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PASSIVE CONTROL OF EARTHQUAKE-INDUCED VIBRATIONS IN ASYMMETRIC BUILDINGS

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SUMMARY

The performance of structures during past earthquakes has shown that asymmetric-plan buildings are especially vulnerable to earthquake damage due to excessive edge deformations resulting from coupled lateral-torsional motions. This investigation examined how supplemental viscous damping can be used to control these excessive deformations in asymmetric-plan buildings. It was found that symmetric distribution of supplemental damping devices in the building plan is not necessarily the best way to control excessive deformations in an asymmetric-plan building; a value of the damping eccentricity equal to the structural eccentricity in magnitude but opposite in algebraic sign leads to higher reduction. A larger reduction is also obtained by providing a larger value of the damping radius of gyration that can be obtained by spreading the damping devices as far away as physically possible from the center of supplemental damping in the system plan.

INTRODUCTION

Recognizing that asymmetric-plan buildings are especially vulnerable to earthquake damage, numerous investigations in the past have investigated the earthquake behavior of asymmetric-plan buildings. As a result, procedures to account for undesirable effects of plan asymmetry, such as increased force and ductility demands on lateral load-resisting elements, have been developed and incorporated into seismic codes of many countries (*International*, 1992). However, control of excessive earthquake-induced deformations in asymmetric-plan buildings has not received much attention. The excessive deformations may lead to premature failure in nonductile elements, cause pounding between closely spaced adjacent buildings, and may lead to increased second-order (P-Δ) effects.

Although the effectiveness of supplemental damping for reducing earthquake deformations in structural systems is not well established (e.g., Aiken and Kelly, 1990; Constantinou and Symans, 1992; Hanson, 1993; Reinhorn et al, 1995), the focus in the past has been on planar (symmetric) systems. There has been a lack of efforts toward developing a fundamental understanding of how these devices and their plan-wise distribution may be used to control the lateral-torsional coupling in asymmetric-plan systems. Therefore, the objectives of the research reported in this paper were to (1) to identify the system parameters that control the seismic response of asymmetric-plan buildings with fluid viscous dampers; (2) to investigate the effects of the controlling parameters on edge deformations in asymmetric-plan buildings; and to develop a fundamental understanding of the reasons that lead to reduction in edge deformations. Only summary of the findings are presented in this paper; details are available elsewhere (Goel, 1998a, 1998b, 1998c).

SYSTEM AND GROUND MOTION

The system considered was the idealized one-story building of Figure 1 consisting of a rigid deck supported by structural elements (wall, columns, moment-frames, braced-frames, etc.) in each of the two orthogonal

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directions. Supplemental damping is provided by incorporating fluid viscous dampers in the building bracing system. The mass properties of the building were assumed to be symmetric about both the *X*- and *Y*-axes whereas the stiffness and the damper properties were considered to be symmetric only about the *X*-axis. The distance between the center of mass (CM) and the center of rigidity (CR) was denoted as the stiffness eccentricities, e, and the distance between the CM and the center of supplemental damping (CSD) was characterized by the supplemental damping eccentricity, e_{sd}. For comparison purposes, earthquake responses of a reference symmetric-plan building were also computed. This reference building was defined as a system with no supplemental damping and coincidental CM and CR but with relative locations and stiffnesses of all resisting elements identical to those in the asymmetric-plan building.

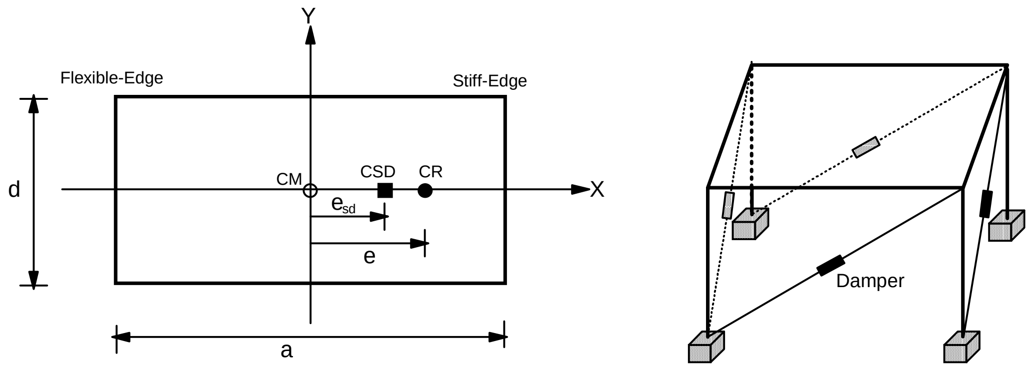

Figure 1. One-story system considered.

