Kalpa Publications in Civil Engineering
Volume 1, 2017, Pages 16–29
ICRISET2017. International Conference on Research and Innovations in Science, Engineering &Technology. Selected papers in Civil Engineering

Impact Response of Base Isolated Building with Adjacent Structures

Niraj V. Shinde[1]Devesh P. Soni[2]
[1]P.G. Student, [2] Professor & Head, Department of Civil Engineering,
Sardar Vallabhbhai Patel Institute of Technology, Vasad-388306, Gujarat, India.
niraj.15mecisg001@gmail.com, devesh18@gmail.com

Abstract

The seismic behavior of multi-storied building supported on Friction pendulum system (FPS) during impact with adjacent structure is examined. One lateral degree of freedom is considered at each floor, base mass and slider. Adjacent structure (i.e. retaining walls or entry bridges) is modeled as an impact element in form of spring and dashpot. The impact response of FPS bearing is studied under 60 records consisting of service level, design basis and maximum credible earthquakes. Newmark's step by step iteration method is used to solve the differential equations of motion for the isolated system. The impact response of isolated building is studied under the variation of important system parameters such as size of gap and stiffness of impact element. To reduce the influence of impact a viscous damper is employed between the isolated building and adjacent structure. It is concluded that during impact with adjacent structure the superstructure acceleration and base shear increases while bearing displacement decreases. The employment of viscous damper shows considerable reduction in bearing displacements, base shear and impact force during DBE and MCE events. Further, the effects of impact are found critical if the superstructure is flexible and greater stiffness of impact element. The top floor acceleration increases with the isolation gap up to certain limit and again reduces with the increase in isolation gap.

Keywords - Adjacent Structure; isolation; Sliding bearing; Viscous Damper; Gap effect; Floor acceleration; Impact

C.D. Modhera, G.J. Joshi, D. Soni, I.N. Patel, A.K. Verma, L.B. Zala, S.D. Dhiman, D.R. Bhatt, J.M. Rathod, B.C. Goradiya, M.S. Holia and D.K. Patel (eds.), ICRISET2017 (Kalpa Publications in Civil Engineering, vol. 1), pp. 16–29

1 Introduction

Seismic isolation is becoming more effective solution for protecting structure from earthquakes. The principle of isolation is to decouple the structure from ground and hence reducing the forces transmitted to super structure. Due to this novel idea, varieties of isolation systems are developed such as Elastomeric bearings, sliding bearings and roller bearings to study the effectiveness of base isolation. In isolated structures, addition of flexible layer between superstructure and foundation increases the fundamental time period of system to a value higher than predominant energy containing time periods of earthquake ground motions. A significant amount of research in base isolation is focused on the effectiveness of friction type sliding systems. The advantage of a frictional type system is that it ensures maximum acceleration transmissibility equal to maximum limiting frictional force.

However, the provision of excessive flexibility at isolation system to minimize the superstructure acceleration may lead to impact [1]. Further in long buildings if the provided expansion gap is not sufficient to accommodate the isolator displacements, there are likely chances of impact to occur at the expansion gapes when buildings vibrate out of phase. Such impact incidences were noted during 1994 Northridge earthquake resulting higher accelerations in superstructure than predicted accelerations [2].

Matsagar and Jangid [3] carried out the seismic response of multi-storeyed base isolated building during impact with adjacent structure by varying various system parameters such as flexibility of superstructure, number of story, stiffness of adjacent structure and size of isolation gap for different isolation systems. The effect of impact is found to be critical for the system with flexible super structure, stiffer adjacent structure and increased eccentricities [4]. Polycarpou and komodromos [5] observed that earthquake induced poundings occurring at base are unfavourable for the structure as it increases peak floor accelerations and inter-story deflections. It was also concluded that the implementation of viscous damper can cause considerable reduction in such pounding problems. The above review indicates that very few studies are reported for the minimizing the impact reduction for the impact between isolated building with adjacent structure. Therefore it will be interesting to study the dynamic behaviour of multi-storey isolated building by FPS and reduction of impact with the implementation of viscous damper.

In this paper, the impact response of base isolated building by FPS is investigated under three different level ground motions. The specific objectives of study are: (1) To study the response of isolated building during impact incident, (2) To understand the effect of variation in properties of adjacent structure such as stiffness and seismic gap on impact response results, (3) To study the response of isolated building during impact with the application of viscous damper.

