The 14th World Conference on Earthquake Engineering
October 12-17, 2008, Beijing, China

EFFECTS OF DAMPER DISTRIBUTION IN CONTROLLING MULTIPLE TORSIONAL RESPONSE PARAMETERS OF ASYMMETRIC STRUCTURES

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ABSTRACT :

Supplemental viscous dampers with suitable distribution are very effective to mitigate the earthquake induced damage in buildings with asymmetric plan. The main advantage of these types of dampers is that their forces are out of phase with the other forces applied to the structure so they can decrease the responses efficiently. Using supplemental viscous dampers decreases lateral displacement (drift) of the structures in earthquake but it may increase lateral acceleration of stories and injure secondary systems. The aim of this investigation is to find suitable distribution of these devices to decrease lateral displacement (drift) efficiently and also control lateral acceleration. To achieve this aim, several single-story structures with one-way stiffness, strength and damping eccentricities are considered. For each structure parameters of eccentricities changes and nonlinear time history analyses are performed on each case. The results show that for lower stiffness eccentricities, some suitable distribution of dampers could be found that make both lateral displacement and acceleration near to the symmetric case.

KEYWORDS: Supplemental dampers, Torsional balance, Asymmetric, Non-classical, Flexible edge

1. INTRODUCTION

During last decade, using energy dissipation devices such as supplemental dampers for reducing the earthquake response of structures has been the subject of many investigations, Specifically, many researches have been performed for suitable distribution of dampers to control torsional effects of asymmetric structures (Goel et al., 1998-2001 - Lin and Chopra, 2001- De La Llera et al., 2005-2006). The dampers were deformation control (such as friction and hysteretic dampers), velocity control (such as viscous dampers) or a combination of these two types (such as viscoelastic dampers).

Previous researches show that viscous dampers are very effective in controlling torsional response of asymmetric buildings. The reasons can be summarized into four categories: first, their forces are out of phase with other forces applies to the building. Second, the static loads such as thermal loads (which have low velocity) do not lead to continuous stress as the damper forces are velocity dependent not deformation dependent. Third, the centers of strength and stiffness can be defined independent of damper distributions as the ideal vicious dampers have no strength and stiffness and fourth, after an earthquake the structure returns to its initial positions but for example this can't be obtained in a structure with frictional dampers because of its plastic deformations.

Since supplemental viscous dampers decrease the ductility of structures in earthquakes, larger values of acceleration may transmit to the stories which are undesired for the secondary systems. Thus, it is necessary to find damper distributions in which both lateral acceleration and displacement of the asymmetric structure come near to the symmetric case. Also, contrary to structural systems with base isolation, systems with dampers are expected to enter nonlinear ranges during intensive earthquakes (FEMA, 450, 2001). This fact shows the importance of studying the effects of supplemental damper distribution on seismic response of asymmetric structures in nonlinear range. This investigation concentrates on Controlling of torsional response of steel structures with viscous dampers considering both lateral acceleration and displacement considering nonlinear behavior of structural elements.

2. TORSIONAL BALANCE CONCEPT

In this paper, torsional balance concept (De La Llera et al., 2005) which is derived for structures with supplemental dampers is introduced: Torsional balance is defined as a characteristic of an asymmetric structure that leads to similar or near similar lateral deformation in specific points of the diaphragm. This concept can be classified as strong balance (STB) or weak balance (WTB). The former implies an uncoupling of the lateral and torsional motions that leads to equal deformation demand in all resisting planes in the diaphragm. In the latter (which is studied here), the rotation of diaphragm is allowed and only an equal norm of displacement demand on resisting planes in equal distant from the center of diaphragm (GC) is expected. In order to achieve this condition, an optimum distribution of stiffness, damping and strength should be applied. As a designer usually has limitation in the stiffness and strength distribution, use of supplemental dampers can be very effective. In this case, after determination of stiffness and strength distribution, an appropriate damper distribution can be found to achieve WTB condition.

