Probabilistic Evaluation of Seismically Isolated Building Using Quintuple Friction Pendulum Isolator

Ankit Sodha, Sandip A. Vasanwala and Devesh Soni

Abstract Multiple-level performance of building provided with seismic isolation by Quintuple Friction Pendulum Isolator (QTFP) is investigated multiple-level seismic hazards (design basis earthquake (DBE), service level earthquake (SLE), and maximum considered earthquake (MCE)). Five independent pendulum mechanisms along with six concave surfaces are included in this isolator. The paper describes nonlinear mathematical model and seismic response of isolated with Quintuple friction pendulum bearing. To control the demand of super-structure in different hazard levels, QTFP represents a novel invention of multi-phase adaptive friction pendulum isolation system. Total six design configurations of Quintuple Friction Pendulum isolator results from two different displacement capacities and three types of effective period and effective damping are considered. Probabilistic study of engineering demand parameters like isolator displacement, base shear for the isolated building, and top floor absolute acceleration under different levels of seismic hazards are to be carried out. It is found that, Quintuple Friction Pendulum isolator is very effective in all different level of seismic hazards under all seismic demand parameters.

Keywords Seismic isolation · Quintuple friction pendulum system · Probabilistic evaluation · Multi-hazard level earthquake

1 Introduction

Research works in the last one decade is focused on the utilization of frictional type of base isolation. Its effectiveness for a wide range of frequency input is the reason for

A. Sodha (✉) · S. A. Vasanwala
Applied Mechanics Department, Sardar Vallabhbhai National Institute of Technology Surat Ichchhanath, Surat, Gujarat 395007, India
e-mail: aankitsodha@gmail.com

D. Soni
Department of Civil Engineering, Sardar Vallabhbhai Patel Institute of Technology, Vasad, Anand District, Gujarat 388306, India

D. Deb et al. (eds.), *Innovations in Infrastructure*, Advances in Intelligent Systems and Computing 757, https://doi.org/10.1007/978-981-13-1966-2_13

its popularity in the domain of base isolation. Resilient-friction base isolator system [1] and friction pendulum system [2] are the force restoring devices, performing based on the concept of sliding friction. A variety of restoring force devices such as Recently, a concept of multiple friction pendulum systems has been introduced with a view to reduce heat due to friction, to increase displacement capacity and to exhibit adaptive behavior compare to friction pendulum system [3]. With reference to above advantages, Double Concave Friction Pendulum (DCFP) bearing with two concave surfaces [4] and Triple Friction Pendulum (TFP) bearings with four sliding surfaces have been developed [5–7]. To optimize the performance in terms of coefficients of friction for different sliding surfaces and radius of curvature, the DCFP and TFP offers the designer extra design parameters. Further, the isolation system with multiple surfaces having elliptic sliding geometry has also been studied to avoid tuning of isolation frequency with excitation frequency [8].

Very recently developed Quintuple Friction Pendulum (QTFP) bearing [9] is an extension of the FP isolator consisting of four spherical sliding surfaces. It offers a more complex multi-stage behavior than the FP isolator, which may be implemented to control the response of the isolated structure when advanced performance objectives are considered or when the isolator displacement demand needs to be within acceptable limits during very strong seismic event.

2 Adaptive Behavior Quintuple Friction Pendulum Bearing

Quintuple Friction Pendulum (QTFP) isolator is an extended technology of Triple Friction Pendulum (TFP) isolator having nine stage sliding regimes operation with five effective pendula. Quintuple Friction Pendulum system shows highly adaptive behavior, due to its distinct hysteretic properties for different stages of displacement. As shown in Fig. 1, d_i is the displacement capacity for surface i, R_i is the radius of curvature of surface i, and μ_i is the coefficient of friction at the sliding interface. The motion due to internal construction of these bearings with different combinations of sliding surfaces, resulting in changes of stiffness and damping [4].

