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SEISMIC RESPONSE CONTROL OF ASYMMETRIC BUILDING USING FRICTION DAMPERS

S.N. Madhekar (Corresponding Author)
College of Engineering Pune, Pune-411005, India
Email: *suhasinimadhekar@gmail.com*

D.R. Tulankar
College of Engineering Pune, Pune-411 005, India
Email: *dhanashree.tulankar@gmail.com*

ABSTRACT

Friction damper dissipates energy through friction forces. During severe seismic excitations, the friction damper slips at a pre-determined load, providing the desired energy dissipation by means of friction. In the present study, Coulomb friction model of friction damper is used for response mitigation of an eight storey asymmetric building, subjected to two Indian earthquake ground motions. The eight storey building is modeled as a shear building with lateral and torsional degrees-of-freedom at each floor. The performance of the building is studied by solving the governing differential equations of motion using state space approach. The earthquake ground motions used in the study are Koyna (1967) and Bhuj (2001). While studying the uncontrolled response, it was observed that the storey drift exceeds the limit specified by IS 1893 (Part I) [1]. The efficiency of the friction dampers is investigated by installing them at different storeys. Exhaustive parametric studies are performed to identify the optimum parameters and optimum location of the dampers. The uncontrolled response of the building is then compared with the controlled response. It is observed that the friction dampers are quite effective in reducing the force and displacement-response of the asymmetric-plan eight storey building. Hence, friction dampers can be implemented for upgrading the seismic performance of existing structures.

KEYWORDS: Asymmetric Building, Friction Dampers, Seismic Response, Torsional Coupling

INTRODUCTION

Studies on the seismic response of asymmetric-plan buildings have always aroused considerable interest among the researchers. The importance of torsional effects on the seismic behavior of structures, having an irregular distribution of mass and stiffness is generally taken into account in the seismic provisions and guidelines for the design of earthquake resistant buildings.

Since early 1990, assessment studies were started to evaluate the possibilities of utilizing extra structural damping, in order to reduce the seismic demand in asymmetric buildings. Recent studies have demonstrated the effectiveness of utilizing extra structural damping control strategies in controlling both; the linear and non-linear seismic response of symmetric buildings, using passive and semi-active devices.

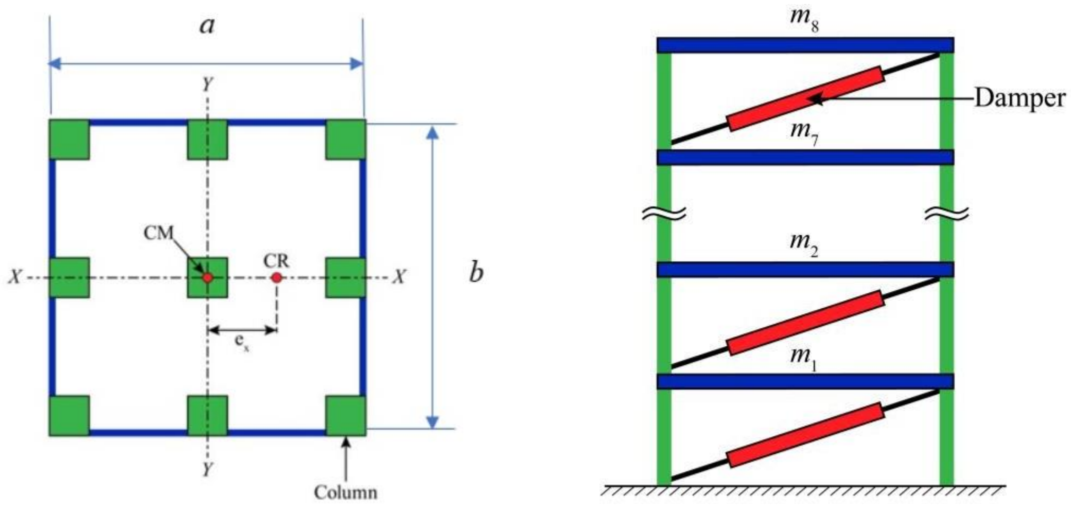
However, further research is needed to develop techniques that will control the earthquake-induced lateral and torsional deformations in asymmetric-plan buildings. The lateral and torsional deformations may lead to premature failure in brittle and non-ductile detailed elements and; may result in sudden loss of strength and stiffness of the structure, leading to complete catastrophic collapse. Excessive lateral deformations may also cause pounding between closely spaced adjacent structures.

