SEISMIC RESPONSE OF TWO-WAY ASYMMETRIC BUILDING INSTALLED WITH VISCOSOUS AND FRICTON DAMPER UNDER BI-DIRECTIONAL EXCITATIONS

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Abstract: This article present a comparative study of the linearly elastic, single-storey, two-way asymmetric system under bi-directional earthquake excitation. The comparative study includes the following dampers: linear and non-linear fluid viscous dampers and semi-active friction damper. The response is obtained by numerically solving the governing equations of motion. The effect of power law coefficient, supplemental damping ratio and friction force on peak response which includes lateral, torsion displacement and acceleration are investigated. To study the effectiveness of dampers, the controlled response of asymmetric system is compared with the corresponding uncontrolled response. It is shown that the non-linear viscous dampers are quite effective in reducing the responses and the damper force depends on system asymmetry and supplemental damping. Furthermore, friction damper is more effective in reducing edge displacement and viscous damper is effective in reducing edge acceleration.

Keywords: Asymmetric building, Bi-directional excitation, Semi-active damper, Optimum.

I. INTRODUCTION

Until few years ago, most of research studies on the seismic response of plan asymmetric buildings were conducted by using uni-directional earthquake motions as input. It is well known that asymmetric-plan buildings are especially vulnerable to earthquakes. Under the earthquake loads, plane-asymmetric buildings with irregular distributions of mass or stiffness are likely to undergo torsional responses coupled with the translational vibrations. The excessive deformations in structure may lead to premature failure in brittle, nonductile elements and may result in a sudden loss of the building’s strength and stiffness leading to eventual failure. In general, excessive deformation in asymmetric-plan buildings may be reduced by redistributing the stiffness and/or mass properties to minimize the stiffness eccentricity. This attracted attention of many researchers to investigate the seismic response of asymmetric buildings with supplemental energy dissipation devices to severe damages. In the past, several studies had been done to investigate the effectiveness of viscous damper in asymmetric structures under uni-directional earthquake.
Goel [1] studied the effects of supplemental viscous damping on seismic response of one-way asymmetric system and found that edge deformations in asymmetric systems can be reduced than those of the same edges in the corresponding symmetric systems. Lin and Chopra [2] investigated understanding of how and why plan-wise distribution of fluid viscous dampers (FVDs) influences the response of linearly elastic, one-story, asymmetric-plan systems. Asymmetric distributions of supplemental damping that are more effective in reducing the response compared to symmetric distribution. Mevada and Jangid [3] investigated effect of supplementary viscous damping on response of single-storey, one-way asymmetric system and found that response of building depends on supplemental damping eccentricity ratio and eccentricity ratio.

In this paper, comparative study of the seismic response of a single-storey two-way asymmetric building model installed with PVD and SAFD dampers, subjected to bi-directional real earthquakes is investigated.

II. STRUCTURAL MODEL

The system considered is an idealized one-storey building which consists of a rigid deck supported by structural element (wall, columns, and moment-frames) shown in Figure 1. Following assumptions are made for the structural system under consideration: (i) floor of superstructure is considered as axially rigid and flexural rigid, (ii) columns are axially rigid, (iii) force-deformation relationship of superstructure is considered as linear and within elastic range, (iv) thickness of frame is neglected and (v) the structure is excited by bi-directional horizontal component of earthquake ground motion.

![Figure 1: Plan and isometric view of two-way asymmetric structure](image)

The mass of floor is assumed to be uniformly distributed and hence centre of mass (CM) coincides with the geometrical centre of the floor. The columns are arranged in a way such that it produces the stiffness asymmetry with respect to the CM in two directions and hence, the centre of rigidity (CR) is located at an eccentric distance, ex from CM in X-direction and ey from CM in Y-direction. The system is unsymmetric about both X-direction and Y-direction; therefore system has three degrees of freedom (3-DOF) are namely lateral displacement in X-direction, \( u_x \), Y-direction, \( u_y \), and torsional displacement, \( u_\theta \) as represented in Figure 1. Plan wise distribution of PVD and SAFD is symmetric about both axes. Hence the centre of supplemental damping (CSD) coincides with the centre of mass. Edge of
building near the CR is considered as stiff edge and Edge of building far from the CR is considered as flexible edge. In Figure 1. Stiff and flexible edges in X-direction and Y-direction are shown as $X_s, X_f, Y_s$, and $Y_f$ respectively.

