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EXPERIMENTAL AND ANALYTICAL STUDY OF ASYMMETRIC STRUCTURES WITH DIFFERENT VISCOUS DAMPER DISTRIBUTIONS

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ABSTRACT

The past studies on the effect of dampers for controlling structural responses in earthquake show that using a suitable distribution of such devices may have extra advantages by minimizing torsional effects in the buildings. This paper deals with a comparison study of experimental and numerical dynamic behavior of a 1/6 scaled structure with different viscous damper distributions. The setup consists of a one-story model with one-way stiffness asymmetry which is connected to a rigid base structure by two viscous dampers. Both structures are located on the shaking table and the tests are conducted using 6 earthquake records. Several damper distributions have been considered and for each one, lateral displacement, lateral acceleration and diaphragm rotation of the model are recorded. The comparison between the experimental and numerical models shows a suitable similarity in the response time histories. The results indicates that although the asymmetry effects on lateral displacement is minimized if the damping center is located at a distance equal to stiffness eccentricity in the opposite side of stiffness center with respect to the center of mass, but to minimize the diaphragm rotation, the damping center should be located on the center of mass with a high damping radius of gyration. The results for lateral acceleration show no unique distribution for controlling torsional effects on this response.

Introduction

Studies on the damages induced by previous earthquakes shows that the asymmetry of structures which causes torsional effects, has been one of the main causes of structural failure. The basis of such effects in structural systems is due to mass, stiffness and strength eccentricities in the building plans. One approach to decrease such undesirable effects is to design and build completely symmetric structures without any eccentricities which is impossible because of

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several factors such as architectural and construction constraints. Also one important part of the problem is related to the existing structures. It seems that controlling torsion of structures by using supplemental dissipating devices can be an effective solution to the problem. Two main reasons could be mentioned for this suggestion: first, ability of such methods in rehabilitation of existing structures and second, high performance of structures containing such devices. In this regard, the key factor to control structural asymmetry effects is a suitable distribution of the supplemental devices.

The researches done during the past decade shows that using viscous damper could be effective in controlling the responses, as their forces are out of phase with the other forces applied to the structures. Despite different analytical studies in this field, few experimental researches have been done in this regard. The experimental studies can have an important role in finding the real behavior of structures and validate the analytical results.

The first part of the present paper includes studying of some previous researches on the behavior of structures with dampers. In the next part, the specification of the experimental model and dampers are explained. Finally, the comparison of experimental and analytical responses of the model with different damper distribution is studied and some suitable distributions are suggested.

Previous Studies

During the past two decades, several researches have been performed about controlling the structural responses using energy dissipating devices such as dampers and base isolations. In one of the analytical researches, the effect of governing parameters of structures with dampers on the responses of a one-story elastic building with one-way stiffness asymmetry has been studied (Goel 1998). The results show that if the center of supplemental damping (CSD) is located at a distance equal to the stiffness eccentricity on the opposite side with respect to the center of mass (CM), the lateral displacement is controlled efficiently. Also increasing the damping radius of gyration decreases the displacement at both sides. Another investigation (Goel 2000) shows that in a one-story building, the damping ratio of the first mode is increased as the damping eccentricity is increased on the flexible side. Since the displacement of the flexible edge is controlled by the first mode, such damper distribution may impose the most decrease on the displacement of the flexible edge.

The studies on the nonlinear behavior of structures with viscous dampers have led to same results for controlling lateral displacement as obtained in the linear behavior (Goel and Booker 2001). Also the study shows that optimum damping eccentricity obtained for the linear behavior will impose the least ductility demand of the elements located on the flexible side.

An innovative concept called “Torsional Balance” has been introduced for controlling of structures with viscous dampers (De La Llera et. al. 2004,2005). Torsional balance is a property of an asymmetric structure that leads to a similar deformation demand in structural members equidistant from the geometric center of the diaphragm (GC). In this concept, it is tried to equalize the mean square values of the deformation of elements equidistant from the GC by using a suitable damper distribution. The results of such distribution show that rotation and lateral displacement of the diaphragm can be controlled efficiently. Also in the case that the CM coincides with the GC, the optimum damper distribution in these researches corresponds with the proposed distribution by Goel (Goel 1998).

Although, several other investigations have been performed using different types of dampers and asymmetric structures, the literature review shows lack of sufficient experimental studies on this subject. In this paper, an experimental and analytical research is done focusing on different damper distribution in order to compare experimental and theoretical results and propose some suitable distribution for controlling torsional responses.