In general, the lateral torsional response in asymmetric-plan buildings may be reduced by redistributing the stiffness and / or mass properties to minimize the stiffness eccentricity. It may not be always feasible because of stringent architectural and functional requirements. Pall [2] studied the influence of friction dampers on the seismic behavior of frames. Pekau and Dasgupta [3] studied the distribution of slip loads of the friction dampers such that their resultant strength eccentricity e_{pb} is the negative of the structural eccentricity e_s between the centers of stiffness CS and mass CM. In general, they found that, especially for strongly asymmetric buildings, maximum seismic edge response is markedly reduced if the friction damper slip loads are distributed over the plan layout of multi-storey buildings. Hanson and Soong [4] studied the design of friction damper for a shear building. Levy et al. [5] proposed the seismic design methodology for friction damped braced frames. Li et al. [6] studied, how to effectively suppress vibrations of a structure with variable friction damper using a new Bang-Bang control input. Recently, Mevada and Jangid [7] investigated the seismic response of the asymmetric building installed with semi-active friction dampers.

In the present study, the reduction in response of an eight-storey asymmetric building installed with friction dampers, subjected to two Indian earthquake ground motions, viz. Koyna (1967) and Bhuj (2001), is investigated. The response of the building installed with friction dampers is then compared with the corresponding uncontrolled response. The specific objectives of the study are: (i) to study the effect of installation of friction dampers on the seismic response of asymmetric-plan building, (ii) to investigate the effectiveness of friction dampers in controlling the lateral and torsional displacements, (iii) to study the effects of torsion with friction dampers, and (iv) to investigate the impact of critical parameters on the effectiveness of friction dampers, for the asymmetric-plan building. The key parameters considered are the eccentricity ratio of structure and the natural period of vibration.

1 Asymmetric Building Model

Figures 1 (a) and (b) respectively show the plan and elevation of an idealized eight storey asymmetric building, modeled as a shear type building. The asymmetry is introduced by arranging the columns in a way such that, the arrangement produces the stiffness asymmetry with respect to the Center of Mass (CM) in one direction. Centre of Rigidity (CR) is located at an eccentric distance, e_x from the CM in the x-direction. At each floor, two degrees-of-freedom (DOF) considered are, lateral displacement in y-direction (u_y) which is coupled with the rotational degree-of-freedom (u_θ), under uni-directional earthquake excitation along y direction.



(a) Plan (b) Elevation

Fig. 1 Schematic plan and elevation of asymmetric-plan building

The acceleration time history of Koyna earthquake (11th December, 1967) that occurred near the site of Koyna dam, is shown in Figure 2. The M 6.6 shock hit with a maximum Mercalli intensity of VIII (severe).

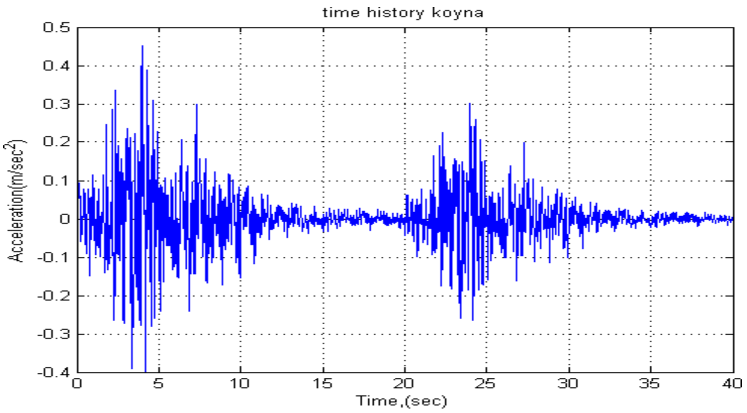


Fig. 2 Acceleration time history for Koyna earthquake (1967)

The Bhuj earthquake (26th January, 2001) lasted for over 2 minutes. The intraplate earthquake reached M 7.7 on the moment magnitude scale, and had a maximum felt intensity of X (extreme) on the Mercalli intensity scale. The acceleration time history of Bhuj earthquake is shown in Figure 3.