### III. SOLUTION OF EQUATIONS OF MOTION

The governing equations of motion of the building model with coupled lateral and torsional degrees-of-freedom are obtained by assuming that the control forces provided by the dampers are adequate to keep the response of the structure in the linear range. The equations of motion of the system in the matrix form are expressed as

$$M\dot{\delta} + C\dot{\delta} + Ku = -MF\dot{u}_g + \Lambda F$$

Where $M$, $C$, and $K$ is the mass, damping and stiffness matrix of the system, respectively; $\delta = \begin{bmatrix} u_x & u_y & u_\theta \end{bmatrix}^T$ is the displacement vector; $\Gamma$ is the influence coefficient vector; $\dot{u}_g = \begin{bmatrix} \dot{u}_{gx} & \dot{u}_{gy} \end{bmatrix}^T$ ground acceleration vector; $\ddot{u}_{gx}$ is ground acceleration in X-direction and $\ddot{u}_{gy}$ is the ground acceleration in Y-direction; $\Lambda$ is the damper location matrix which depends on the location of dampers; $F = \begin{bmatrix} F_{dx} & F_{dy} & F_{d\theta} \end{bmatrix}^T$ is the vector of control forces; $F_{dx}, F_{dy}$ and $F_{d\theta}$ are resultant control forces of damper along $x$-, $y$- and $\theta$- direction, respectively.

The mass matrix can be expressed as,

$$M = \begin{bmatrix} m & 0 & 0 \\ 0 & m & 0 \\ 0 & 0 & mr^2 \end{bmatrix}$$

Where $m$ represent the lumped mass of the deck; and $r$ is the mass radius of gyration about the vertical axis through CM which is given by, $r = \sqrt{\frac{a^2 + d^2}{12}}$, where $a$ and $d$ is the plan dimension of the building.

The stiffness matrix given by A. K. Chopra book\textsuperscript{4} can be expressed as

$$K = \begin{bmatrix} k_{xx} & k_{yx} & k_{x\theta} \\ k_{yx} & k_{yy} & k_{y\theta} \\ k_{x\theta} & k_{y\theta} & k_{\theta\theta} \end{bmatrix}$$

$$k_{xx} = \sum_i k_{xi}, \quad k_{yy} = \sum_i k_{yi} \quad \text{where} \quad k_{xx} \text{ and } k_{yy} \text{ are the total lateral stiffness in } X- \text{ and } Y- \text{ direction respectively.}$$

$$k_{x\theta} = k_{\theta x} = \sum_i (y_i \times K_{xi}) \quad \text{and} \quad k_{y\theta} = k_{\theta y} = \sum_i (x_i \times K_{yi})$$

$k_{\theta\theta}$ denotes that $u_x$ and $u_y$ are uncoupled degrees of freedom.

$$k_{\theta\theta} = \sum_i k_{x_i}y_i^2 + k_{y_i}x_i^2$$

$k_{\theta\theta}$ is torsional stiffness of system about vertical axis at CM. Where $k_{x_i}$ and $k_{y_i}$ indicate the lateral stiffness of $i^{th}$ column in $x$-direction and $y$-direction respectively; $x_i$ and $y_i$ are the $x$-coordinate and $y$-coordinate distance of ith column with respect to CM respectively. The damping matrix of the system is not known explicitly and it is constructed from the Rayleigh’s damping considering mass and stiffness proportional as,

$$C = \alpha M + \beta K$$
in which α and β are the coefficients depends on damping ratio of two vibration modes. For the present study 5% damping is considered for both modes of vibration of system.

The governing equations of motion are solved using the state space method Hart and Wong \[5\] and written as,

\[
\dot{z} = A z + H F - E \ddot{u}_g \tag{7}
\]

Where \(z = \{u \ u\}^T\) is a state vector; \(A\) is the system matrix; \(H\) is distribution matrix of control force; and \(E\) is the distribution matrix of excitation. These matrices are expressed as,

\[
A = \begin{bmatrix}
0 & I \\
-M^{-1}k & -M^{-1}C
\end{bmatrix} \\
H = \begin{bmatrix}
0 \\
M^{-1}A
\end{bmatrix} \quad \text{and} \quad E = \begin{bmatrix}
0
\end{bmatrix}
\tag{8}
\]

In which \(I\) is the identity matrix.