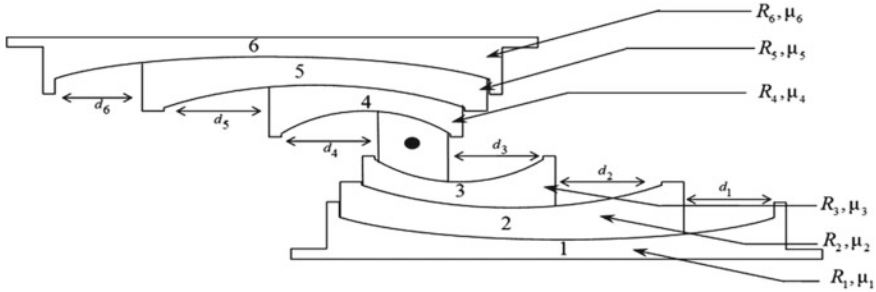

Fig. 1 Schematic diagram of QTFP

2.1 Different Stages of Sliding for QTFP

A generic model comprises the sloshing, impulsive, and rigid masses in terms of liquid mass and QTFP bearing is considered to explore the seismic performance of Isolated Building using QTFP. Different levels of excitation at different stages of sliding have been illustrated (refer Fig. 1):

Stage I: Motion starts on surfaces 3 and 4. Motion occurs on surfaces 3 and 4.
Stage II: Motion stops on 4 and starts on 5. Motion occurs on surfaces 3 and 5.
Stage III: Motion stops on 3 and starts on 2. Motion occurs on surfaces 2 and 5.
Stage IV: Motion stops on 5 and starts on 6. Motion occurs on surfaces 2 and 6.
Stage V: Motion stops on 2 and starts on 1. Motion occurs on surfaces 1 and 6.
Stage VI: Motion reaches end on 6 and stops. Motion starts on 5. Motion occurs on surfaces 1 and 5.
Stage VII: Motion reaches end on 1 and stops. Motion starts on 2. Motion occurs on surfaces 2 and 5.
Stage VIII: Motion reaches end on 5 and stops. Motion starts on 4. Motion occurs on surfaces 2 and 4.
Stage IX: Motion reaches end on 2 and stops. Motion starts on 3. Motion occurs on surfaces 3 and 4.

3 Governing Equation of Motion and Its Solution

For an N-story superstructure total dynamic Degree-of-freedom (DOF) considering one DOF at each floor is $N + 5$, owing to five friction pendulum elements connected in series in the QTFP. Therefore, the governing equations of motion in matrix structure are expressed as

$$[M]\{\ddot{u}\} + [K]\{\dot{u}\} + [C]\{u\} = -[M]\{r\}(\ddot{u}_b + \ddot{u}_g) \tag{1}$$

where $[M]$, $[K]$, and $[C]$ are N sized square matrices for mass, stiffness, and damping of the superstructure, respectively. $\{u\} = \{u1, u2, \ldots uN\}$ is the vector of relative displacement of the superstructure; $u1, u2, \ldots uN$ is the floor lateral displacement relative to the base; $\ddot{u}g$ is the ground acceleration of earthquake; and here, derivative with respect to time is indicated by over dots; $\{r\} = \{1, 1,\ldots\}$ is the influence coefficient vector; $\ddot{u}b$ is the base mass acceleration relative to ground.

To solve the above equations, the incremental form of Newmark's step-by-step method is adopted. It was assumed that the linear variation of acceleration with small time interval was 1×10^{-6} s. Further, for each time step of incremental hysteretic displacement components in hysteretic model are solved by fourth-order Runge–Kutta method.

4 Earthquake Ground Motions

The present study is focused on the investigation of multi-stage performance of seismically isolated Building over different hazard levels, using Quintuple Friction Pendulum Isolator (QTFP). To achieve this objective, a suite of time history developed for Boston, Seattle, and Los Angeles which represents a range of seismic hazard levels from seismic Zone 2 to Zone 4 has been selected. They are comprised of three probabilities of occurrence: service level earthquake (50% in 50 years), design basis earthquake (10% in 50 years), and maximum considered earthquake (2% in 50 years) and (Somerville et al. [10]). It provides an effective mean of study for the multi-stage performance of QTFP with various frequency content and intensities. Table 1 shows the suite of 60-time histories for Los Angeles used in this study.

