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Seismic retrofit of asymmetric structures using steel plate slit dampers

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ABSTRACT

A seismic design and retrofit procedure were developed for estimating the proper amount of steel plate slit dampers required to keep the seismic response of low-rise asymmetric structures within a given target performance level. Parametric studies for displacement response of a single story plan-wise asymmetric structure were conducted with varying eccentricities between center of mass and center of stiffness. Then a procedure was developed to distribute the damper based on the ductility demand of the structure. The procedure was applied to install slit dampers at proper locations of low-rise structures with horizontal and/or vertical irregularities subjected to an earthquake load. According to the nonlinear static and dynamic analysis results, the structure with hysteretic dampers installed in accordance with the proposed procedure showed satisfactory inter-story drifts in both the stiff and the flexible edges when they were subjected to the design level seismic load.

1. Introduction

It has been reported that asymmetric structures are especially vulnerable to earthquake-induced damage. According to the ASCE 7-13 [1], torsional irregularity is defined to exist where the maximum story drift at one end of the structure transverse to an axis is more than 1.2 times the average of the story drifts at the two ends of the structure. Many researchers have investigated the seismic response mitigation of asymmetric buildings using supplemental energy dissipation devices. Goel [2] studied the effects of supplemental viscous damping on seismic response of one-way asymmetric system and found that edge deformations in asymmetric systems could be reduced by proper selection of supplemental damping parameters. Kim and Bang [3] proposed a strategy based on modal analysis for an appropriate plan-wise distribution of viscoelastic dampers to minimize the torsional responses of an asymmetric structure with one axis of symmetry subjected to an earthquake-induced dynamic motion. They also found that the viscoelastic dampers were more effective than viscous dampers in controlling the torsional response of a plan-wise asymmetric building structure. Lin and Chopra [4] investigated the effectiveness of viscous dampers for elastic single story asymmetric system, and showed that the reduction in the seismic response achieved by a judiciously selected asymmetric distribution of viscous dampers can be significantly larger compared to symmetric distribution. De La Llera et al. [5] carried out analytical and experimental research of linear asymmetric structures with frictional and viscoelastic dampers, and showed that the energy dissipation devices prove useful in controlling the uneven deformation demand occurring in structural members of torsionally unbalanced structures. Petti and De Iuliis [6] proposed a method to optimally locate the viscous dampers for torsional response control in asymmetric plan systems by using modal analysis techniques. It was found that optimal damping eccentricity moves from the flexible edge to the mass center by reducing the structural eccentricity. Mevada and Jangid [7] investigated the seismic response of linearly elastic, single-story, one-way asymmetric building with linear and non-linear viscous dampers. It was shown that the non-linear viscous dampers were quite effective in reducing the responses and the damper force depends on system asymmetry and supplemental damping. Khante and Nirwan [8] applied a tuned mass damper for mitigation of torsional effect in an asymmetric structure subjected to seismic load, and investigated the optimum parameters for TMD with respect to the design variables such as eccentricity ratios, uncoupled torsional to lateral frequency ratios, mass ratios etc. Bharti et al. [9] investigated the seismic behavior of an asymmetric plan building with MR (Magnetorheological) dampers, and found that MR damper-based control systems are effective for plan asymmetric systems. They also investigated the influence of the building parameters and damper command voltage on the control performance through a parametric study. Almazána et al. [10] studied the response of asymmetrical linear and nonlinear structures subjected to unidirectional and bidirectional seismic excitations, equipped with one or two Tuned Mass Dampers (TMDs), and obtained the optimized parameters of each TMD by applying the concept of general torsional balance.

Most of the previous studies on mitigation of asymmetric behavior using energy dissipation devices were focused on elastic behavior of structures [2–9]. Paulay [11] suggested a rational design philosophy for performance-based seismic design of asymmetric structures subjected to inelastic deformation. He recommended a design procedure in which the ductility demand in each structural element does not exceed a given limit state. The same approach was applied in this study for application

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of steel plate slit dampers to mitigate torsional effect as well as overall responses. Parametric studies for displacement response of a single story plan-wise asymmetric structure were conducted with the eccentricity ratio as a main parameter. Then a systematic and practical design procedure was developed to distribute the steel damper based on the ductility demand of the structure. The procedure was applied to install proper amount of steel plate slit dampers at stiff and flexible edges of low-rise structures with horizontal and vertical irregularities to reduce torsional effect as well as overall seismic responses.

2. Seismic retrofit design procedure for a plan asymmetric structure

2.1. Ductility demand in a single-story asymmetric structure

Fig. 1 shows an idealized one-story structural plan with lateral stiffness eccentricity along the x axis. The floor is considered as rigid diaphragm, and the model structure belongs to a torsionally rigid system. When lateral force of V is applied to the center of mass, CM, along the y axis, torsional moment M_t is generated due to the eccentricity between CM and the center of rigidity, CR, and the force at each vertical element contributed from the direct shear and the torsional moment can be obtained as follows [11]

$$\mathrm{V_{iy}} = \left(\frac{k_{iy}}{\sum k_{iy}}\right) V_y + y_i k_{iy} \frac{M_t}{K_t} \tag{1}$$