2 Modeling of Isolated Building and Adjacent Structure

Fig. 1 shows the mathematical model of N storey isolated building considered for present study. At each floor one lateral degree of freedom is considered at each floor and base mass. The adjacent structure such as retaining walls, entry bridges moat walls etc are modelled as impact element characterised by stiffness and damping properties required in the analysis of impact problem. Following assumptions are made for considered structural system: (1) The impact is considered at the location of base mass. As no rotational degree of freedom is considered the impact is in normal direction. (2) Both side impacts are considered and the isolation gap remains same for adjacent structures. (3) The superstructure remains in elastic limit during impact phenomenon. (4) The system is subjected to horizontal component of earthquake ground motions. (5) The effect of soil-structure interaction is not considered.

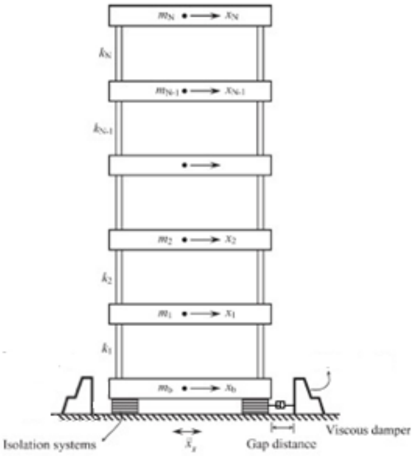

Figure 1 Mathematical model of multi-storied building isolated with the FPS with Viscous Damper

3 Governing Equations of Motion

The governing equations of motion for the N-storey superstructure model are expressed in matrix form as ,

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

Where $[M]$, $[C]$ and $[K]$ are the mass, damping and stiffness matrices of the superstructure, respectively; of size NxN; $\{x\} = \{x_1, x_2, \ldots x_N\}^T$ is the relative displacement vector of the superstructure; $\{\dot{x}\}$ and $\{\ddot{x}\}$ are the floor velocity and acceleration vectors, respectively; x_i is the lateral displacement of ith floor relative to base mass; $\ddot{x}_b$ and $\ddot{x}_g$ are the relative acceleration of base mass and earthquake ground acceleration, respectively; and $\{\ell\}$ is the vector of influence coefficients. The respective equation of motion for the base mass under earthquake ground motion is given by:

$$m_b\ddot{x}_b + F_b - c_1\dot{x}_1 - k_1x_1 = -m_b\ddot{x}_g \tag{2}$$

Where m_b and F_b are base mass and restoring force developed in the isolation system, respectively; k_1 is the storey stiffness of the first floor and c_1 is first storey damping.

The impact takes place when the bearing displacement, x exceeds the isolation gap distance, d between the isolated building and the adjacent structure. The differential equation of equilibrium for the base mass during impact with adjacent structure is expressed as:

$$m_b\ddot{x}_b + F_b - c_1\dot{x}_1 - k_1x_1 + k_g(|x_b| - d)\mathrm{sign}(x_b) + c_g\dot{x}_b = -m_b\ddot{x}_g \tag{3}$$

Where k_g and c_g are the stiffness and damping coefficient of the adjacent structure, respectively; and sign denotes signum function. With the implementation of damper the governing equation of motion is modified as;

$$m_b\ddot{x}_b + F_b + F_d - c_1\dot{x}_1 - k_1x_1 + k_g(|x_b| - d)sign(x_b) + c_g\dot{x}_b = -m_b\ddot{x}_g \qquad (4)$$

Where F_d is the Damper Force.

3.1 Friction Pendulum System

The FPS consists of housing plate connected with superstructure, a spherical sliding concave surface and an articulated slider sandwiched between them [7]. The force displacement behavior of FPS is modeled as a parallel arrangement of a friction element with plasticity governed by a modified Bouc-Wen model [8] and linear elastic spring element with stiffness based on the curvature of spherical concave surface.

The lateral force, F_b, developed by FPS is given by:

$$F_b = \frac{W}{R}x + \mu WZ \qquad (5)$$

Where, W is the weight carried by the bearing, x is the displacement, μ is the friction coefficient of sliding surface and Z is a hysteretic variable ranging from [-1~1].