A single-story structure with an arbitrary location of the center of mass (CM), stiffness eccentricity E_s and damping eccentricity E_d is considered (Figure 1). All eccentricities are in y-direction and the system is symmetric in x-direction. Normalized stiffness eccentricity (e_s) and normalized damping eccentricity (e_d) are defined as $e_s = E_s / L_x$ and $e_d = E_d / L_x$ respectively. The degrees of freedom $u(t)^T = [u_y(t, e_d), au_\theta(t, e_d)]$ of the structure are located at the CM and computed for an assumed location e_d of the dampers. The displacement (velocity or acceleration) at a distance p from the CM would be $\tilde{u}_y^{(p)}(t, e_d) = u_y(t, e_d) + Pu_\theta(t, e_d)$ and hence the mean square value (MSV) of the displacement is as follows:

$$E\left[\tilde{u}_y^{(p)}(t, e_d)^2\right] = E\left[u_y(t, e_d)^2\right] + 2PE\left[u_y(t, e_d)u_\theta(t, e_d)\right] + P^2E\left[u_\theta(t, e_d)^2\right] \tag{2.1}$$

The minimum value for the function $E(\tilde{u}_y^{(p)}(t, e_d)^2)$ is achieved at a point with a distance p* from the CM in which the first differential of Eqn. 2.1 with regard to p is equal to zero. This point is called empirical center of balance (ECB) in which the lateral and torsional motions are uncoupled ($E(\tilde{u}_y^{(p^*)}u_\theta) = 0$). Also it can be shown that at a distance d from the ECB, the expected value of the square of lateral displacement can be determined as:

$$E\left[\tilde{u}_y^{(d)}(t, e^*_d)^2\right] = E\left[\tilde{u}^* y^2\right] + d^2E\left[u^*{}_\theta{}^2\right] \tag{2.2}$$

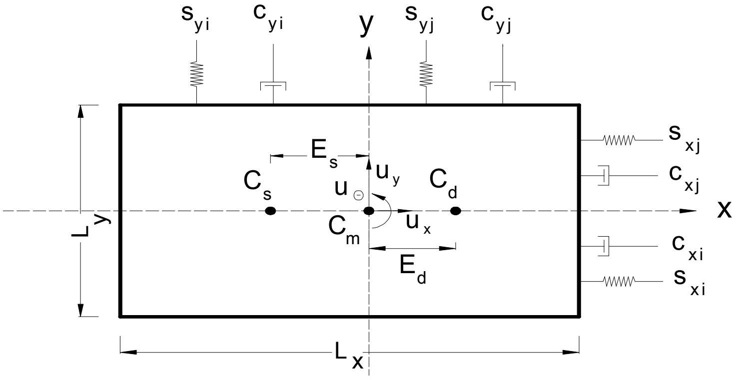


Figure 1: one-story structure with one-way damping and stiffness asymmetry

Eqn. 2.2 shows that if the ECB is located at the GC, the MSV of the lateral displacement in the resisting planes is symmetric with respect to the GC and consequently the WTB is achieved.
Since WTB concept is defined based on structural response to earthquake excitation, not system parameters, it can be applied in different cases such as linear and nonlinear system behavior and also for different responses such as acceleration and displacement.

3. DAMPING PARAMETERS

In a structure with supplemental dampers, damping matrix consists of two parts as following:

$$C = C_0 + C_{Sd} = (\alpha M + \beta K) + C_{sd} \tag{3.1}$$

Where C_0 is the inherent viscous damping and α and β are Raleigh coefficients. C_{sd} is the supplemental damping matrix which is dependent to the capacity and distribution of dampers.

Let consider a linear single-story structure with one-way damping and stiffness asymmetry as presented in figure 1. The displacement vector is defined by $u = [u_y \quad L_x u_\theta]^T$ where L_x is the story length in x direction. Assume C_{xi} and C_{yi} represent the damping coefficient for the i-th damper in x and y direction, S_{xi} and S_{yi} represent the stiffness of i-th resisting plane in x and y direction and y_{di} and x_{di} are the distance of the i-th damper from CM in x and y direction respectively. The translational and torsional damping coefficients with respect to CM are obtained as:

$$C_y = \sum_i C_{yi} \qquad C_\theta = \sum_i C_{xi} y_{di}^2 + \sum_i C_{yi} x_{di}^2 \tag{3.2}$$