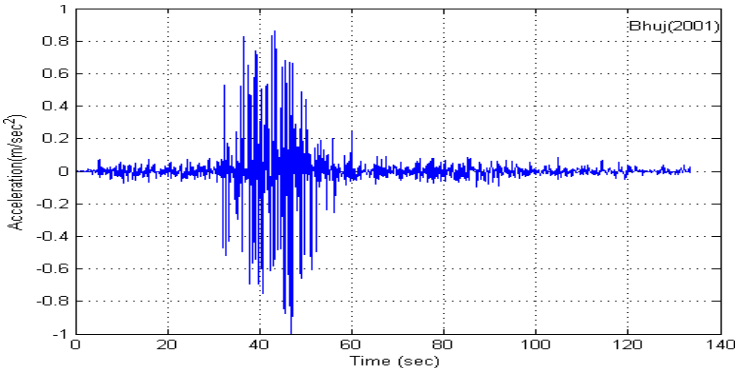


Fig. 3 Acceleration time history for Bhuj earthquake (2001)

2. Governing Equations of Motion

For the system under consideration, the governing equations of motion are obtained by considering the equilibrium of forces at the location of each DOF. The governing equations of motion for the single-degree-of-freedom (SDOF) structure with two degrees of freedom under earthquake ground acceleration are expressed in matrix form as shown in Equation (1).

$$\begin{bmatrix} m & 0 \\ 0 & I_0 \end{bmatrix} \begin{Bmatrix} \ddot{u}_y \\ \ddot{u}_\theta \end{Bmatrix} + [C] \begin{Bmatrix} \dot{u}_y \\ \dot{u}_\theta \end{Bmatrix} + \begin{bmatrix} k_y & e_x k_y \\ e_x k_y & k_{\theta\theta} \end{bmatrix} \begin{Bmatrix} u_y \\ u_\theta \end{Bmatrix} = -\begin{bmatrix} m & 0 \\ 0 & I_0 \end{bmatrix} \begin{Bmatrix} 1 \\ 0 \end{Bmatrix} \ddot{u}_{gy}(t) \tag{1}$$

where, m is the mass of the storey, $I_0 = m(a^2 + b^2)/12$, is the moment of inertia of the diaphragm about the vertical axis passing through CM, e_x is the eccentricity, k_y is the stiffness of the storey and $k_{\theta\theta}$ is the torsional stiffness of the floor.

Equation (1) is extended to get the equation of motion for eight storey one-way asymmetric multi-degree-of-freedom (MDOF) building.

$$[M]\{\ddot{X}(t)\} + [C]\{\dot{X}(t)\} + [K]\{X(t)\} = F_e(t) + [D]\{f_c(t)\} \tag{2}$$

$$F_e(t) = -[M]\{\Gamma\}\ddot{u}_g(t) \tag{3}$$

where, $[M]$ is mass matrix, $[K]$ is stiffness matrix, $[C]$ is Rayleigh's damping matrix; and $\{\ddot{X}(t)\}$ is the acceleration vector, $\{\dot{X}(t)\}$ is velocity vector, $\{X(t)\}$ is the displacement vector, $[D]$ is called the control force distribution matrix, and $\{f_c(t)\}$ is the control force vector. $F_e(t)$ is external earthquake force, given by Equation (3), $\{\Gamma\}$ is the influence vector; and $\ddot{u}_g(t)$ is the ground acceleration.

The solution of the governing equations of motion is obtained by state space method. State space method calculates the response of the system using both; displacement and velocity as independent variables. These variables are defined as states. The vector $\{z(t)\}$ represents the two states, viz. the displacement and velocity of the system. The response variables can be expressed independently as,

$$\{z(t)\} = \begin{Bmatrix} X(t) \\ \dot{X}(t) \end{Bmatrix} \tag{4}$$

For each degree of freedom, displacement and velocity are the two states. Hence, if the degree of freedom for a structure is n, then it will be $2n$ states; primary n of displacement and remaining n of velocity.