Table 1 Multiple hazard level ground motions [10]

SLE		DBE		MCE	
Record Label	Scale Factor	Record Label	Scale Factor	Record Label	Scale Factor
LA41	0.590	LA01	0.461	LA21	1.283
LA42	0.333	LA02	0.676	LA22	0.921
LA43	0.143	LA03	0.393	LA23	0.418
LA44	0.112	LA04	0.488	LA24	0.473
LA45	0.144	LA05	0.302	LA25	0.868
LA46	0.159	LA06	0.234	LA26	0.944
LA47	0.337	LA07	0.421	LA27	0.927
LA48	0.308	LA08	0.426	LA28	1.330
LA49	0.318	LA09	0.520	LA29	0.809
LA50	0.546	LA10	0.360	LA30	0.992
LA51	0.781	LA11	0.665	LA31	1.297
LA52	0.632	LA12	0.970	LA32	1.297
LA53	0.694	LA13	0.678	LA33	0.782
LA54	0.791	LA14	0.657	LA34	0.681
LA55	0.518	LA15	0.533	LA35	0.992
LA56	0.379	LA16	0.580	LA36	0.101
LA57	0.253	LA17	0.569	LA37	0.712
LA58	0.231	LA18	0.817	LA38	0.776
LA59	0.769	LA19	1.019	LA39	0.500
LA60	0.478	LA20	0.987	LA40	0.657

5 Numerical Study and Results

To study adaptive behavior of QTFP, the example building was subjected to three levels of ground excitations, LA 42 (SLE), LA 1 (DBE), and LA 27 (MCE). The hysteresis behavior for each level of earthquake is shown in Figs. 2, 3, and 4 for the QTFP1-6 having time period of 4–6 s and damping of 10 to 20% as shown in Table 2.

The isolator deforms into sliding regimes I and II, with rigid linear behavior of force deformation. As radius of curvature of inner surfaces is relatively smaller, the isolator stiffens during SLE. The isolator deforms into sliding regime III and IV with rigid bi-linear behavior during DBE. The isolator deforms into sliding regimes V–IX.

For SLE, The inner sliding surfaces 3 and 4 with lower value of coefficient of friction get activated, as the lateral force acting on isolator is comparatively low (Fig. 3).