The ground motion considered was the North-South (360°) component recorded at the Sylmar County Hospital parking lot during the 1994 Northridge earthquake. The peak values of the ground acceleration, velocity, and displacement recorded at this site were $826.8\,\text{cm/s}^2$, $128.9\,\text{cm/s}$, and $32.55\,\text{cm}$, respectively.

SYSTEM PARAMETERS AND RESPONSE QUANTITIES

System Parameters

The linear elastic response of one-story, asymmetric-plan buildings without supplemental damping depends on (1) transverse vibration period, $T_y = 2\pi/\omega_y$ (ω_y = transverse vibration frequency) of the reference symmetric building; (2) normalized stiffness eccentricity, $\bar{e} = e \div a$; (3) ratio of the torsional and transverse frequencies, Ω_θ; (4) aspect ratio, α; (5) mass and stiffness proportional constants, a_0 and a_1, which in turn depend on the natural damping ratio in the two vibration modes of the system. The additional parameters needed to include supplemental damping are (Goel, 1998a): (1) supplemental damping ratio, ζ_{sd}; (2) normalized supplemental damping eccentricity, $\bar{e}_{sd} = e_{sd} \div a$; and (3) normalized supplemental damping radius of gyration, $\bar{\rho}_{sd} = \rho_{sd} \div a$.

The following system parameters were selected. Selected values of T_y in the range of 0.05 s to 3 s represent many low-rise and mid-rise buildings and $\Omega_\theta = 1$ represents buildings with strong coupling between lateral and torsional motions in the elastic range. The normalized stiffness eccentricity $\bar{e}$ was selected as 0.2 to represent an eccentricity of 20% of the plan dimension. The aspect ratio, α, of the selected buildings was fixed at two. The constants a_0 and a_1 were selected such that damping ratios in both vibration modes of the building were equal to 5%, i.e., $\zeta_1 = \zeta_2 = \zeta = 5\%$.

The value of ζ_{sd} was fixed at 10% for most cases; for a limited number of cases, however, variations of ζ_{sd} in the range of 0 to 50% were considered. In general, three values of $\bar{e}_{sd}$ = 0.2, 0, and –0.2 were selected. The first corresponds to the supplemental damping eccentricity equal to and in the same direction as the selected stiffness eccentricity, i.e., coincidental locations of the CR and CSD. The second value corresponds to even distribution of supplemental damping about the CM and thus the identical location of the CM and CSD. The last value corresponds to equal values of the two eccentricities, but with the CSD located on the opposite side of the CM from the CR. For selected cases, variations of $\bar{e}_{sd}$ in the range of –0.5 to 0.5 were also considered. The selected values of $\bar{\rho}_{sd}$ = 0, 0.2, and 0.5 represent low, medium, and large spread of damping about the CSD.

Response Quantities

The response quantities of interest were the peak deformations u_f and u_s at the flexible and the stiff edge, respectively, of the building. If the building plan were symmetric, these deformations would be identical, i.e., $u_f = u_s = u_o$. The deviations in u_f and u_s from u_o are indicative of the effects of plan asymmetry. Therefore, the response quantities selected in this investigation were the deformations of the flexible and stiff edges in asymmetric-plan building normalized by the deformation of the reference symmetric building, $\bar{u}_f = u_f \div u_o$ and $\bar{u}_s = u_s \div u_o$. A value of the normalized edge deformation by more than one indicates a larger edge deformation in the asymmetric-plan building as compared to the reference symmetric building; conversely, a value of normalized edge deformation smaller than one implies a smaller edge deformation in the asymmetric-plan building.

EFFECTS OF SUPPLEMENTAL DAMPING

Effects of various system parameters related to the supplemental damping – $\bar{e}_{sd}$, $\bar{\rho}_{sd}$, and ζ_{sd} – are evaluated by comparing the normalized edge deformations, $\bar{u}_f$ and $\bar{u}_s$, of buildings with supplemental dampers with those of buildings without supplemental dampers; the later is denoted as the ζ_{sd} = 0 case. Following is a detailed discussion of these effects.