In a system with viscous damper, damping eccentricity is defined as the distance between the cancroids of damper forces (which is defined damping center or CSD) and the center of mass (CM) when the system is subjected to a uniform translational velocity in the direction under consideration. Mathematically the Normalized damping eccentricity and torsional damping coefficient with respect to CSD are obtained by:

$$e_{dx} = \frac{1}{L_x C_y} \sum_i x_{di} C_{yi} \qquad C_{\theta,CSD} = C_\theta - L_x e_{dx}^2 C_y \tag{3.3}$$

Also the damping radius of gyration in x and y directions are defined as:

$$\rho_{dy} = \sqrt{\frac{C_{\theta,CSD}}{C_y}} \tag{3.4}$$

Finally the supplemental damping matrix for the system is obtained by:

$$C_{sd} = \begin{bmatrix} C_y & e_{dx} C_y \\ e_{dx} C_y & e_{dx}^2 C_y + \frac{1}{L_x^2} C_{\theta sd} \end{bmatrix} \tag{3.5}$$

It is obvious from Eqn. 3.1 and 3.5 that the damping matrix C is dependent to damper distribution and consequently the structure is classified as system with Non-proportional damping.

4. SYSTEMS AND GROUND MOTIONS

4.1. Basic Symmetric Model

The system considered for the parametric study is a one-story steel structure consisting of a rectangular rigid deck ($18\text{m} \times 15\text{m}$) supported by four moment-resisting frames in each of the two orthogonal directions. The height of the system is 3.2 m and the supplemental viscous dampers are located in the bracing system. It is assumed that the bracing system does not incorporate in the lateral stiffness and strength of the system. Figure 2 shows 3D view of the basic model.
The system is designed in the symmetric state (excluding all torsional effects) according to national Iranian building code and Iranian 2800 seismic code for high seismic risk area (A=0.35) and stiff soil (T_s=0.5 sec). Since FEMA 450 (2003) lets a reduction in the design base shear of structural systems with supplemental dampers, the modification factors of the code are also considered.

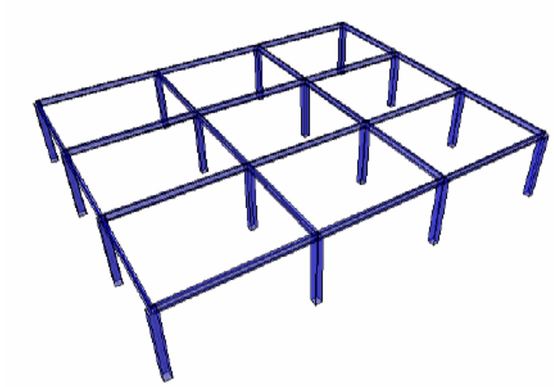


Figure 2: 3D view of the basic model

4.2. Asymmetric Models

The asymmetric models (No. 2 to 7) are derived by changing the beam and column sections of the basic model. The mass properties of all models are assumed to be symmetric about both x and y axis whereas the stiffness, strength and the damping properties are asymmetric only about the y axis.

The stiffness and strength asymmetry are generated by increasing the dimensions of the elements of two left frames and decreasing the dimensions of the elements of two right frames in a way that the total lateral strength of the system about y axis remains equal to the basic model. Several pushover analyses have been performed to obtain the strength, stiffness and yield displacements of the frames. The analyses are performed by OpenSees program using fiber elements for beam and columns and an strength hardening behavior for steel. Also the pushover curves are idealized as bilinear curves according to FEMA 356 (2000). Table 4.1 shows different parameters of models 1 to 7. In this table e_s and e_r represent stiffness and strength eccentricity, T_y and T_θ represents uncoupled lateral and torsional periods and T_1 and T_2 represents first and second periods of the structures respectively. Comparing T_y and T_θ specifies that all models are torsional stiff ($T_y > T_\theta$)