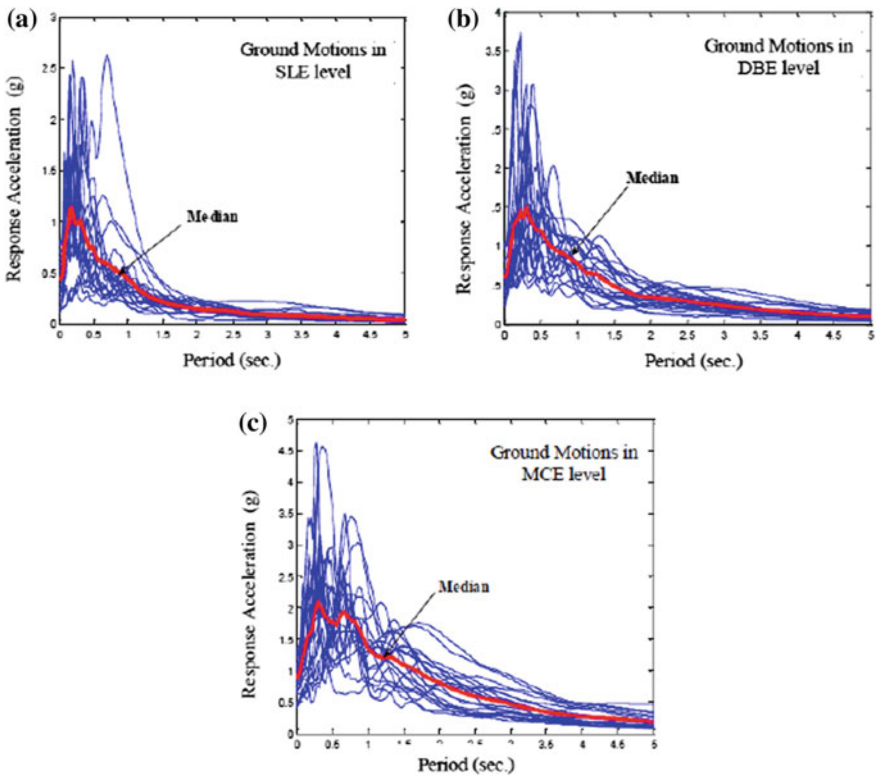

Fig. 2 Response acceleration spectra. **a** SLE, **b** DBE, and **c** MCE

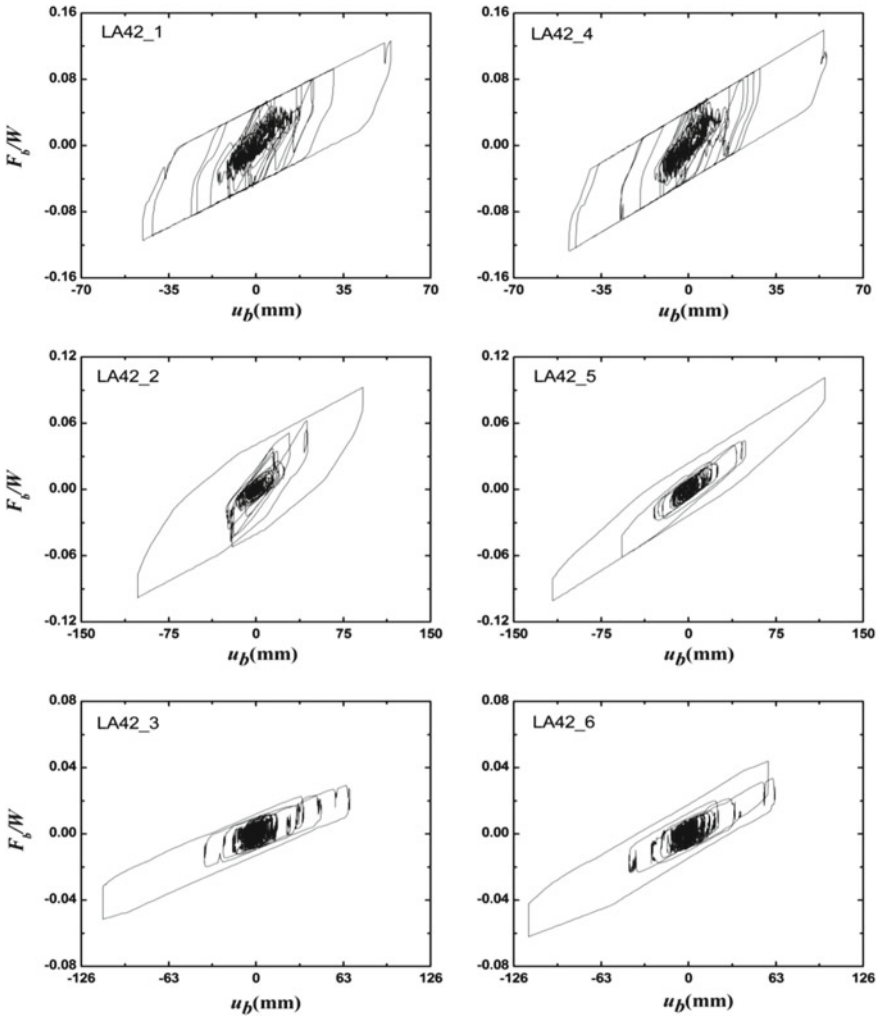

Fig. 3 Hysteretic behavior of QTFP1 to QTFP6 under LA 42 (SLE)

For DBE earthquake, due to increased lateral force after motion stops on surfaces 3, it starts on surfaces 2 further increases in lateral force the motion occurs on surfaces 2 and 5 then again motion stops on 5 and starts on 6 then motion occurs on surfaces 2 and 6 (Fig. 4).

The lateral force is so large to start motion on surface 1. Surface 1 has the largest friction during MCE event. Increasing in lateral force further, the motion occurs on surfaces 1 and 6; and the motion on surface 2 stops (Fig. 5).