3. Seismic Vibration Control Using Energy Dissipation Devices

Seismic vibration control using energy dissipation devices is a very widely implemented practical technique. The energy dissipating devices are divided into three groups, viz. passive systems, semi-active systems, and active systems. Passive systems include base isolation and supplemental energy dissipation devices. Semi-active de- vices typically require a small external power source for operation and utilize the motion of the structure to develop the control forces; the magnitude of which can be adjusted by the external power source, such as a battery. Active control systems require high power and huge actuators; hence maintenance of continuous supply of power is practically not viable. Thus, passive and semi-active control strategies are more efficient, for field applications.

4. Friction Damper

Friction damper dissipates energy through sliding contact friction between adjoining surfaces. It is also called as hysteretic device, as its energy dissipation depends primarily on the relative displacements within the device, rather than the relative velocity. Thus, a friction damper can be modelled with force-displacement hysteretic relationship. In the present study, Coulomb friction damper model is used to control the response of the asymmetric-plan building. The force-displacement loop for a typical friction device is as shown in Figure 4.

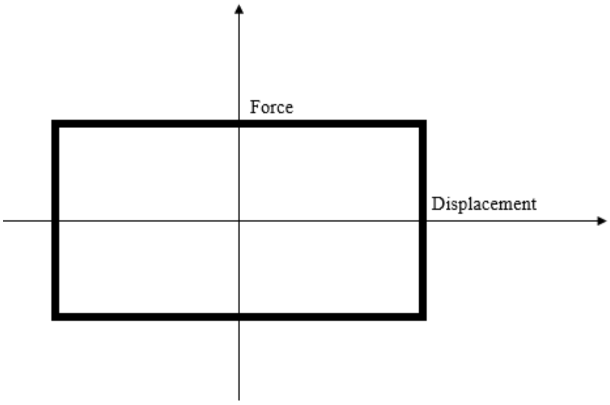


Fig. 4 Force-displacement loop for friction damper

Coulomb friction damper model is the oldest and frequently used model. In this model, the coefficient of friction remains constant and the friction force *(F)* is expressed as,

$$F = -\mu \times F_N sgn(\dot{u}) \tag{5}$$

where F_N is the normal force on the sliding surface, F is the frictional resistance, which is same for both; stick phase and sliding phase, μ is the coefficient of friction, $(\dot{u})$ is the relative sliding velocity, and *sgn* is the signum function, that assumes a value of +1 for positive sliding velocity, and –1 for negative sliding velocity. The signum function determines the direction of sliding

NUMERICAL STUDY

Seismic response of eight storey asymmetric-plan building, installed with friction dampers is investigated for the Koyna (1967) and Bhuj (2001) earthquake ground excitations. To study the effectiveness of friction dampers, they are installed at each storey. The peak controlled response is obtained and compared with the corresponding uncontrolled response.

The response of the building depends on the parameters; (i) fundamental time period (T_y), (ii) eccentricity ratio (e_x/a), (iii) ratio of the torsional and transverse frequencies, $\Omega_\theta = (\omega_\theta/\omega_y)$, (iv) aspect ratio, β (b/a), (v) natural damping ratios, ζ_1 and ζ_2, in the two vibration modes of the system, (vi) supplemental damping radius of gyration (ρ_d), and (vii) the supplemental damping eccentricity (e_d).

The input parameters considered in the present study are the mass of each storey m = 3,45,600 kg, fundamental time period T_y = 1 s, the eccentricity ratio between CM and CR of the system (e_x/a) = 0.2, considering symmetric arrangement of dampers, e_d = 0, and coefficient of friction μ = 0.04. The critical response quantities of interest are the lateral displacement (u_y), base shear (v_y), torsional displacement (u_θ), and the base torque (v_q). These response quantities are important because, floor accelerations developed in the building are proportional to the forces exerted due to earthquake ground motion. a and b are the plan dimensions of the building.