Supplemental Damping Eccentricity

Edge deformations are plotted in Figures 2 and 3 for three values of $\bar{e}_{sd}$: –0.2, 0, and 0.2. These results show that the supplemental damping reduces edge deformations. However, the degree of reduction depends significantly on the normalized supplemental damping eccentricity, $\bar{e}_{sd}$. For the flexible edge, $\bar{e}_{sd}$ = –0.2 led to the largest reduction whereas $\bar{e}_{sd}$ = 0.2 resulted in the smallest reduction (Figure 2). These trends are reversed for the stiff edge, for which $\bar{e}_{sd}$ = 0.2 led to the largest reduction and $\bar{e}_{sd}$ = –0.2 resulted in the smallest reduction (Figure 3). For both edges, $\bar{e}_{sd}$ = 0 led to an intermediate reduction.

Figure 4 shows variation of the edge deformations with $\bar{e}_{sd}$; $\bar{e}_{sd}$ is varied between –0.5 to 0.5 while keeping all other parameters the same (T_y = 1 s and $\bar{\rho}_{sd} = 0.2$). The extreme values of $\bar{e}_{sd}$ = –0.5 and 0.5 correspond to all dampers located either at the flexible or at the stiff edge, respectively. These results show that deformation of the flexible edge decreases and that of the stiff edge increases as $\bar{e}_{sd}$ decreases from 0.5 to –0.5, i.e., the CSD moves from the right to the left of the building plan (Figure 1). These results also show that $\bar{u}_f$ is the smallest for $\bar{e}_{sd}$ = –0.5 indicating that the largest reduction in deformation of the flexible edge would be obtained by concentrating all dampers at the flexible edge. The stiff edge deformation, on the other hand, is the smallest for $\bar{e}_{sd}$ = 0.5, implying that the largest reduction would be obtained by locating all dampers at the stiff edge.

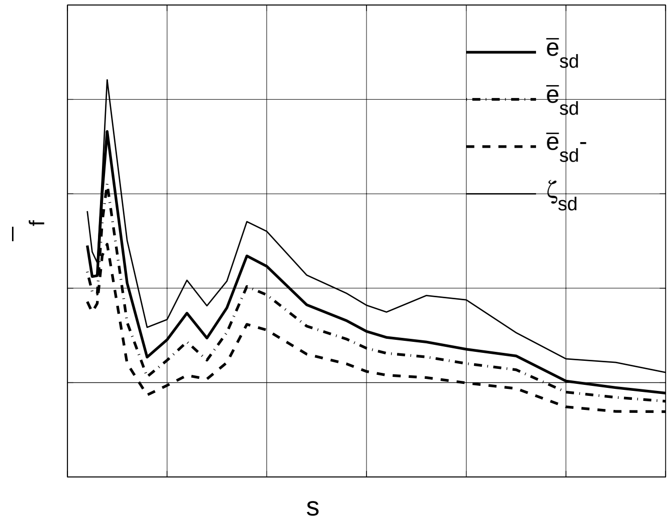

Figure 2. Deformations at flexible edge for asymmetric-plan buildings ($\bar{e} = 0.2; \Omega_\theta = 1; \alpha = 2; \zeta = 5\%$) with supplemental damping ($\zeta_{sd} = 10\%$ and $\bar{\rho}_{sd} = 0.2$) and without supplemental damping ($\zeta_{sd} = 0$).

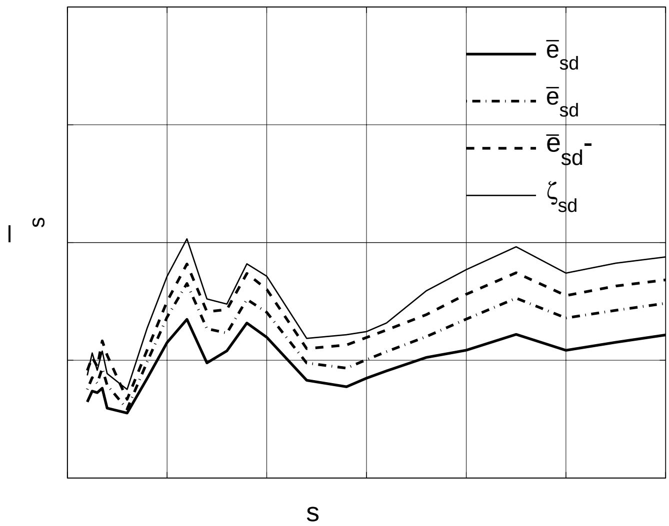

Figure 3. Deformations at stiff edge for asymmetric-plan buildings ($\bar{e} = 0.2; \Omega_\theta = 1; \alpha = 2; \zeta = 5\%$) with supplemental damping ($\zeta_{sd} = 10\%$ and $\bar{\rho}_{sd} = 0.2$) and without supplemental damping ($\zeta_{sd} = 0$).