Experimental Setup

The structural model considered in this study is a one-story steel building consists of 4 columns connected to a rigid diaphragm. Because of the limitations of the shaking table, the model is built with a geometric scale of 1/6. Fig. 1 shows the 3D view of the experimental setup on the shaking table. The diaphragm consists of a steel plate with dimensions of $1000 \times 500 \times 15mm$ as shown in Fig. 1. Two other plates are welded to the diaphragm to increase the effective mass of the model. Also several longitudinal and transverse stiffeners are added under the diaphragm plate to guarantee its in-plane rigidity. A plate with 14 holes on it is welded to one longitudinal side of the diaphragm to connect the dampers to the model. Another plate is also welded to the other longitudinal side to prevent undesired mass asymmetry. The total experimental weight of the model is 236kgf.

The height of the columns is 519mm having rectangular sections with dimensions of $30.2 \times 8.2mm$ for the columns of the stiff edge and $29.1 \times 6.2mm$ for the columns of the flexible edge. Each column is bolted to the shaking table and the diaphragm plate by using two connection plates. Since the columns participate in the lateral stiffness of the structure, tension tests have been performed on the steel of the columns to determine its modules of elasticity and yielding stress. The results of the test have led to $E = 2.1 \times 10^7 \, kg / cm^2$ and $F_y = 2535 kgf / cm^2$ for the columns. By considering the column dimensions, a stiffness eccentricity of $E_{sx} = -18.7cm$ is calculated for the model. It should be noted that because of one-component vibration of the shaking table, only one-way stiffness asymmetry is considered in the model (direction y). Therefore, the model is completely symmetric in the x direction. Table 1 shows the uncoupled and modal periods of the model.

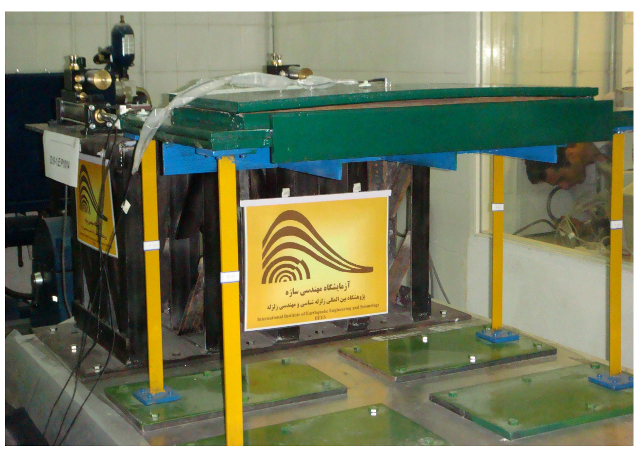


Figure 1. 3D view of the experimental model.

The shaking table of International Institute of Earthquake Engineering and Seismology (IIEES) has been used for the experimental study. It is a $1450mm \times 1200mm$ table which is able to apply displacement time histories or harmonic excitations by actuator to the table platform. The actuator is able to apply a maximum of 50mm displacement and 50kN force.

Table 1. Uncoupled and modal periods of the model

Uncoupled modes		
$T_x (sec)$	$T_y (sec)$	T_θ (sec)
0.0874	0. 3438	0.1169
Coupled modes		
T_1 (sec)	T_2 (sec)	$T_3 = T_x$ (sec)
0.3516	0.1166	0.0874

Damper Properties

Two "hydraulic speed regulator" viscous dampers are used in the test. The dynamic properties of the dampers could be changed by two control valve located on them to control the flows of fluid of dampers. Fig 2 shows the 3D view and dimensions of dampers. As the model is a one-story building, the dampers could be connected horizontally to the model in a way that one end is connected to the diaphragm and the other end is connected to the roof of a rigid structure with a similar height located on the shaking table. The rigid structure consists of 4 truss elements with a high lateral stiffness which transfers the same displacements and acceleration of the table to its roof where one end of the dampers is connected. This rigid structure is shown in Fig. 1 behind the main model. Horizontal installation of dampers has the advantage of complete transfer of the lateral displacement of the diaphragm to them. As such, a better performance of dampers is achieved specially during weak vibration.