Table 4.1: Static and dynamic parameters of models 1 to 7

Model No.	$\%e_s$	$\%e_r$	Y Strength (ton)	T_y(sec) (Uncoupled)	T_θ (sec) (Uncoupled)	T_1(sec)	T_2(sec)
1	0.0	0.0	152.8	0.3926	0.3074	0.3926	0.3074
2	-5.1	-5.0	153.2	0.3919	0.3061	0.3973	0.3036
3	-10.0	-9.9	152.8	0.396	0.3091	0.4146	0.3005
4	-10.2	-7.1	152.4	0.3895	0.3063	0.4112	0.297
5	-15.4	-11.1	152.8	0.386	0.3045	0.4331	0.2867
6	-20.2	-15.7	153.2	0.3817	0.3007	0.4607	0.2751
7	-25.2	-21.1	153.4	0.3655	0.2946	0.4944	0.2589

4.3. Damper Distribution

Viscous dampers are assigned to the models as a bracing system in y direction which leads to one-directional damping asymmetry. For comparison between the responses of models in different cases two assumptions are made:

1. The total lateral damping capacity of all models (C_y) is set to a fixed value of 100 ton.s/m which leads to a damping ratio of 20% for the lateral mode of the symmetric model. Using constant value of lateral damping capacity makes the suitable distributions to be based on damping equipment expenses which is related to the capacity and plays an important role in design.

2. A linear distribution of damping is considered between four frames to catch a desired damping eccentricity. Figure 3 shows linear damper distribution for different ranges of damping eccentricity between four frames. In this investigation, damping eccentricity changes from e_d=-0.5 to e_d=0.5 with an interval of Δe_d=0.05. Since damping capacity is set to a constant value and dampers are only located in y direction, damping radius of gyration is maximum for e_d=0 and it decreases to zero for e_d=0.5 and -0.5.