The Eq. (7) is discretized in time domain and the excitation and control forces are assumed to be constant within any time interval, the solution may be written in an incremental form

\[
z_{k+1} = A_k z_k + H_k F_k - E_k \ddot{u}_g_k \tag{9}
\]

Where \(k\) denote the time step; and \(A_k = e^{A \Delta t}\) represent the discrete time step system matrix with \(\Delta t\) is a time interval. The constant coefficient matrices \(H_k\) and \(E_k\) are discrete time counterparts of matrices \(H\) and \(E\) and can be written as

\[
H_k = A^{-1}(A_k - I)H \quad \text{and} \quad E_k = A^{-1}(A_k - I)E
\tag{10}
\]

IV. MODELING OF DAMPER

A. Fluid Viscous Damper

Fluid dampers operate on the principle of fluid flowthrough orifices and provide forces that always resist structure motion during a seismic event. A typical viscous damper consists of a cylindrical body and central piston which strokes through a fluid filled chamber. The commonly used fluid is silicone based fluid which ensures proper performance and stability. The differential pressure generated across the piston head results in the damper force. The force in a viscous damper, \(F_{di}(= F_{df} \text{ or } F_{ds})\) is proportional to the relative velocity between the ends of a damper and given by,

\[
F_{mdi} = C_{mdi} |\ddot{u}_{di}|^\alpha \text{sgn}(\ddot{u}_{di}) \tag{11}
\]

Where, \(C_{mdi} = 2m_\omega \alpha \zeta\), \(C_{mdi}\) is damper coefficient of the \(i^{th}\) damper, \(\ddot{u}_{di}\) is relative velocity between the two end of damper which is to be consider corresponding to the position of the dampers, \(\alpha\) is the power law coefficient or damper exponent ranging from 0.1 to 1 for seismic applications and \(\text{sgn}(\cdot)\) is signum function. The value of exponent is primarily controlled by the design of piston head orifices. When \(\alpha = 1\), a damper is called a linear viscous damper (LVD) and with the value of \(\alpha\) smaller than unity, a damper will behave as nonlinear viscous damper (NLVD).

B. Semi active friction damper

A typical viscous damper may not provide maximum reduction in structural responses during a seismic event due to the dynamic nature of loading. Lu \[6\] develop an algorithm to behave a SAFD in slip state.

\[
F[k] = \alpha_f (G_z z[k-1] + G_u u[k-1] + G_w w[k-1])
\tag{12}
Where \( u_k \) is the damper friction force vector, \( \alpha_f \) is a parameter between \( 0 \leq \alpha_f \leq 1 \). \( K_b \) is a diagonal matrix where \( r \) is a number of SAFD in system \( G_d = K_b D(A_d - I), G_w = K_b D E_d \). \( D \) is a constant matrix and has a dimension of \( (r \times 2n) \) where \( n \) is a number of DOFs of the structure.

\[ G_d = K_b D(A_d - I), G_w = K_b D E_d \]

V. NUMERICAL STUDY

The seismic response of linearly elastic, idealized single-storey, two-way asymmetric building installed with passive PVD and SAFD are investigated by numerical simulation study. The response quantities of interest are lateral and torsional displacements of floor mass obtained at the CM (\( u_x, u_y \)), lateral and torsional accelerations of floor mass obtained at the CM (\( \ddot{u}_x, \ddot{u}_y \), and \( \ddot{u}_\theta \)). The response of the system is investigated under following parametric variations: additional damping (\( \xi_d \)), power law coefficient of damper (\( \alpha \)), \( K_b \), and \( \alpha_f \). The peak responses are obtained corresponding to the important parameters which are listed above for Imperial Valley (1940) earthquake ground motions with peak ground acceleration (PGA) 0.31 in EQx and 0.22 in EQy. For the study carried out herein, the aspect ratio of plan dimension is kept as unity and the mass and stiffness of system are considered such as to have required lateral time period. Further, total four dampers are installed in the building as shown in Figure 1.

In order to study the effectiveness of control system the responses are expressed in terms of indices \( Re \). The value of \( Re \) less than unity indicates that the control system is effective in reducing the responses. \( Re \) is defined as

\[ Re = \frac{\text{Peak response of controlled asymmetric system}}{\text{Peak response of corresponding uncontrolled system}} \]

Physical quantities of system for analysis are taken as follow; plan dimension of 6m×6m and storey height of 6m. Out of four column two column are of dimension 0.3m×0.3m, one column is of 0.350m×0.350m and another one column is of 0.4m×0.4m is taken, so two-way asymmetry is achieved. Total lumped mass (\( m \)) of the building is \( 4.009 \times 10^4 \) Kg.