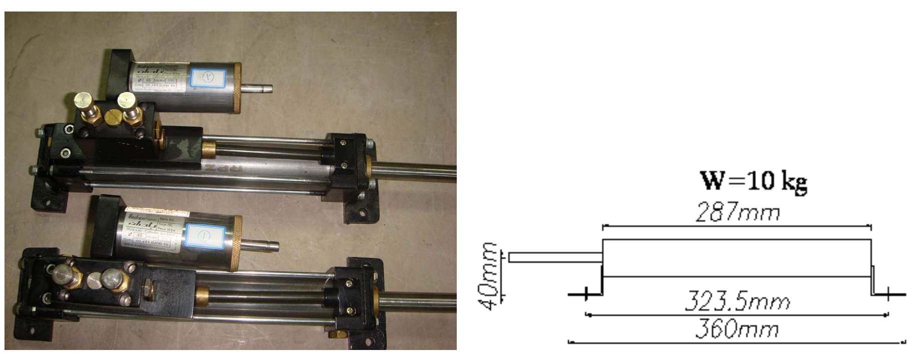
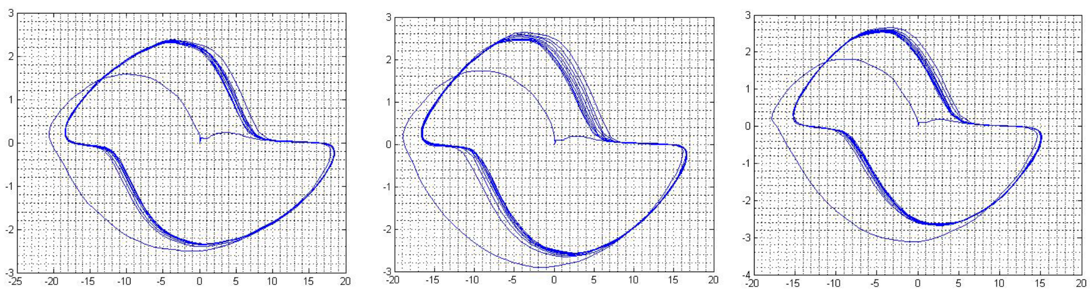


Figure 2. 3D view and dimensions of the dampers

Cyclic tests with different frequency from 1Hz to 6Hz have been done on the dampers using a 5 ton hydraulic jack. The first test for each damper has showed a different behavior in tension and compression. Thus, several tests have been done using a specific frequency by setting the control valve of dampers in each test. After receiving similar tension and compression behavior, the main tests have been done on each damper for different loading frequencies. Fig 3 shows force-displacement diagram of damper No. 1 in three frequency values of 3Hz, 3.5Hz and 4Hz. The horizontal parts of the diagrams show the unavoidable slip because of damper connection to the jack. By removing these horizontal parts, the figures show a viscous behavior for the dampers (horizontal ellipse). Table 2 shows damping coefficients obtained from test of the dampers in different frequencies. As the table shows, loading frequency has a considerable effect on the damping coefficient. Also, loading amplitude and environmental temperature are two factors affecting the coefficient. Because of the variation of damping coefficient in the results, only the values obtained in frequencies around the natural frequency of the model is considered. Thus, the average values for f=3Hz, f=3.5Hz and f=4Hz is set to nominal damping coefficient for each damper (C). The obtained values of C should be calibrated before using in the analytical model to compare its results with the experimental results.



(a) (b) (c)

Figure 3. Behavior curves for damper No. 1 for values of loading frequencies: (a) 3Hz, (b)3.5Hz and (c) 4Hz. (The horizontal axis is displacement in mm and the vertical axis is force in kN)

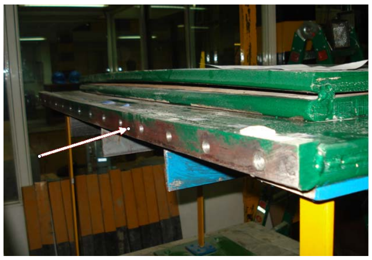
Table 2. Damping coefficient obtained for dampers in different loading frequencies

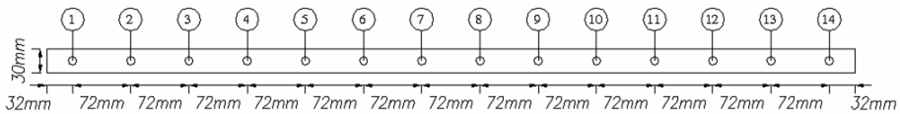
Frequency(Hz)	1	2	3	3.5	4	4.5	5	6
C_1(N.s/m)	8488	10250	8214	8757	8804	8681	8116	6150
C_2(N.s/m)	9324	12012	9431	9852	9852	9195	9947	7692