The presented results show that the same distribution of dampers does not provide the largest reduction in deformations of both edges: the distribution that results in the largest reduction in the flexible edge deformation leads to the smallest reduction in the stiff edge deformation and vice versa. For asymmetric-plan buildings, the flexible edge is generally the most critical edge because of higher earthquake-induced deformations (Goel, 1998a). Therefore, the design goal should be to obtain the largest reduction in deformation of the flexible edge. For this purpose, damping should be distributed such that the CSD is as far away from the CM, on the side opposite to the CR, as physically possible. Although this distribution does not lead to the largest possible reduction in deformation of the stiff edge, it none the less reduces deformations as compared to deformation of the same edge in buildings without dampers.

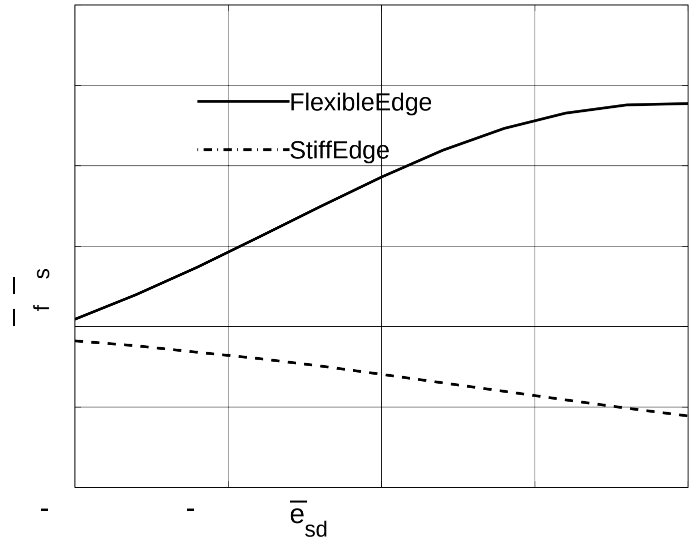

Figure 4. Variation of edge deformations with damping eccentricity: $\bar{e} = 0.2; \Omega_\theta = 1; \alpha = 2; \zeta = 5\%; T_y = 1s;$ $\zeta_{sd} = 10\%$ and $\bar{\rho}_{sd} = 0.2$ **.**

Supplemental Damping Radius of Gyration

In order to investigate how the effects of plan asymmetry vary with the supplemental damping radius of gyration, the results for buildings with $\bar{\rho}_{sd}$ = 0 and 0.5 were also computed and are in included in Figure 5. For reasons of brevity, results are presented only for the flexible edge. These results show that a larger value of $\bar{\rho}_{sd}$ leads to a larger reduction in edge deformations. This trend applies to deformations at both edges. However, the effect is not as strong as observed previously for $\bar{e}_{sd}$.

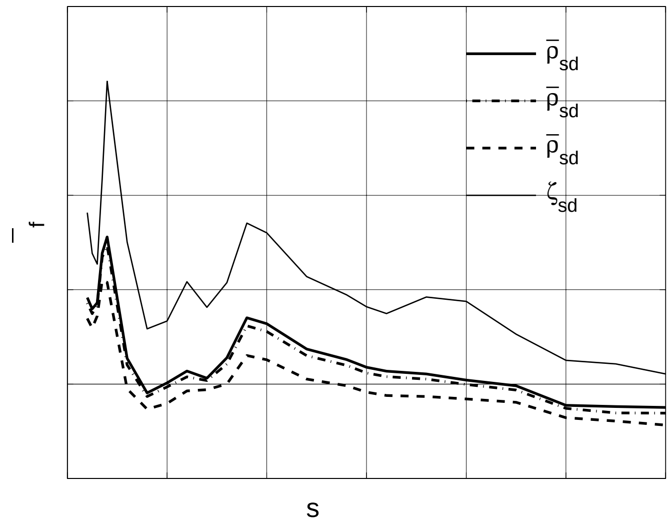

Figure 5. Deformations at flexible edge for asymmetric-plan buildings ($\bar{e} = 0.2; \Omega_\theta = 1; \alpha = 2; \zeta = 5\%$ **) with supplemental damping (** $\zeta_{sd} = 10\%$ and $\bar{e}_{sd} = -0.2$ **) and without supplemental damping (** $\zeta_{sd} = 0$ **).**