To simplify the direct comparison and to find the capabilities of the friction dampers, the response is evaluated in terms of ratio R_e and R_t. R_e is defined as the ratio of the peak controlled response of asymmetric building, to its peak uncontrolled response. The value $R_e < 1$, shows that the installed friction dampers are effective in reducing the response of the asymmetric building. To study the effect of eccentricity created due to asymmetric distribution of stiffness, ratio R_t is defined as the ratio of the peak response of the controlled asymmetric building to the peak response of the corresponding symmetric building with eccentricity, $e_d = 0$. The value of R_t indicates the effects of eccentricity on the seismic behavior of the asymmetric building. $R_t > 1$ indicates that the response of asymmetric building increases due to eccentricity, as compared to the corresponding response of the symmetric building.

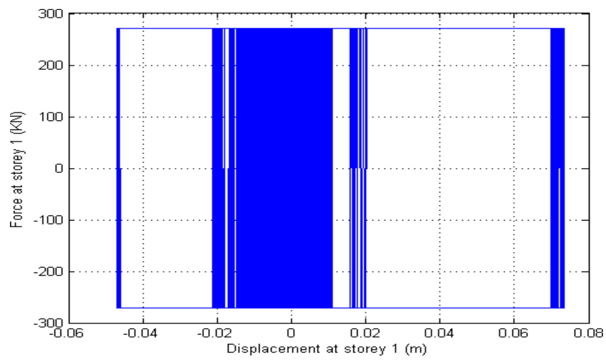
1. Effect of Eccentricity Ratio (e_x/a) on the Response Ratio (R_e)

Table 1 shows the effect of eccentricity ratio (e_x/a) on the response ratio (R_e), for all the response quantities, viz. u_y, v_y, u_θ and v_q. The value $R_e < 1$, shows that installed friction dampers are effective in reducing the response of the asymmetric building. It is also noticed that the reduction in lateral displacement is substantial, as compared to the torsional displacement. When friction dampers are installed, there is more reduction in the base shear, than the base torque. As the eccentricity ratio (e_x/a) increases, the response ratio (R_e) for the lateral and torsional displacement increases. It is observed from Table 1 that, with the increasing eccentricity ratio (e_x/a), the effectiveness of the installed friction dampers decreases.

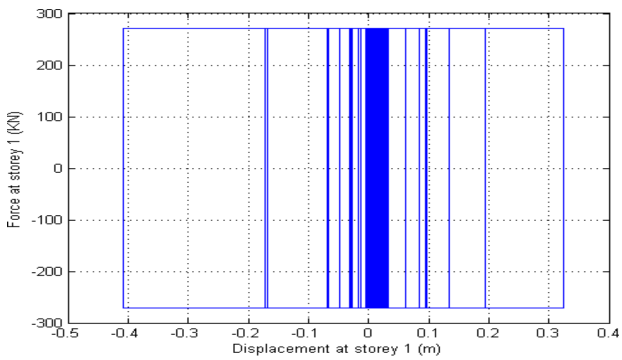
Table 1: Effect of eccentricity ratio (e_x/a), on the response ratio (R_e) with friction dampers

Earthquake	Koyna (1967)				Bhuj (2001)			
e_x/a	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4
Lateral displacement (m)	0.96	0.98	0.71	0.99	2.60	2.58	2.43	3.06
Controlled lateral displacement (m)	0.10	0.19	0.20	0.20	0.10	1.11	1.65	1.89
R_e	**0.10**	**0.19**	**0.28**	**0.20**	**0.04**	**0.43**	**0.68**	**0.62**
Torsional Displacement (m)	0.16	0.17	0.19	0.21	0.56	0.45	0.65	0.82
Controlled torsional displacement (m)	0.04	0.07	0.09	0.12	0.09	0.29	0.5	0.65
R_e	**0.27**	**0.38**	**0.50**	**0.58**	**0.17**	**0.64**	**0.77**	**0.80**
Base shear × 10^3 (kN)	5.43	5.95	6.32	6.52	13.33	13.18	13.77	14.75
Controlled base shear × 10^3 (kN)	4.25	4.49	5.49	6.07	5.13	7.50	9.661	10.97
R_e	**0.78**	**0.75**	**0.87**	**0.93**	**0.39**	**0.57**	**0.70**	**0.74**
Base torque × 10^3 (kNm)	1.43	1.45	1.47	1.50	4.87	4.62	4.90	5.12
Controlled base torque × 10^3 (kNm)	1.20	1.30	1.32	1.37	1.59	2.06	3.23	4.61
R_e	**0.84**	**0.90**	**0.90**	**0.92**	**0.33**	**0.45**	**0.66**	**0.90**

Force-displacement loops for Koyna (1967) and Bhuj (2001) ground motion are shown in Figure 5. Figure 6 shows the variation of response ratio (R_e) with the eccentricity ratio (e_x/a), for both earthquakes.