3.2 Viscous Damper

The restoring force developed in viscous damper is due to pressure difference across the piston head [9]. At the time of earthquake, as the fluid is compressible, the change in fluid volume takes place due to the movement of piston which generates the spring like restoring force. To reduce the impact response of base isolated structure with adjacent structure, a viscous fluid damper is placed between the isolated building and adjacent structure as shown in Fig. 1 The damper force F_d is given by,

$$F_d = \mathrm{sgn}(\dot{x})c_d|\dot{x}^{\lambda}| \qquad (6)$$

Where, $\dot{x}$ is the velocity across the damper; $c_d=2\zeta_d m_d \omega_b$ is the damping coefficient; and λ is the velocity exponent which ranges from 0.3 to 2. For present study the value of λ is taken as 1 for linear viscous damper.

4 Solution Procedure of Equations of Motion

Because of nonlinear force-displacement behavior of the FPS, the governing equations of motion of isolated building cannot be solved using classical modal superposition technique. Hence the governing equations of motion are solved in the incremental form using Newmark's step-by-step method assuming linear variation of acceleration over small time interval, Δt/200 for this study.

5 Numerical Study

Seismic response of a base isolated building is examined under three different level earthquake ground motions such as Service Level Earthquake (SLE), Design Basis Earthquake and Maximum Credible Earthquake (MCE) during impact with adjacent structure. The earthquake motions selected for the present study are given in TABLE I.

TABLE I. Details of SLE, DBE and MCE ground motion selected for study

Sr. No	Earthquake	PGA(cm/sec2)
Service Level Earthquake ground motions (50% probability in 50 years)		
LA41	Coyote Lake, 1979	578.34
LA42	Coyote Lake, 1979	326.81
LA43	Imperial Valley, 1979	140.67
LA44	Imperial Valley, 1979	109.45
LA45	Kern, 1952	141.49
LA46	Kern, 1952	156.02
LA47	Landers, 1992	331.22
LA48	Landers, 1992	301.74
LA49	Morgan Hill, 1984	312.41
LA50	Morgan Hill, 1984	535.88
LA51	Parkfield, 1966, Cholame 5W	765.65
LA52	Parkfield, 1966, Cholame 5W	619.36
LA53	Parkfield, 1966, Cholame 8W	680.01
LA54	Parkfield, 1966, Cholame 8W	775.05
LA55	North Palm Springs, 1986	507.58
LA56	North Palm Springs, 1986	371.66
LA57	San Fernando, 1971	248.14
LA58	San Fernando, 1971	226.54
LA59	Whittier, 1987	753.70
LA60	Whittier, 1987	469.07
Design Basis Earthquake ground motions (10% probability in 50 years)		
LA01	Imperial Valley, 1940, El Centro	452.03
LA02	Imperial Valley, 1940, El Centro	662.88
LA03	Imperial Valley, 1979, Array #05	386.04
LA04	Imperial Valley, 1979, Array #05	478.65
LA05	Imperial Valley, 1979, Array #06	295.69
LA06	Imperial Valley, 1979, Array #06	230.08
LA07	Landers, 1992, Barstow	412.98
LA08	Landers, 1992, Barstow	417.49
LA09	Landers, 1992, Yermo	509.70
LA10	Landers, 1992, Yermo	353.35
LA11	Loma Prieta, 1989, Gilroy	652.49
LA12	Loma Prieta, 1989, Gilroy	950.93
LA13	Northridge, 1994, Newhall	664.93
LA14	Northridge, 1994, Newhall	644.49
LA15	Northridge, 1994, Rinaldi RS	523.30
LA16	Northridge, 1994, Rinaldi RS	568.58
LA17	Northridge, 1994, Sylmar	558.43
LA18	Northridge, 1994, Sylmar	801.44
LA19	North Palm Springs, 1986	999.43
LA20	North Palm Springs, 1986	967.61
Maximum Credible Earthquake ground motions (2% probability in 50 years)		
LA21	1995 Kobe	1258.00
LA22	1995 Kobe	902.75
LA23	1989 Loma Prieta	409.95
LA24	1989 Loma Prieta	463.76