The results presented so far indicate that in order to obtain the largest reduction in deformation of the flexible edge, dampers should be distributed in the building plan such that both $\bar{e}_{sd}$ and $\bar{\rho}_{sd}$ take on the largest possible values; the value of $\bar{e}_{sd}$ should also be negative. However, $\bar{e}_{sd}$ and $\bar{\rho}_{sd}$ cannot physically take on the largest possible values simultaneously. Therefore, following simple guidelines may be used to establish a near-optimal solution: (1) Use as few dampers as possible in the direction under consideration and locate the outermost dampers at the two building edges; (2) Proportion the dampers such that the damping eccentricity is nearly equal to the structural eccentricity, but opposite in sign, i.e., CSD should be located on the opposite side of the CM from the CR; and (3) Include dampers in the perpendicular direction to further increase the value of $\bar{\rho}_{sd}$. Although an arrangement with just two dampers in each direction is preferable because it leads to the largest possible value of the $\bar{\rho}_{sd}$, at least three dampers should be used in order to provide some redundancy in the system.

Supplemental Damping ratio

Figure 6 shows the normalized edge deformation in asymmetric-plan buildings against ζ_{sd} for $\bar{e}_{sd}$ = –0.2, $\bar{\rho}_{sd}$ = 0.2, and T_y = 1 s; values of ζ_{sd} in the range of 0 to 0.5 are considered. These results show that edge deformation become smaller as supplemental damping ζ_{sd} increases, an effect that is stronger for smaller values of ζ_{sd}. This means that the reduction in edge deformation is greater due to the initial 5% supplemental damping (i.e., increase in ζ_{sd} from 0 to 5%), compared with the reduction due to an increase in supplemental damping by the same amount at a later stage (i.e., increase in ζ_{sd} from 10% to 15%). This is also apparent from the reduction in the slope (or flattening) of the curves as ζ_{sd} increases.

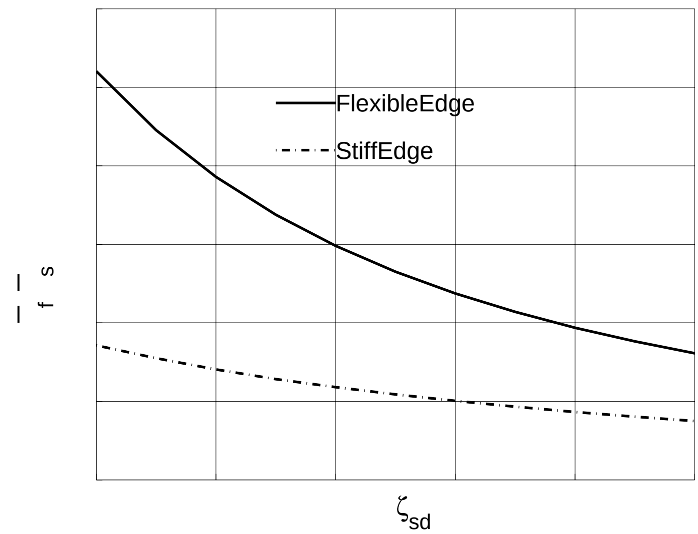

Figure 6. Variation of edge deformations with damping ratio: $\bar{e} = 0.2; \Omega_\theta = 1; \alpha = 2; \zeta = 5\%; T_y = 1s;$ $\bar{e}_{sd} = -0.2$ **and** $\bar{\rho}_{sd} = 0.2$ **.**

APPARENT MODAL DAMPING RATIOS

In order to understand why the edge deformations are affected so significantly by the plan-wise distribution of damping, apparent modal damping ratios were computed and are plotted in Figure 7. These damping ratios were computed by solving the damped eigen value problem in the complex domain (Inman, 1996). The presented results show that apparent modal damping ratios are significantly affected by both $\bar{e}_{sd}$ and $\bar{\rho}_{sd}$. In particular, ζ_1 decreases and ζ_2 increases as the CSD moves from left to right in the system plan, i.e., $\bar{e}_{sd}$ varies from –0.5 to 0.5, and both ζ_1 and ζ_2 become larger as $\bar{\rho}_{sd}$ increases.

The presented results also show that damping ratios much higher than that obtained by evenly distributing the supplemental damping in the system plan, i.e., $\bar{e}_{sd}$ = 0, are possible with careful distribution. Consider, for example, the damping ratios in systems with $\bar{\rho}_{sd}$ = 0.5. The apparent value of ζ_1 is nearly two-and-a-half times for $\bar{e}_{sd}$ = –0.5 compared that for $\bar{e}_{sd}$ = 0.

