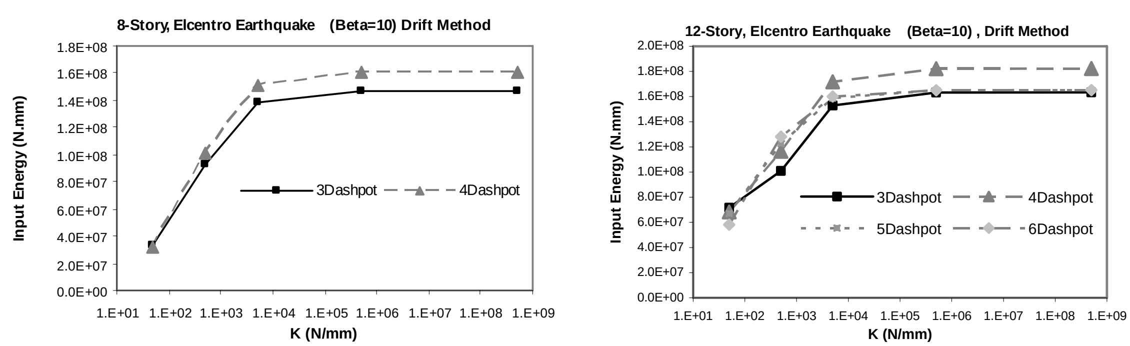

Figure 4. Input energy versus VE dampers stiffness, and number of dampers for Drift Method

As a result of Fig.5 for the 8 stories compound structure, the best method for damper arrangement has been the Drift Method that by utilizing this method more seismic energy has been dissipated and minimum energy in the structural elements remained. Besides, the minimum dampers number has been achieved. Moreover, the results of 12 stories compound structure show that the required number of the dampers is the same for three methods, and it can be inferred that the best method for dampers arrangement has been Drift Method, Fig.6. In both figures 5 and 6 the method of optimization under Elcentro record and the average results of 7 records have had similar outcomes that imply the Drift Method has been the best optimization method between three methods. Besides, the selection of the best optimization method from the presented methods is independent to the earthquake records and the number of building stories.

In the Drift Method, the vertical dampers positions might vary in the stories for different records. Therefore, it is proposed if there are specific sites and records the Drift Method is the best solution to evaluate and develop the dampers arrangement. But if there are not specific sites and records it is suggested the Mode Shape Method to be used due to have more compatibility with the structural behavior.

In comparison of the Last Level Method results with the Mode Shape Method, it is found out that the arrangement of the dampers based on the Last Level Method results less input energy to the structural elements. Although, it is probable that in some cases of using Last Level Method for the dampers arrangement especially in the high rise buildings, the middle stories responses might exceed the allowable displacement limits, therefore, for these cases other described methods are more appropriate.

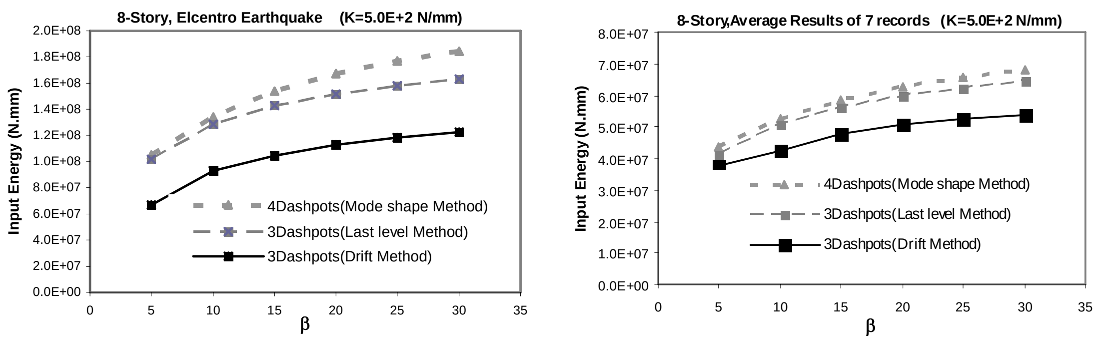

Figure 5. Input energy versus VE dampers damping for the optimization methods in the 8-story structure

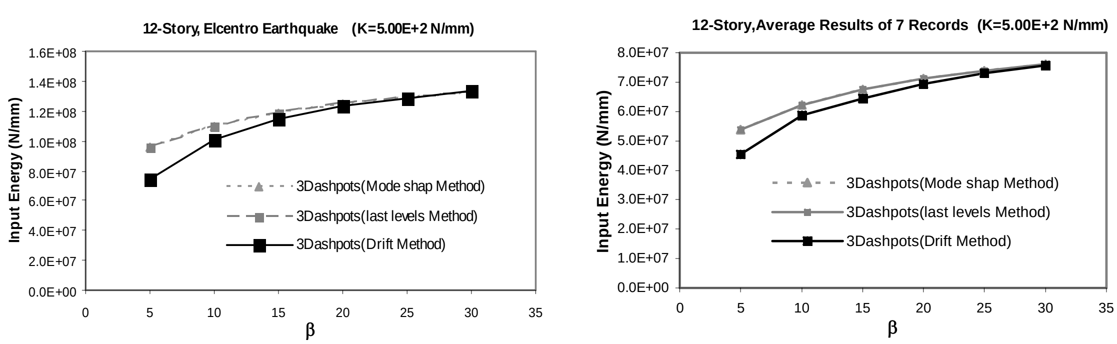

Figure 6. Input energy versus VE dampers damping for the optimization methods in the 12-story structure

5. CONCLUSIONS

The summarized results from the theoretical and analytical study on the seismic design and of the structures by using MIS with the VE dampers can be pointed out as follows:

- With use of the introduced mass isolated structure with VE dampers not only the fundamental period of the compound system increases similar to the base-isolated buildings but also the damping ratios with contributions of the dampers damping extend in the modal responses, which can be inferred that the seismic responses will be significantly reduced and the structure performance will be improved in comparison with the conventional design methods.
- The dampers stiffness, number and arrangement have considerable influences in the seismic energy dissipation.
- With reference to the studied several seismic records, it is observed that the trends of seismic energy dissipation have been similar in the MIS with VE dampers for the records.
- By using the compound structures with suitable number, stiffness, damping ratio and arrangement of the visco-elastic dampers, most of the structural elements remain at the elastic ranges and nearly 50% of the input energy will be dissipated by the VE dampers.
- It is found out that the Drift Method for the dampers arrangement is more effective and economic than the other methods.
- The selection of the best optimization method from the presented methods is independent to the earthquake records and the number of building stories.
- In the Drift Method, the vertical dampers positions might vary in the stories for different records. Therefore, it is proposed if there were specific sites and records the Drift Method would be the best solution to evaluate and develop the dampers arrangement, otherwise the Mode Shape Method can be used.
- The damper characteristics and numbers can be extracted from the given graphs considering the minimum input energy for the studied structures.

ACKNOWLEDGEMENTS

This work has been supported by Sazeh Consultants Engineers Company. The supports are gratefully acknowledged.

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