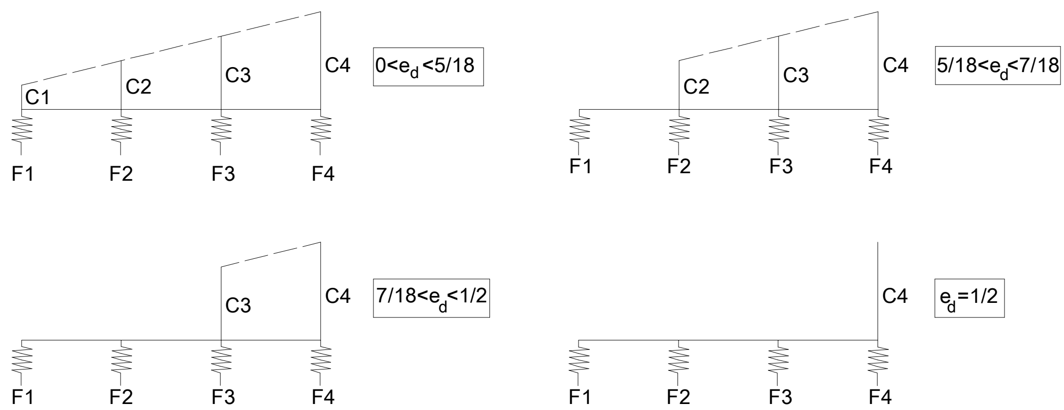


Figure 3: damping distribution between the structural frames

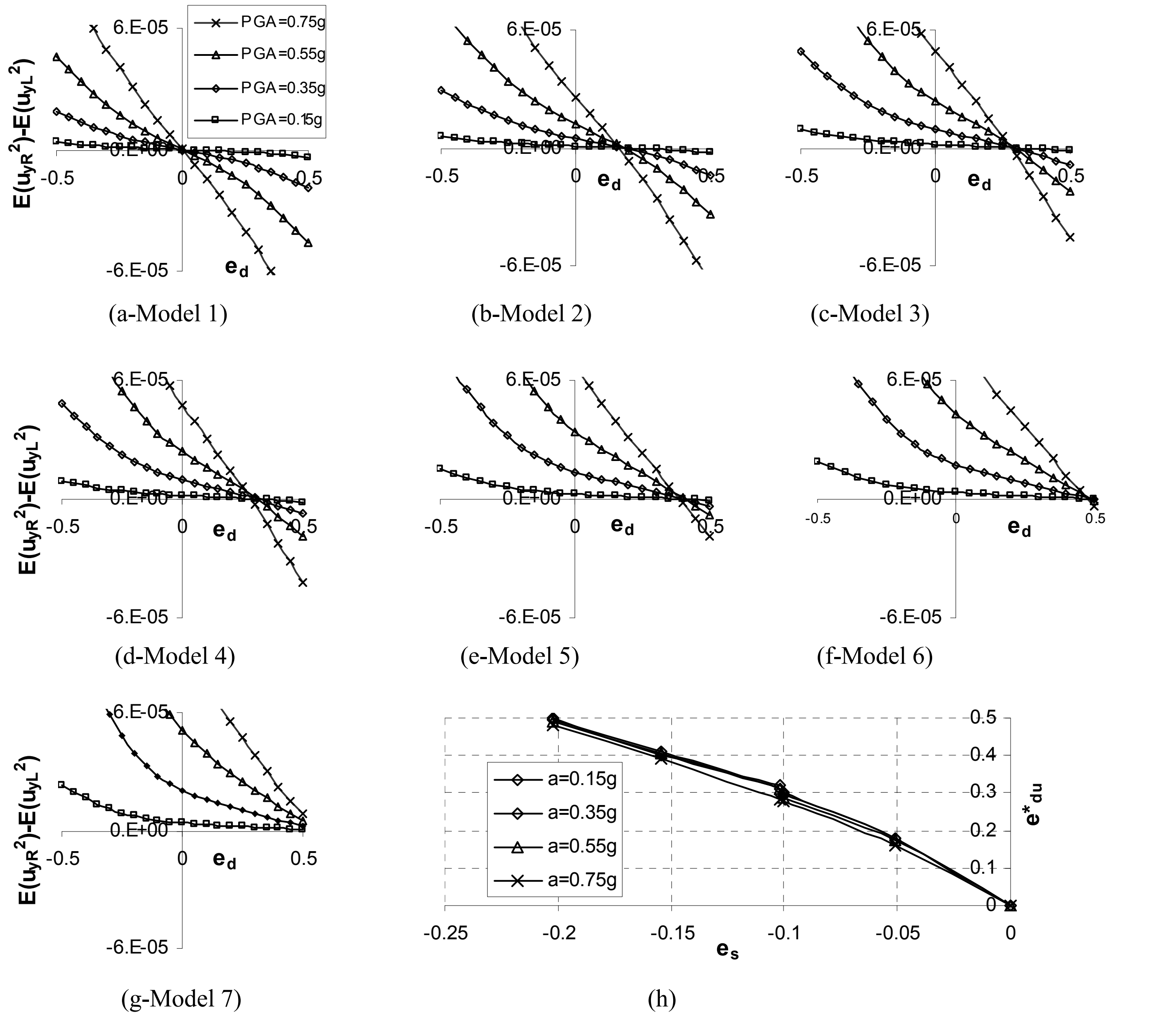
4.4. Modeling Characteristic and ground motions

Numerical models are built in Opensees and several nonlinear analyses are performed. In order to consider nonlinear effects, fiber elements with a strength hardening behavior for steel are used for beams and columns. The dampers are modeled as linear viscous zero length elements. Seven far field earthquakes (Chi-Chi, Manjil, Imperial Valley, Kern County, N. Palm Spring, Northridge and San Fernando) all recorded on stiff soil type B (in accordance with NEHRP recommended provisions code) are used for time history analysis. All records are scaled to four values of PGA=0.15g, PGA=0.35g, PGA=0.55g and PGA=0.75g and applied to the models in y-direction.

5. ANALYSIS RESULTS

The results of time-history analyses are derived for lateral displacement and lateral acceleration using torsional balance concept. All results are calculated for 7 earthquakes in 4 PGA levels and the final results are the mean values for each PGA. For simplicity, expected values used in the concept are shown only in flexible and stiff edges of the diaphragm.