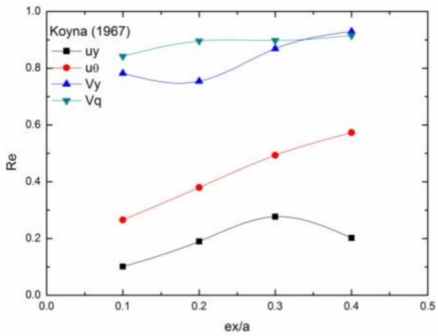


Koyna Earthquake (1967)



Bhuj Earthquake (2001)

Fig. 5 Force displacement loops for Koyna (1967) and Bhuj (2001) earthquakes



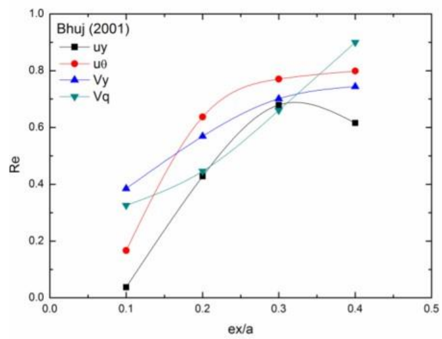


Fig. 6 Variation of response ratio (R_e) with eccentricity ratio (e_x/a) for Koyna and Bhuj earthquakes

2. Effect of Fundamental Time Period (T_y) on the Response Ratio (R_e)

The variation of response ratio (R_e) against fundamental time period (T_y) with inter- mediate value of eccentricity ratio (e_x/a = 0.2), and with $\Omega_\theta = 1$ is presented in Table 2 and Table 3, for Koyna and Bhuj earthquakes, respectively. The value of T_y is varied from 0.25 s to 3 s, representing the variation from stiff to flexible structural systems. The values of response ratio (R_e) obtained are less than one for friction dampers. This indicates that the installed friction dampers are quite effective in reducing the torsional, and the lateral displacements of stiff and flexible structural systems. Further, with the increase in T_y, the ratio R_e for lateral and torsional displacement increases which indicates that the effectiveness of the friction dampers decreases for the stiff structural systems. Figure 7 shows the variation of response ratio R_e, against time period T_y.

Table 2: Effect of time period (T_y) on the response ratio (R_e) with friction fampers for Koyna (1967) earthquake

T_y (s)	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
Lateral displacement (m)	0.69	1.29	0.92	0.96	1.38	1.57	1.29	1.40	1.32	1.27	1.28	1.11
Controlled Lateral displacement (m)	0.15	0.14	0.14	0.09	0.17	0.21	0.32	0.37	0.38	0.41	0.44	0.52
R_e	**0.22**	**0.11**	**0.15**	**0.10**	**0.12**	**0.13**	**0.25**	**0.27**	**0.29**	**0.32**	**0.35**	**0.47**
Torsional displacement (m)	0.13	0.19	0.23	0.16	0.20	0.25	0.17	0.23	0.26	0.25	0.21	0.23
Controlled torsional displacement (m)	0.05	0.04	0.06	0.04	0.08	0.09	0.11	0.12	0.13	0.14	0.12	0.14
R_e	**0.35**	**0.24**	**0.27**	**0.27**	**0.42**	**0.35**	**0.62**	**0.51**	**0.50**	**0.56**	**0.51**	**0.60**
Base shear × 10^3 (kN)	12.95	8.54	6.86	5.43	5.84	5.53	5.22	5.00	4.82	4.75	4.71	4.68
Controlled base shear × 10^3 (kN)	6.33	5.36	6.168	4.25	5.17	5.13	5.07	4.95	4.59	4.48	4.44	4.38
R_e	**0.49**	**0.63**	**0.90**	**0.78**	**0.88**	**0.93**	**0.97**	**0.99**	**0.95**	**0.94**	**0.94**	**0.94**
Base torque × 10^3 (kNm)	2.20	1.68	1.60	1.43	1.31	1.21	1.16	1.17	1.14	1.12	1.11	1.10
Controlled Base torque × 10^3 (kNm)	1.82	1.40	1.41	1.20	1.04	0.85	0.85	0.92	0.87	0.90	0.94	0.95
R_e	**0.83**	**0.83**	**0.88**	**0.84**	**0.79**	**0.70**	**0.73**	**0.79**	**0.76**	**0.80**	**0.85**	**0.87**