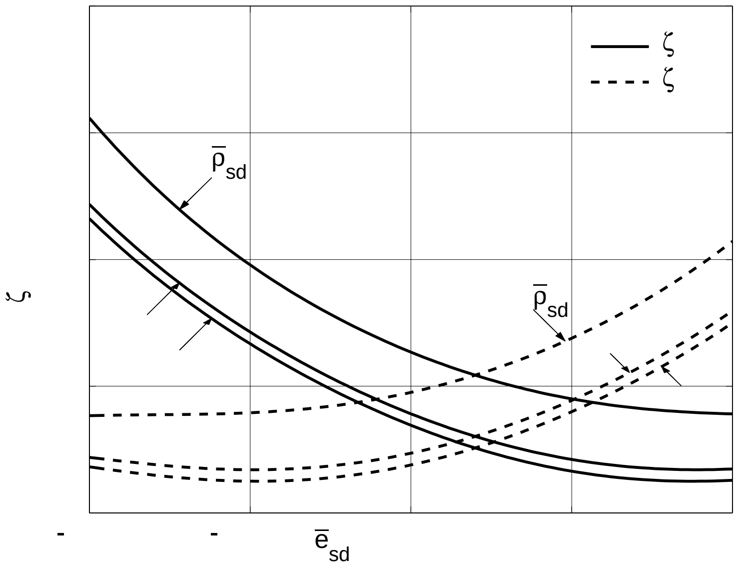

Figure 7. Variation of apparent modal damping ratios with plan-wise distribution of damping: $\bar{e} = 0.2; \Omega_\theta = 1; \alpha = 2; \zeta = 5\%; T_y = 1s;$ **and** $\bar{e}_{sd} = -0.2$**.**

The largest possible values of ζ_1 and ζ_2 do not necessarily occur for the same values of $\bar{e}_{sd}$: ζ_2 is nearly at its minimum value when ζ_1 reaches its maximum value and vice versa. This indicates that the plan-wise distribution of the supplemental damping, i.e., selection of $\bar{e}_{sd}$, should depend on which of the two modes dominates the response. If the first mode dominates, the supplemental damping should be distributed to maximize ζ_1 by locating the CSD as far away from the CM, on the side opposite to the CR, as possible, i.e., $\bar{e}_{sd}$ as close to –0.5 as possible. If the second mode dominates, then the supplemental damping should be distributed to maximize ζ_2 by locating the CSD as far away from the CM, on the same side of the CR, as possible, i.e., $\bar{e}_{sd}$ as close to 0.5 as possible.

The trends for the apparent modal damping are directly related to the previous observations on the edge deformations. The flexible edge deformation is larger due to the first mode whereas the stiff edge deformation is larger due to the second mode. The flexible edge deformation decreases (Figure 2) and stiff edge deformation increases (Figure 3) as $\bar{e}_{sd}$ decreases from 0.5 to –0.5, i.e., the CSD moves from the right to the left of the building plan, because the apparent modal damping ratio in the first mode increases and in the second mode decreases with such a variation of $\bar{e}_{sd}$.

CONCLUSIONS

This investigation on seismic behavior of linearly-elastic, one-story, asymmetric-plan buildings with supplemental viscous damping devices showed that supplemental damping reduced edge deformations. However, the degree of reduction strongly depends on the plan-wise distribution of the supplemental damping. In particular, it was found that (1) asymmetric distribution of the supplemental damping led to a higher reduction in edge deformations as compared to symmetric distribution; (2) largest reduction in the critical edge, i.e., flexible edge, deformation occurred when the CSD was as far away as physically possible from the CM and on the side opposite to CR; and (3) largest reduction in the flexible edge deformation was also obtained when the supplemental damping is distributed as far away from the CSD as possible.

Since $\bar{e}_{sd}$ and $\bar{\rho}_{sd}$ can not physically take on the largest possible values simultaneously, a near-optimal reduction may be obtained by (a) using as few dampers as possible in the direction under consideration, (b) locating the outermost dampers at the two edges, and (c) providing dampers in the perpendicular direction.

It is also found that the trends for the edge deformations can be easily explained by examining the apparent modal damping ratios. The apparent modal damping in the first mode becomes the largest when the CSD was as far away as physically possible from the CM and on the side opposite to CR. Since the flexible edge deformation is controlled primarily by the first mode, such a distribution of supplemental damping also led to the largest reduction in the deformation of this edge.

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