Figure 4a to 4g shows the difference between MSV of lateral displacement in flexible (right) and stiff (left) edges in y-direction ($E(u_{yR}^{\,2}) - E(u_{yL}^{\,2})$) versus damper eccentricity (e_d) for 7 models. Unit for vertical axis is m^2. Each plot is related to 4 PGA levels 0.15g, 0.35g, 0.55g and 0.75g. The place of coincidence of each curve with horizontal axis specifies the optimum damping eccentricity due to displacement for that case (e^*_{du}). As presented in the figure, for the symmetric case of stiffness and strength (model 1) e^*_{du} is equal to zero as expected. By increasing in stiffness and strength eccentricity (e_s<-0.25 and e_r<-0.21) e^*_{du} increases with a higher rate in the opposite side of e_s and e_r with respect to center of mass. For model 7 with e_s =0.25 the maximum damping eccentricity e_d =0.5 couldn't balance the displacement and shows that a larger values of damping capacity is needed than 100 ton.s/m. A comparison between Figure 4c to 4d (which have the same stiffness eccentricity but different strength eccentricities) shows that structural nonlinear behavior has a little effect on the responses which is reasonable for structures with supplemental dampers. Figure 4h is a summary of results and shows e^*_{du} against e_s for different PGA levels. It is clear in this figure that the rate of e^*_{du} is much more than e_s and PGA levels does not affects the results.



(a-Model 1) (b-Model 2) (c-Model 3)

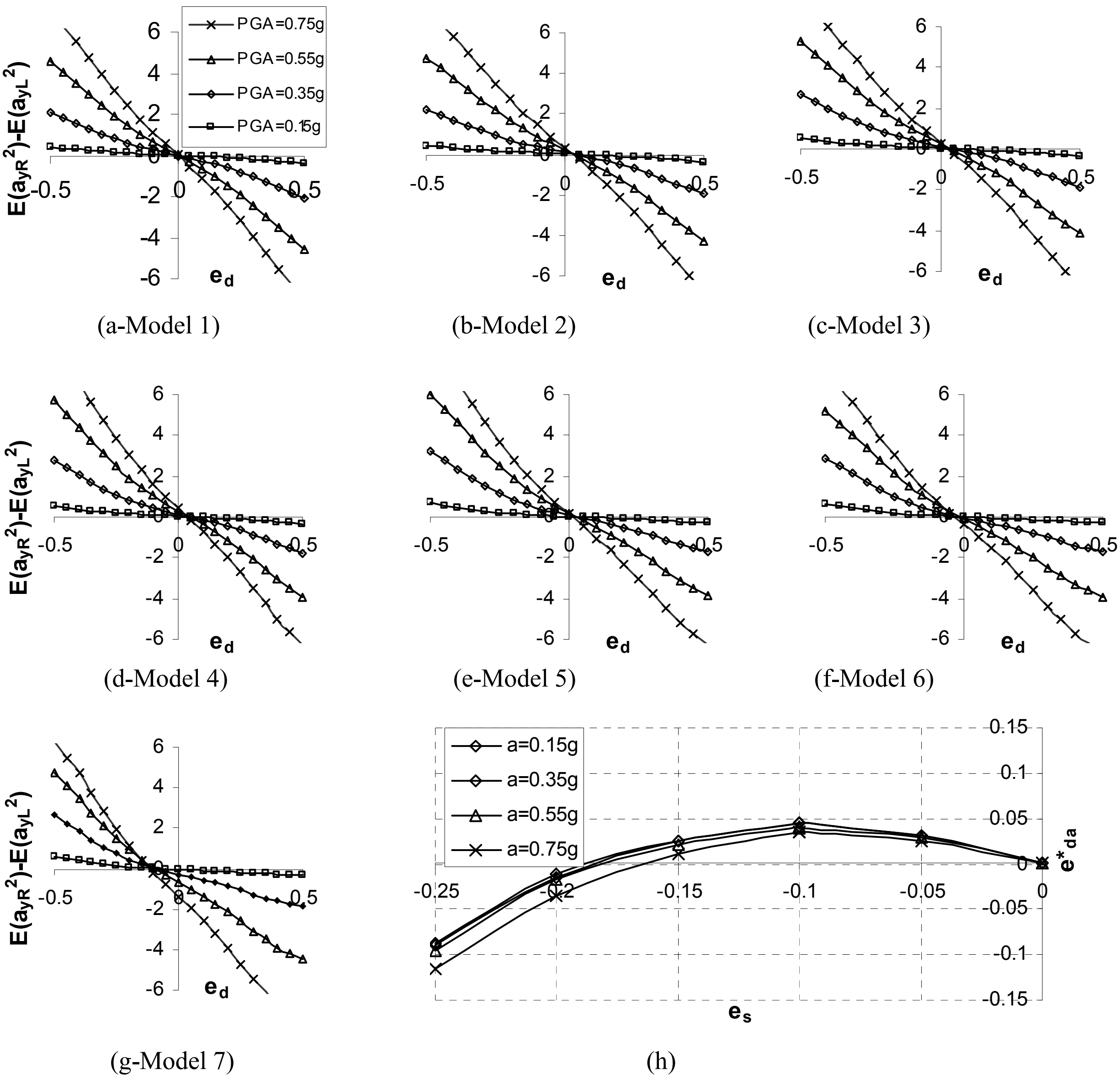
(d-Model 4) (e-Model 5) (f-Model 6)