Damper Distributions on the Model

Five cases of damper distributions is investigated in this study. These cases include:
1) Locating the dampers on flexible and stiff edges to locate the center of supplemental dampers (CSD) near to the stiffness center.
2) Locating the dampers on both sides of the diaphragm in a way that the CSD is near to the center of mass (CM).
3 and 4) Cases in which the CSD is on the opposite side of the stiffness center (CS) with respect to CM in a way that the damping eccentricity (e_d) is equal to the stiffness eccentricity (e_s).
5) The case in which the CSD is near to the flexible side (both dampers on the possible extreme of the flexible side.

The difference between the case 3 and case 4 is the value of damping radius of gyration (ρ_{sd}) which is one of the key parameters governing the behavior of structures with dampers. In the case 3, the distance between the dampers is more than the case 4 which implies a higher value of damping eccentricity. In order to connect the dampers to the diaphragm, a steel strap with 14 holes are welded to one of the diaphragm sides. One ends of the dampers are located in the holes while the other ends are bolted on the ceiling of the rigid structure. Fig. 4 shows the steel strap with its hole numbers and the different cases of damper distribution. In this figure, holes number 1 and 14 are located in the stiff and flexible sides of the model respectively and the center of mass is located between holes 7 and 8.





Case number	Location of Damper 1	Location of Damper 2
1	9	1
2	1	13
3	6	14
4	9	11
5	12	14

(a) (b)

Figure 4. (a)Location of Steel strap, (b) Location dampers in different cases of distribution

Ground Motion Records

The records for the vibration test of the model are selected considering the displacement limitations of the shaking table (3.5 cm). Also strong ground motions have been used to satisfy sufficient relative displacement between the model and the rigid structure for a better performance of dampers. In this regard, different records have been verified by several steps of scaling to 1.0g and filtering high frequencies to limit their peak displacement to 3.5 cm. Finally, 6 corrected records with specifications corresponding Table 3 have been selected. All records are applied to the model in the y direction by scaling to 1.0g.

Table 2. Specification of ground motion records

	Record No.*	Record Name	Year	PGA(g)	PGD(cm)
1	P0746	Loma Prieta	1989	0.323	3.26
2	P0248	Mammoth Lakes	1980	0.408	6.41
3	P0885	Northridge	1994	0.217	2.77
4	P0078	San Fernando	1971	0.366	1.65
5	P0629	Whittier Narrows	1987	0.299	0.78
6	P1041	Kobe	1995	0.251	5.83

*The record numbers are according to PEER website

Data Acquisition System

The data from the test has been recorded by 4 accelerometers and 3 displacement sensor. One accelerometer was installed on the table platform to measure the applied acceleration. Three other were installed on the flexible and stiff edges of the model and the center of mass. The displacement sensors were installed between the rigid structure and the model diaphragm in each of the flexible and stiff edges and the middle of the diaphragm side. The sensors were displaced if they had encountered the dampers and their acquired data were corrected considering the rigidity of the diaphragm. Obtaining data from different channels had the advantage of checking the data considering rigidity of the diaphragm for eliminating possible errors.

Analytical Model

An analytical model with the properties similar to the experimental setup has been analyzed using Opensees program (McKenna F. et. al. 2000). As the experimental model may experience nonlinear behavior, Fiber elements have been used in modeling of structure to consider such effects. The properties for the steel fibers are the same as the experimental setup and the shear and torsional specifications of the columns are aggregated to the fibers. Because of the high rigidity of the diaphragm, the experimental setup acts as a shear structure which has been considered in the analytical modeling. The dampers are assigned by viscous zero-length elements located according to the experimental setup. The input ground motions are obtained from the recorded data of the accelerometer on the table platform by filtering its noises.

Performance of a damper is very complicated and its properties are dependent to several environmental and loading specifications. As the conditions are not inevitably the same when the dampers and the experimental setup are tested, the obtained damper properties have the most uncertainty and calibration of the properties is required. For damper calibration the time histories of lateral displacement of the analytical and experimental models in the second case of damper distribution has been compared for six ground motion inputs. The comparison has showed a similar trend of both cases with different peak values. By using simple trial and error process of changing the damping coefficient, the calibrated damping coefficients of C_1=3550 N.s/m and C_2=4550 N.s/m have been obtained for the dampers. These corrected coefficients minimize the differences of peak values in experimental and analytical time histories.