Table 3: Effect of time period (T_y) on the response ratio, R_e with friction dampers for Bhuj (2001) earthquake.

T_y (s)	0.25	0.5	0.75	1	1.25	1.5	1.75	2	2.25	2.5	2.75	3
Lateral displacement (m)	5.81	5.81	3.40	2.56	2.32	1.98	1.36	1.15	1.24	1.09	0.88	0.85
Controlled Lateral displacement (m)	0.11	0.38	0.24	0.01	0.89	0.83	0.79	0.97	1.12	1.04	0.83	0.81
Re	**0.02**	**0.07**	**0.077**	**0.04**	**0.38**	**0.42**	**0.58**	**0.84**	**0.91**	**0.96**	**0.94**	**0.96**
Torsional displacement (m)	0.79	1.09	0.84	0.56	0.45	0.51	0.42	0.41	0.46	0.47	0.42	0.39
Controlled torsional displacement (m)	0.04	0.09	0.10	0.09	0.18	0.25	0.29	0.31	0.36	0.39	0.35	0.34
R_e	**0.05**	**0.08**	**0.12**	**0.17**	**0.37**	**0.50**	**0.68**	**0.76**	**0.79**	**0.82**	**0.84**	**0.87**
Base shear × 10 ^{3} (kN)	43.91	28.14	16.22	13.32	12.04	10.95	9.87	9.48	9.55	9.05	9.02	8.80
Controlled base shear × 10 ^{3} (kN)	31.03	18.6	9.66	5.13	9.94	8.92	8.65	8.25	8.07	7.95	8.17	8.08
R_e	**0.71**	**0.66**	**0.60**	**0.39**	**0.83**	**0.81**	**0.88**	**0.87**	**0.85**	**0.88**	**0.91**	**0.92**
Base torque × 10^3 (kNm)	8.57	6.75	5.25	4.87	4.62	4.55	4.49	4.30	4.19	4.20	4.19	4.17
Controlled base torque × 10^3 (kNm)	6.45	5.27	3.79	1.59	2.11	2.58	2.85	3.39	3.77	3.40	3.40	3.40
R_e	**0.75**	**0.78**	**0.72**	**0.33**	**0.46**	**0.57**	**0.64**	**0.79**	**0.90**	**0.81**	**0.81**	**0.82**