where the torsional stiffness K_t is expressed as follows

$$\mathrm{K_t} = \sum y_i^2 k_{ix} + \sum x_i^2 k_{iy} \tag{2}$$

where x_i and y_i are the distances from CR to ith element, k_{xi} and k_{yi} are the element lateral stiffness for x and y axes, respectively, expressed in the form

$$k_i = \frac{V_i}{\Delta_i} \tag{3}$$

where V_i is the applied load to the ith element and Δ_i is the resulting deflection. The maximum displacement at CM, Δ_m, is obtained by summation of the displacement due to lateral load, $\Delta_m^{'}$, and torsion, $\Delta_m^{''}$, as follows

$$\Delta_m = \Delta_m^{'} + \Delta_m^{''} = \frac{V}{\sum k_i} + \theta_t e_r \tag{4}$$

where e_r is the structural eccentricity between CM and CR of the system. The rotation angle, θ_t, and the maximum displacement at CM can be obtained as follows

$$\theta_t = M_t K_t = e_r \frac{V}{K_t} \tag{5}$$

$$\Delta_m = V\left[1\Big/\sum k_i + e_r^2\Big/K_t\right] \tag{6}$$

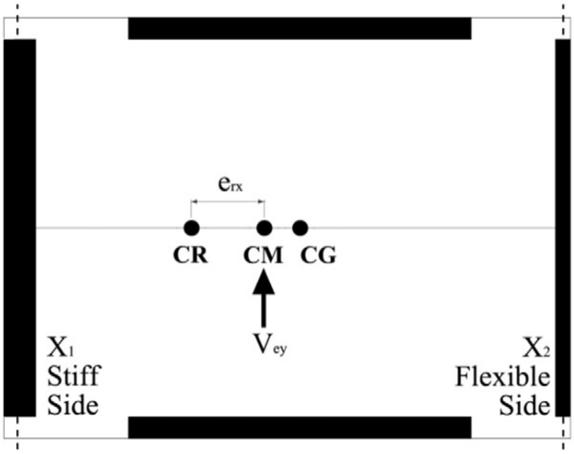

Fig. 1. Structural plan of an idealized asymmetric structure.

The yield displacements of each element and at CM along the y axis are obtained by Eqs. (7a) and (7b), respectively:

$$\Delta_{yi} = \frac{V_{yi}}{k_i} \quad \Delta_y = \frac{\sum V_{iy}}{\sum k_i} \tag{7a, b}$$

where V_{yi} is the yield force of the ith element. The post-yield displacement, Δ_u, of the system at CM is obtained as follows:

$$\Delta_u = (\mu_\Delta - 1)\Delta_y \tag{8}$$

where μ_Δ is the ductility demand at CM. When all structural elements are designed to have similar demand to strength ratio for design load, all members start to yield almost at the same time when the load reaches a yield level. In this case the element with largest stiffness will show the smallest yield displacement. If post-yield stiffness is zero, the torsional moment and the twisting angle at yield no longer increase until collapse. After yielding of the system lateral displacements of all elements increase without rotation and the post-yield displacements of all elements are the same. In this case the element with largest stiffness will have the largest ductility demand. In a structure with post-yield stiffness the torsional deformation and the twisting angle change after yielding. When a seismic story force V_E, higher than the yield force V_y, is acting on the structure, the post-yield rotation angle θ_{tu} can be obtained as follows considering the post-yield stiffness of the structure along y axis, a:

$$\theta_{\mathrm{tu}} = \mathrm{e_r}\frac{\mathrm{V_y}}{\mathrm{K_t}} + \mathrm{e_r}\frac{(\mathrm{V_E} - \mathrm{V_y})}{\mathrm{K_{tu}}} \tag{9}$$

$$K_{tu} = \sum y_i^2 k_{xi} + \alpha \sum x_i^2 k_{yi}. \tag{10}$$

In Fig. 1 the maximum displacements at the stiff edge, Δ_{u1}, and at the flexible edge, Δ_{u2}, are obtained as follows:

$$\begin{aligned} \Delta_{u1} &= \Delta_y + (\mu_\Delta - 1)\Delta_y - x_1\theta_{tu} \\ \Delta_{u2} &= \Delta_y + (\mu_\Delta - 1)\Delta_y + x_2\theta_{tu}. \end{aligned} \tag{11a, b}$$

According to Paulay [11], the primary aim of the design strategy for asymmetric structure should be to ensure that the expected displacement demand on the system does not exceed the displacement ductility capacity of elements. In this reasoning the ductility demand at each side, obtained as follows, should be less than or equal to the given ductility limit state, μ_L:

$$\mu_1 = \frac{\Delta_{u1}}{\Delta_{y1}} = \mu_\Delta \frac{\Delta_y}{\Delta_{y1}} - x_1 \frac{\theta_{tu}}{\Delta_{y1}} \leq \mu_L \tag{12a}$$

$$\mu_2 = \frac{\Delta_{u2}}{\Delta_{y2}} = \mu_\Delta \frac{\Delta_y}{\Delta_{y2}} - x_2 \frac{\theta_{tu}}{\Delta_{y2}} \leq \mu_L \tag{12b}$$

where μ_Δ is the ductility demand at CM.

2.2. Required damping for seismic retrofit

In this section a simple design procedure was proposed to estimate the required added damping for seismic retrofit of an asymmetric