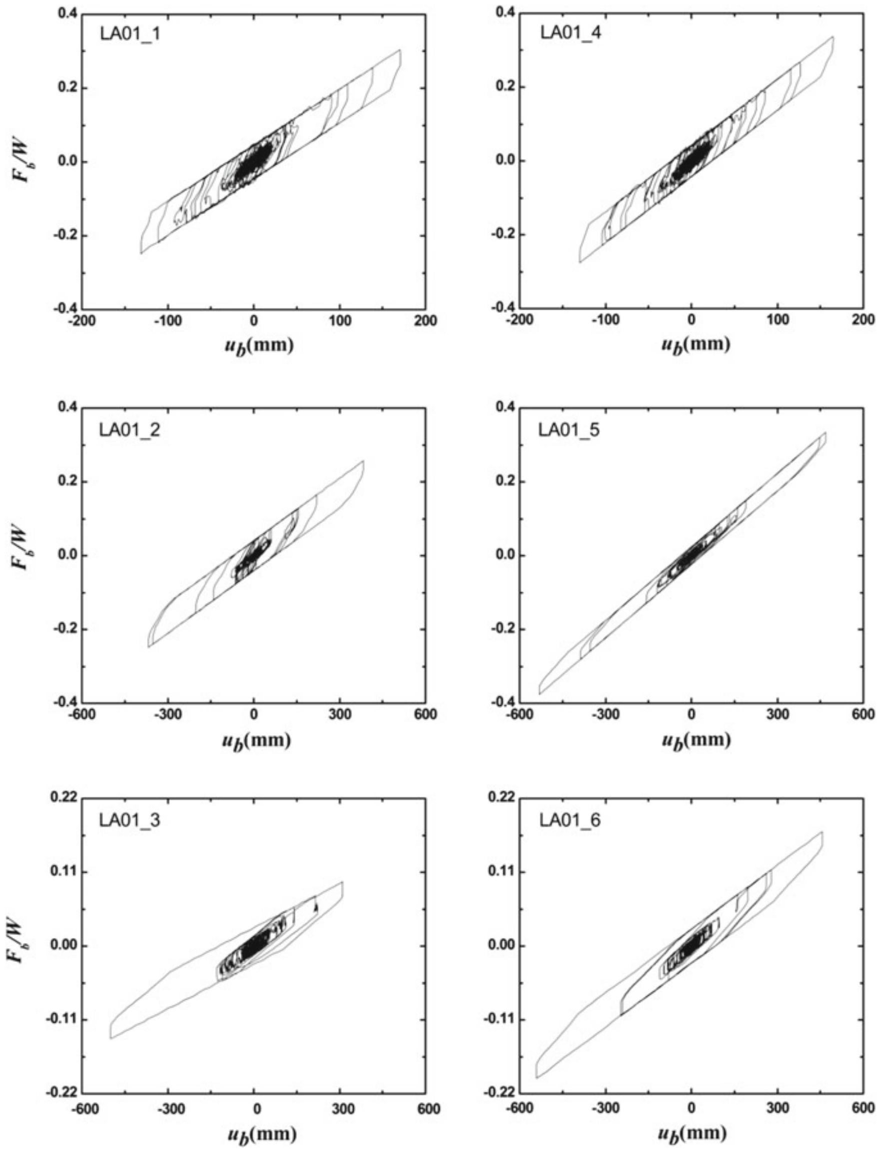

Fig. 4 Hysteretic behavior of QTFP1 to QTFP6 under LA 1 (DBE)

Table 2 Properties of the six QTFP design configurations

Q	ξ	T	R_1	R_2	$R_3=_4$	R_5	R_6	μ_1	μ_2	$\mu_{3,4}$	μ_5	μ_6
1	10	4	2.8	0.8	0.1	0.7	2	0.09	0.05	0.01	0.04	0.06
2	15	5	4.5	2	0.25	1.5	4	0.09	0.06	0.01	0.04	0.07
3	20	6	7.5	3.5	0.3	4	6	0.1	0.05	0.01	0.04	0.09
4	10	4	2.5	0.8	0.1	0.7	2	0.07	0.05	0.01	0.04	0.05
5	15	5	4.5	2.7	0.25	2	3.5	0.07	0.04	0.01	0.05	0.06
6	20	6	6.5	3.5	0.3	3	5	0.07	0.05	0.01	0.04	0.06

ξ = damping (%), Q = QTFP, T = time period (s)

5.1 Performance of QTFP Under Annual Probability of Exceedance

The responses are categorized for three different annual probabilities of earthquake occurrences, named MCE (2% in 50 year), DBE (10% in 50 year), and SLE (50% in 50 year). Seismic responses of Configurations QTFP1 to QTFP6 are plotted as per suits of time histories of annual probability of exceedance.

As shown in Fig. 6, three responses termed as peak acceleration, normalized base shear, and peak isolator displacement have been plotted against annual probability of exceedance. It is observed from the graph that peak accelerations and normalized base shear are maximum for minimum values of damping, time period and displacement capacity. In contrast with these observations, peak isolator displacement is witnessed to be minimum for the minimum values of damping, time period, and displacement capacity.