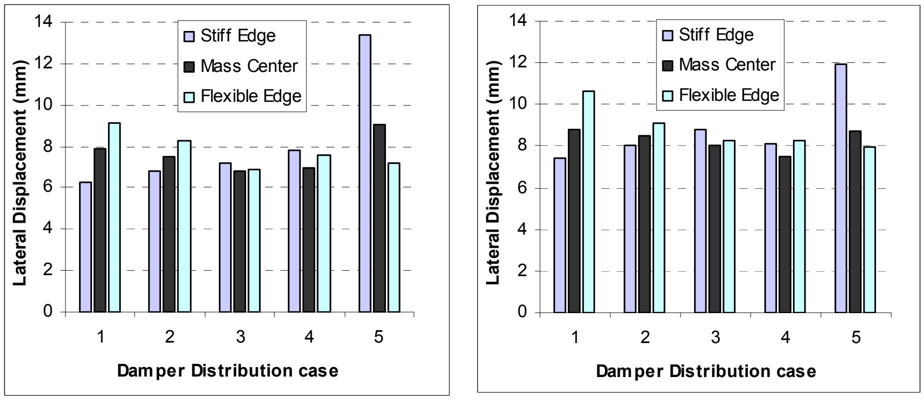
Experimental and Analytical results

Comparison between the time histories of experimental and analytical responses using the corrected damping coefficient shows suitable similarities not presented here due to the space limitations. Here, the average of the maximum responses for the experimental and analytical models for 6 ground motions in different cases of damper distributions is presented.

Lateral Displacement

Fig. 5(a) shows the maximum lateral displacement of flexible and stiff edge and the CM of the experimental model for different cases of damper distribution. Fig 5(b) shows the same results for the analytical model. The results show that there is an acceptable agreement between the experimental and analytical results for choosing the optimum case of damper distribution for controlling the effect of torsion on the lateral displacement. The case 3 and case 4 in which the CSD is on the opposite side of the CS with respect to CM with an equal distance are the optimum distribution of dampers. This is due to similar maximum displacement for the flexible and stiff edges in these cases which is also the minimized displacement between all cases. This minimized lateral displacement causes the least demand force on the model and consequently a better behavior of the asymmetric model is achieved.

There is a little difference between the analytical and experimental cases, because the case 3 is optimum in the experimental results while the case 4 is optimum in the analytical results. This difference is due to the experimental errors and can be neglected. Thus, damping radius of gyration shows negligible effects in this study. Finally, it can be concluded that according to analytical and experimental results with the indicated lateral damping capacity (3550+4550=8100 N.s/m), locating the CSD on the opposite side of the CS with an equal distance can control the effect of torsion on lateral displacement. This result confirms the previous analytical studies done by researches as indicated in the literature review.



(a) (b)

Figure 5. Peak values for lateral displacement of stiff edge, Mass center and flexible edge in different cases of damper distribution for (a) experimental setup and (b) analytical procedure.

Diaphragm Rotation

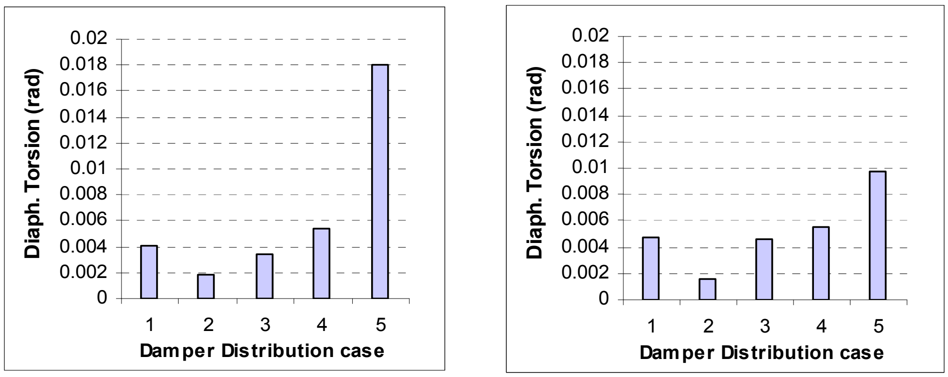
Figs. 6(a) and 6(b) shows the maximum diaphragm rotation for the experimental and analytical models respectively. Comparison of two diagrams indicates that the experimental and analytical responses lead to the same results except for the case 5 in which both dampers are located on the flexible edge. The difference of the results for this case is because of local concentration of damping system in one point of diaphragm that makes the dampers act as supports. Actually, viscous behavior of dampers is not achieved in this case and consequently the experimental results are not valid.