LA25	1994 Northridge	851.62
LA26	1994 Northridge	925.29
LA27	1994 Northridge	908.70
LA28	1994 Northridge	1304.10
LA29	1974 Tabas	793.45
LA30	1974 Tabas	972.58
LA31	Elysian Park (simulated)	1271.20
LA32	Elysian Park (simulated)	1163.50
LA33	Elysian Park (simulated)	767.26
LA34	Elysian Park (simulated)	667.59
LA35	Elysian Park (simulated)	973.16
LA36	Elysian Park (simulated)	1079.30
LA37	Palos Verdes (simulated)	697.84
LA38	Palos Verdes (simulated)	761.31
LA39	Palos Verdes (simulated)	490.58
LA40	Palos Verdes (simulated)	613.28

Source: Somerville et al. (1998)

For present study, the mass matrix of the superstructure [M] is the diagonal matrix and it is generated by the mass of each storey, which is kept constant (i.e. $m_j = m$ for $j = 1,2,3,\ldots,N$). To make the problem simple the stiffness of all stories is taken as constant and expressed as k. The damping matrix of the superstructure [C] is generated by assuming the modal damping ratio in each mode of vibration of superstructure, which is kept constant. Thus, for the model of isolated building under consideration can be completely characterized by specifying parameters such as, the fundamental time period of superstructure (T_s), damping ratio of the superstructure (ζ_s) which is constant for all modes, number of storey in superstructure (N).The adjacent structure with adequate separation gap distance, d is characterized by the stiffness k_g and damping coefficient c_g.

For the numerical study, the damping ratio of superstructure (ζ_s) = 0.02 and mass ratio $m_b/m = 1$ is kept constant. The k_g is taken as some fraction of stiffness of isolated structure, given by stiffness ratio, $k_r = k_g/k_s$ and damping ratio of adjacent structure, ζ_g is kept same as that of isolated building. The superstructure has fundamental time period, $T_s = 0.5$ sec. The time period considered for the bearing $T_b = 2.5$ sec and the value of friction coefficient is considered as, $\mu = 0.5$. The behaviour of fives storied building isolated with FPS is investigated for three cases, (i) Seismic response of isolated building without impact on adjacent structure, (ii) Seismic response of isolated building with impact on adjacent structure and (iii) Impact response of isolated building with provision of viscous damper.

6 TIME HISTORY RESPONSE FOR THE SLE, DBE AND MCE LEVEL EARTHQUAKE GROUND MOTIONS

The response of the example building isolated by FPS is shown in figure 2 and 3 for two Service level Earthquake (SLE) ground motions; 1979 Coyote Lake and 1966 Parkfield earthquake, having peak ground acceleration 0.589 and 0.79g respectively. Time histories of isolator displacement, normalized top floor absolute acceleration, normalized base shear and impact force generated for the FPS are shown. It is observed that the top floor acceleration of superstructure increases during impact and the bearing displacements reduces after impact with adjacent structure. In several ground motions no impact has been noted as the displacements having lower value than the separation gap distance. The normalized base shear also reduced in with impact compared to without impact response.

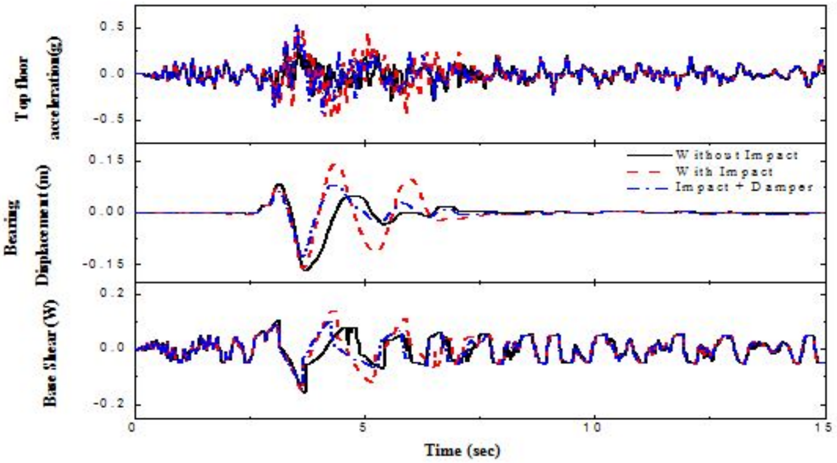

Figure 2 Time variation of top floor acceleration, isolator displacement and base shear of five storey building isolated by FPS isolator subjected to 1979 Coyote lake earthquake