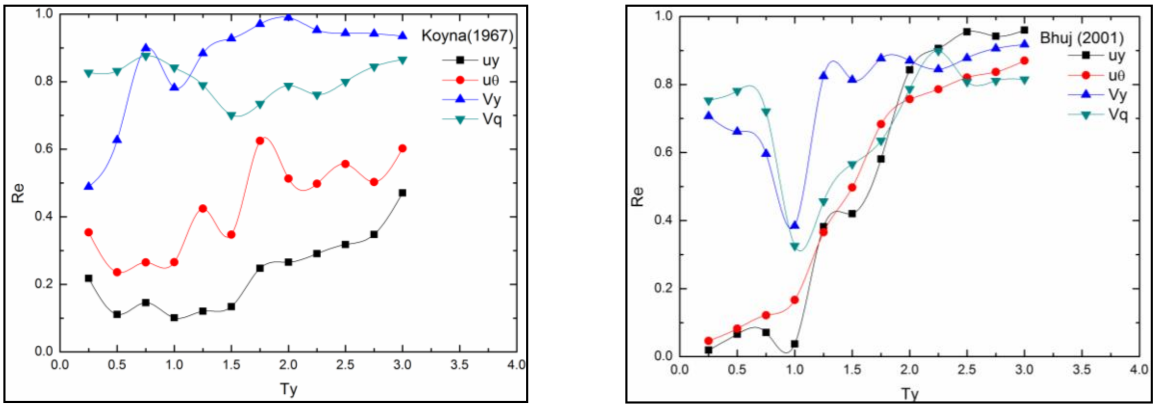


Fig.7 Variation of response ratio (R_e) with time period (T_y)

3. Effect of Eccentricity Ratio (e_x/a) and Fundamental Time Period (T_y) on the Response Ratio (R_t)

Figure 8 illustrates the effect of eccentricity on the seismic response. The response ratio (R_t) is plotted against eccentricity ratio, (e_x/a) and fundamental time period (T_y) for strongly coupled systems. The value of R_t reflects the effect of eccentricity created due to asymmetric distribution of stiffness on the seismic behavior of the building. $R_t > 1$ shows that the response of asymmetric building increases due to eccentricity.

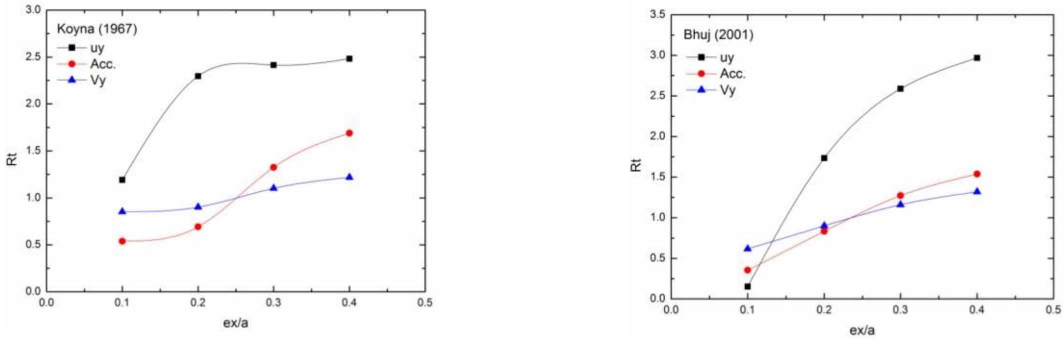


Fig. 8 Variation of response ratio (R_t) with eccentricity ratio (e_x/a)

CONCLUSIONS

The seismic response of eight storey asymmetric-plan building installed with friction dampers is investigated analytically under the horizontal component of Koyna and Bhuj earthquake ground motions. The seismic response of the building with friction dampers is evaluated using the state space approach and the developed MATLAB codes. The comparison of controlled and uncontrolled peak seismic response of the building in- stalled with friction dampers is completed, in order to verify the effectiveness of the friction dampers. With the installation of friction dampers in the asymmetric-plan building, the lateral displacement (u_y) and the torsional displacement (u_θ) due to earthquake ground motion can be controlled within a desirable range. From the trend of the results of the present study, following conclusions are drawn:

1. It is noticed that when the dampers are installed up to seven storeys, the reduction in overall seismic response of the building is considerable, with minimum requirement of damping force. Hence, this configuration is the optimal one.
2. For strongly coupled systems with $\Omega_\theta = 1$, the effectiveness of friction dampers decreases with the increase in the eccentricity ratio.
3. With variation of the eccentricity ratio, it is also observed that there is greater reduction in the base shear than the base torque, when friction dampers are installed.
4. The value of $R_e < 1$ shows that the dampers are effective in reducing the torsional response.
5. For stiff to flexible (T_y = 0.25 s to 3 s) structural systems, value of $R_e < 1$. This indicates that the installed friction dampers are quite effective in reducing the torsional and the lateral displacements of stiff and flexible structural systems.
6. The value of R_t reflects the effect of eccentricity created due to asymmetric distribution of stiffness on the seismic behavior of the building. $R_t > 1$ shows that the response of asymmetric building increases due to eccentricity.

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