6 Conclusion

Presented in this paper is the behavior of QTFP system using nonlinear time history analysis with multi-hazard level excitation and directivity focusing earthquakes. The MDOF system is analyzed for 60 multi-hazard earthquake records consist of 20 SLE, 20 DBE, and 20 MCE records;

1. The QTFP bearing stiffens at low input with service level earthquake (SLE), softens with increasing input of design basis earthquake (DBE), It gets stiffens at higher levels of input with maximum considered earthquake (MCE) again. Thus, it shows highly adaptive behavior, despite being a passive system.
2. With the increase in displacement capacity, isolator displacement increases and base shear decreases for all three events.
3. The QTFP can be very useful in controlling the response parameters of a seismically isolated building due to its six spherical sliding surfaces, five effective

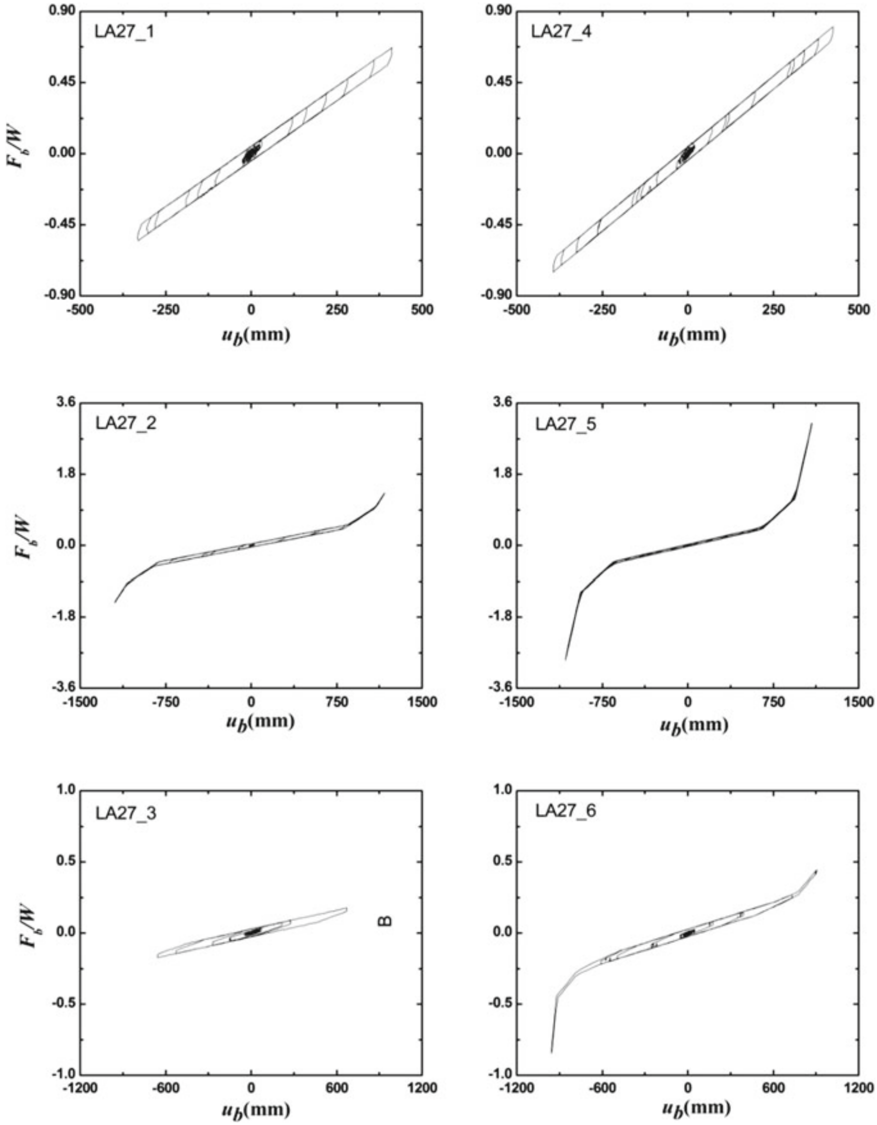

Fig. 5 Hysteretic behavior of QTFP1 to QTFP6 under LA 27 (MCE)

pendula, which can provide an engineer greater flexibility for the selection various design parameters to optimize the isolator performance.