Fig 6 also shows that locating the CSD near to the CM (case 2) is the best case for minimizing the diaphragm torsion. Therefore, the suitable damper distribution in which lateral displacement of diaphragm is controlled is not the same as distribution in which diaphragm torsion is minimized.

Lateral Acceleration

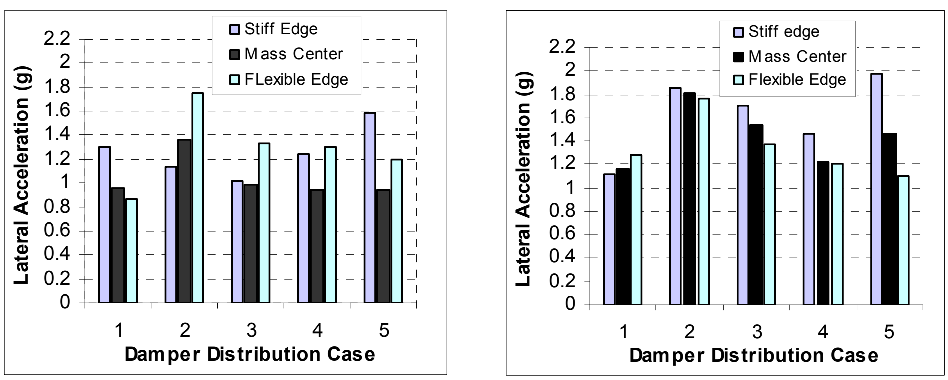
The maximum experimental and analytical results for lateral absolute acceleration of stiff and flexible edges and the CM of the model in different cases of damper distribution are shown in Figs 7(a), and 7(b). Despite displacement and torsion, the figures show considerable difference between the results of analysis and experimental test that could be attributed to noticeable noises in data achieved from the accelerometers. Such noises are because of incomplete isolation of the shaking table and deficiency of accelerometers which causes absorbing of environmental vibrations. The extended data obtained from the accelerometers shows that even filtering the high frequencies of the data could not lead to the correct results as the peak values of the time histories changes irregularly in the filtering process.

In spite of difference between the analytical and experimental cases, both results show case 1 and 4 as optimum cases for controlling acceleration. As these cases indicate completely different distribution of dampers, the results of this investigation could not lead to a unique distribution of dampers for controlling acceleration. Thus, it is suggested that exact accelerometers with a complete isolated shaking table to be used for studying the variation of lateral acceleration.



(a) (b)

Figure 6. Maximum diaphragm rotation in different cases of damper distribution for (a) experimental setup and (b) analytical procedure



(a) (b)

Figure 7. Peak values for lateral acceleration of stiff edge, Mass center and flexible edge in different cases of damper distribution for (a) experimental setup and (b) analytical procedure

Conclusion

The effect of viscous damper distribution on torsional behavior of asymmetric structures has been studied experimentally and analytically. The key results are as follows:

1- The obtained damping coefficients of used dampers show considerable dependency to the frequency and amplitude of affecting load. In this regard, the damping coefficient obtained from the cyclic tests should be calibrated considering such effects.

2- Comparing the results of experimental and analytical cases show more agreement of responses for lateral displacement and diaphragm rotation compared to lateral acceleration. This is due to sensitivity of accelerometers to environmental noise which change the peak values of the time histories and cannot be corrected even by filtering the data.

3- The effect of torsion on the lateral displacement of the diaphragm could be minimized if the center of damping is located on the opposite side of the center of stiffness with respect to the center of mass with an equal distance. In this case the maximum displacement of both stiff and flexible edges is similar and minimum. This result confirms the previous analytical studies.
4- If the center of damping is located near to the center of mass on the flexible side, the diaphragm rotation is minimized.
5- In this study, the difference between the analytical and experimental results for lateral acceleration fails to find a unique optimum damper distribution for controlling this response.
6- Comparing the results of analytical and experimental case for lateral displacement and diaphragm rotation show suitable agreement for these responses. But unacceptable difference of results for acceleration shows that an isolated shaking table with exact accelerometers is important factors for measuring this response.

Acknowledgments

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