In order to investigate the effectiveness of LVDs and NLVDs, the velocity exponent, \( \alpha \) as expressed in Eq. (11) is varied from 0.1 (highly non-linear) to 1 (linear) and damping ratio \( \xi_d \) is varied from 0% to 70%. The response are obtained for system with \( T_y = 0.5188 \) s under four considered earthquake and variations are shown in Figure 3. The response ratio, \( Re \), are obtained for displacement counterpart \( u_x, u_y, u_\theta \) acceleration counterpart \( \ddot{u}_x, \ddot{u}_y, \ddot{u}_\theta \) due to bidirectional excitation and its variation against \( \alpha \) is plotted as shown in Figure 3. It can be observed from the Figure 3 that with increase in value of \( \alpha \), the ratio, \( Re \), increases for response \( u_x, u_y \). On the other hand, with the increase in value of \( \alpha \), the ratio, \( Re \), decreases for response \( \ddot{u}_x, \ddot{u}_y \). It is also observed that torsional displacement \( u_\theta \) and torsional acceleration \( \ddot{u}_\theta \), refractor is more than 1 for \( \alpha \) between 0.1 to 0.4, so in these range of \( \alpha \) the damper is not effective to reduce response of the structure. From the results optimum value of \( \alpha \) and \( \xi_d \) are 0.5 and 60% respectively.

In order to study the effects of \( \alpha_f \) and \( K_b \) for SAFD damper, the variation of \( Re \) against \( \alpha_f \), which is varied from 0.1 to 0.99 and variation of \( Re \) against \( K_b \), which is varied from 0.1 to 5 are shown in Figure 4. It can be observed that with the increase in \( K_b \), the ratio, \( Re \), decreases.
for $u_x, u_y, \ddot{u}_x, \ddot{u}_y$, and also for torsional displacement $u_\theta$ and torsional acceleration $\ddot{u}_\theta$, it is also observed that with the increase in value of $\alpha_f$, between 0 to 0.45 $Re$ reducing for $u_x, u_y$ and $u_\theta$, and on the other hand $\alpha_f$ between 0.5 to 1 $Re$ increasing for $\ddot{u}_x, \ddot{u}_y$ and $\ddot{u}_\theta$. From the results optimum value of $\alpha_f$ and $K_\beta$ are 0.9 and 5 respectively.

![Figure 3: Effect of exponent, $\alpha$ and damping ratio $\zeta_d$, on response ratio. $Re$ for PVD various displacement and acceleration under Imperial Valley, 1940 Earthquake](image)

![Figure 4: Effect of variable, $\alpha_f$ and $K_\beta$, on response ratio. $Re$ for SAFD various displacement and acceleration under Imperial Valley, 1940 Earthquake](image)

Figure 5. Represents the typical hysteresis loops for the normalized damper force with displacement and velocity for PVD and SAFD placed at stiff edges of the building with $Ty = 0.5188$ s, under Imperial Valley, 1940 earthquake. Figure 6. shows the time histories of various displacement and acceleration responses of uncontrolled asymmetric system compared with controlled asymmetric system under Imperial Valley, 1940 earthquake.
The seismic response of linearly elastic, single-storey, two-way asymmetric building with linear and non-linear viscous dampers and semi-active friction damper under bidirectional earthquake excitations is investigated. The response is evaluated with parametric variations to study the comparative performance of LVDs, NLVDs and SAFD for asymmetric system. There are two parameters considered for PVD in investigation are additional damping ratio (\(\xi_d\)) and velocity exponent of dampers (\(\alpha\)) and another two parameters for SAFD in investigation are variable \(\alpha_f\) and \(K_b\). From the patterns of the results of the current study, the following conclusions can be made for the system considered:

1. Semi-active friction damper is more effective than Non-linear viscous damper for reducing the edge displacement and torsional displacement.
2. Non-linear viscous damper is more effective than semi-active friction damper for reducing the edge acceleration.
3. There exist optimum value for power law coefficient and damping ratio for Non-linear viscous damper.
4. Their exist optimum value for gain multiplier and stiffness coefficient for semi-active friction damper.

5. NLVDs are more effective in reducing the edge displacements than LVDs. For edge accelerations, response reduction by NLVDs and LVDs are comparatively less effective than displacements.

REFERENCES

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