4. Maximum peak accelerations and normalized base shear with minimum peak isolator displacement are observed for minimum values of damping, time period and displacement capacity.

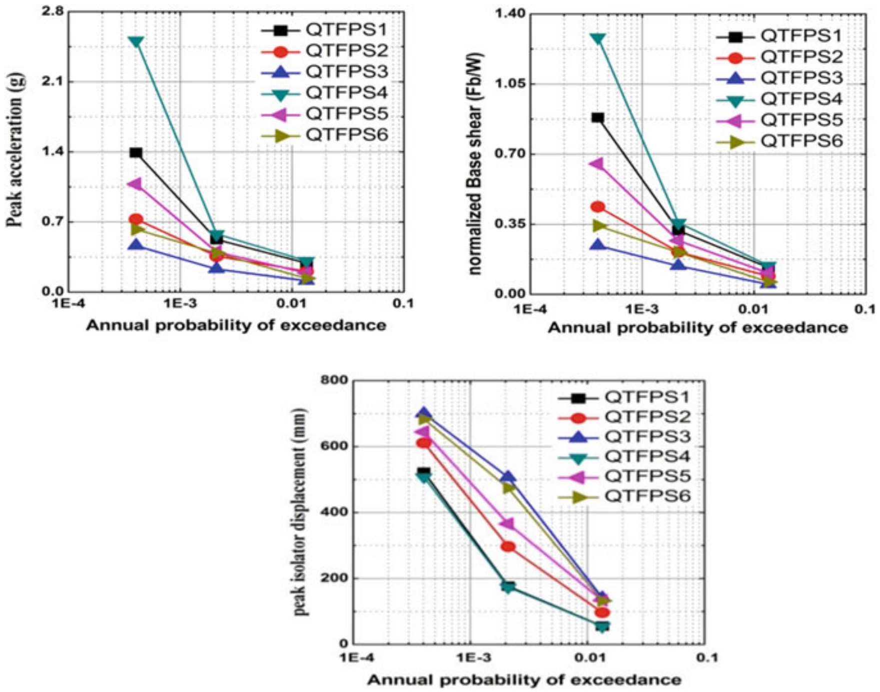

Fig. 6 Comparison of seismic responses for annual probability of exceedance of QTFP1 to QTFP6

References

1. Mostaghel, N., Khodaverdian, M.: Dynamics of resilient-friction base isolator (R-FBI). Earthq. Eng. Struct. Dyn. **15**(3), 379–390 (1987)
2. Zayas, V.A., Low, S.S., Mahin, S.A.: A simple pendulum technique for achieving seismic isolation. Earthq. Spectra **6**(2), 317–333 (1990)
3. Tsai, C.S., Lin, Y.C., Su, H.C.: Characterization and modeling of multiple friction pendulum isolation system with numerous sliding interfaces. Earthq. Eng. Struct. Dyn. **39**(13), 1463–1491 (2010)
4. Fenz, D.M., Constantinou, M.C.: Behaviour of the double concave friction pendulum bearing. Earthq. Eng. Struct. Dynam. **35**(11), 1403–1424 (2006)
5. Fenz, D.M., Constantinou, M.C.: Modeling triple friction pendulum bearings for response-history analysis. Earthq. Spectra **24**(4), 1011–1028 (2008)
6. Becker, T.C., Mahin, S.A.: Approximating peak responses in seismically isolated buildings using generalized modal analysis. Earthq. Eng. Struct. Dyn. **42**(12), 1807–1825 (2013)
7. Dhankot, M.A., Soni, D.P.: Behaviour of triple friction pendulum isolator under forward directivity and fling step effect. KSCE J. Civil Eng. **21**(3), 872–881 (2017)
8. Soni, D.P., Mistry, B.B., Jangid, R.S., Panchal, V.R.: Seismic response of the double variable frequency pendulum isolator. Struct. Control Health Monit. **18**(4), 450–470 (2011)

9. Lee, D., Constantinou, M.C.: Quintuple friction pendulum isolator-behavior, modeling and validation. Technical Report MCEER-15-0007, Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, Buffalo, NY (2015)
10. Somerville, P., Anderson, D., Sun, J., Punyamurthula, S., Smith, N.: Generation of ground motion time histories for performance-based seismic engineering. In: Proceedings 6th National Earthquake Engineering Conference. Seattle, Washington (1998)