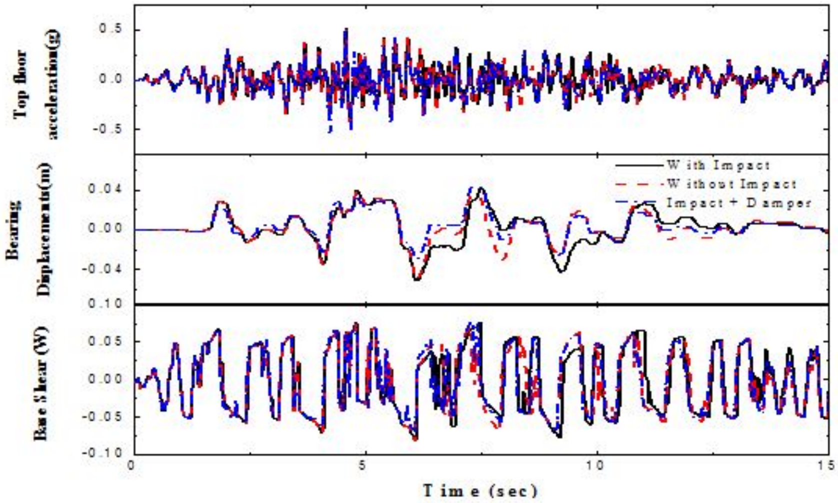

Figure 3 Time variation of top floor acceleration, isolator displacement and base shear of five storey building isolated by FPS isolator subjected to 1996 Parkfield earthquake

TABLE II. Peak Responses of five storey isolated building for SLE ground motions by FPS

Earthquake	Top Floor Acceleration(g)			Bearing Displacements (cm)		
Label No.	Without Impact	With impact	Impact + Damper	Without Impact	With impact	Impact + Damper
LA41	0.319	0.479	0.535	16.68	16.12	12.55
LA42	0.403	0.403	0.377	4.64	4.39	3.11

LA43	0.209	0.363	0.175	6.85	5.66	3.85
LA44	0.238	0.206	0.219	4	4	2.8
LA45	0.258	0.258	0.255	3.91	3.91	3.07
LA46	0.295	0.38	0.296	4.3	4.135	3.65
LA47	0.343	0.382	0.42	8.8	6.92	4.35
LA48	0.383	0.383	0.396	3.13	3.13	2.9
LA49	0.4	0.401	0.418	8.1	7.18	5.4
LA50	0.501	0.501	0.579	4.28	4.25	3.28
LA51	0.549	0.549	0.499	6.23	5.83	4.7
LA52	0.382	0.382	0.381	3.55	3.55	3.45
LA53	0.62	0.696	0.733	5.48	5.39	4.06
LA54	0.508	0.508	0.529	5.09	4.98	4.26
LA55	0.41	0.51	0.47	9.25	7.98	6.59
LA56	0.448	0.469	0.439	8.39	7.3	5.77
LA57	0.36	0.36	0.346	3.0	3.02	2.85
LA58	0.35	0.35	0.357	8.02	6.66	4.8
LA59	0.417	0.69	0.628	12.96	15.3	13.3
LA60	0.485	0.625	0.523	13.92	11.43	9.76

Similar trend of response is observed with higher value of top floor acceleration and bearing displacements for DBE level earthquake as shown in figure 4 and 5 for ground motions; 1940 Imperial Valley (El Centro) and 1989 Loma Prieta,(Gilroy) earthquake, having peak ground acceleration 0.67 and 0.82 respectively.

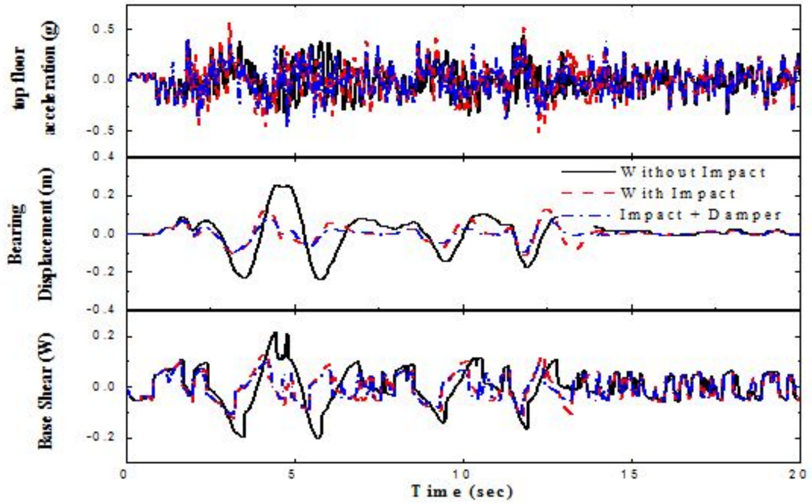

Figure 4 Time variation of top floor acceleration, isolator displacement and base shear of five storey building isolated by FPS isolator subjected to 1940 El Centro earthquake