(g-Model 7) (h)

Figure 4: a to g : Difference between MSV of lateral displacement in diaphragm edges vs. damping eccentricity in models 1 to 7, h: optimum damping eccentricity due to displacement vs. stiffness eccentricity

The results for lateral displacement agrees with results obtained in previous investigations (Goel et al., 1998-2001 and De La Llera et al., 2005-2006) but shows higher rate of e^*_{du} compared to e_s.

Figure 5a to 5g shows the difference between MSV of lateral acceleration of right and left edges ($E(a_{yR}^{\ 2}) - E(a_{yL}^{\ 2})$) versus damper eccentricity (e_d) for 7 models. Unit for vertical axis is $(m/s^2)^2$. As shown in this figure, optimum damper eccentricity due to acceleration e^*_{da} has little and also different variation compared to e^*_{du}. In small stiffness eccentricities, e^*_{da} increases with a lower rate at opposite side of e_s with respect to the CM, but in larger values of e_s it moves to the same side of e_s. Figure 5h is a summary of plots and shows e^*_{da} against e_s for different PGA levels. This figure shows that the effect of PGA levels on e^*_{da} is more than e^*_{du} but still negligible. Also coincidence of the results for models 3 and 4 (having the same e_s but different e_r) shows little effects of nonlinear behavior.



(a-Model 1) (b-Model 2) (c-Model 3)

(d-Model 4) (e-Model 5) (f-Model 6)

(g-Model 7) (h)

Figure 5- a to g : Difference between MSV of lateral acceleration vs. damping eccentricity in diaphragm edges in models 1 to 7, h: optimum damping eccentricity due to acceleration vs. stiffness eccentricity

6. CONCLUSION

In this investigation, several parametric analyses were performed on different one-story asymmetric plan systems with one-way stiffness, strength and damping eccentricities categorized as torsional stiff models. In order to compare the results in various cases, lateral strength and lateral damping capacity of all models in the asymmetric direction were set to fixed values. By using torsional balance concept, mean square value (MSV) of lateral displacement and acceleration were calculated in diaphragm edges and compared for different eccentricities and PGA levels. The summary of results is as follows:

1. Optimum damping eccentricity for controlling displacement (e^*_{du}) is always at the opposite side of e_s with respect to CM but with a larger value compared to e_s.

2. Optimum damping eccentricity for controlling acceleration (e^*_{da}) is dependent to the stiffness eccentricity (e_s). In small values of e_s, e^*_{da} is at the opposite side of e_s with respect to CM, but in large values of e_s, it moves to the same side of e_s.

3. It seems that for structure with small e_s, If damping center locates at the opposite side of stiffness center with respect to CM in a way that e_s=e_d, both lateral displacement and acceleration could be controlled efficiently. But for large values of e_s (i.e. e_s>15%) no suitable distribution could be found to control both responses.

4. PGA variation and nonlinear behavior of structural elements have a negligible effect on the results.

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