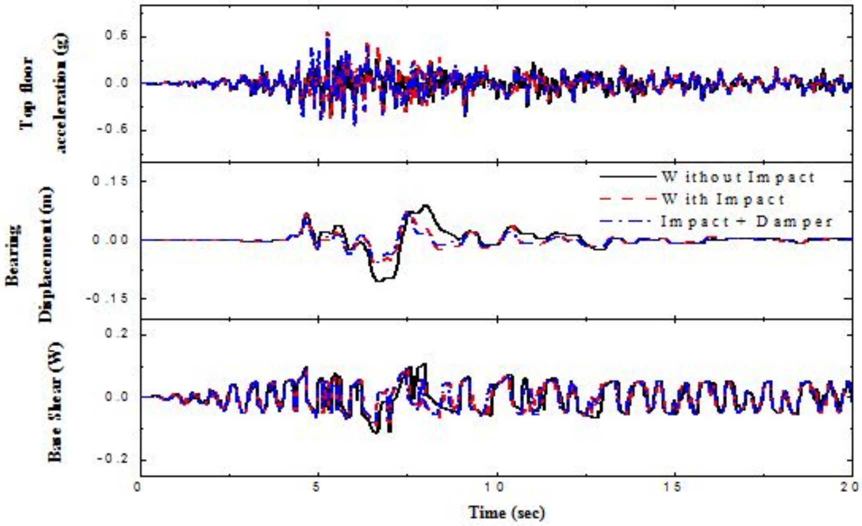

Figure 5 Time variation of top floor acceleration, isolator displacement and base shear of five storey building isolated by FPS isolator subjected to 1989 Loma Prieta earthquake

TABLE III. Peak Responses of five storey isolated building for DBE ground motions by FPS

Earthquake	Top Floor Acceleration(g)			Bearing Displacements (cm)		
Label No.	Without Impact	With impact	Impact + Damper	Without Impact	With impact	Impact + Damper
LA01	0.45	0.577	0.449	25.18	12.36	9.79
LA02	0.419	0.642	0.645	23.91	13.05	10.61
LA03	0.477	0.556	0.513	44.36	18.33	13.26
LA04	0.385	0.559	0.507	23.76	10.13	8.31
LA05	0.477	0.471	0.419	48.61	15.07	11.13
LA06	0.349	0.429	0.4	18.52	9.67	8.46
LA07	0.444	0.498	0.403	10.31	9.88	7.45
LA08	0.342	0.553	0.507	12.82	14.32	9.59
LA09	0.441	1.077	0.623	29.39	32.93	20.34
LA10	0.449	0.64	0.453	18.78	15.45	10.22
LA11	0.542	0.828	0.572	44.46	26.01	17.62
LA12	0.543	0.663	0.648	10.41	7.85	6.66
LA13	0.467	0.678	0.587	20.44	17.26	12.62
LA14	0.471	1.012	0.648	27.76	28.26	15.27
LA15	0.434	0.71	0.603	20.32	23.04	16.05
LA16	0.464	0.846	0.737	31.4	30.22	21.6
LA17	0.516	0.788	0.538	48.15	19.68	14.32
LA18	0.441	0.991	0.622	46.9	33.97	21.61
LA19	0.639	0.606	0.632	14.19	12.08	8.27
LA60	0.485	0.625	0.523	13.92	11.43	9.76

The response of five storey building isolated by FPS is shown in figure 6 and 7 for the Maximum Credible Earthquake (MCE) level ground motions; 1995 Kobe and 1994 Northridge earthqua1ke, having peak ground acceleration 1.28 and 1.32g, respectively. It is observed that in some cases the bearing displacement increases when impact is occurred in comparison to that without impact condition. This is due to typical variation of spectral displacement of earthquake motion in which the peak displacement decreases with the increase of time period. The numerical values of two response quantities; bearing displacement and top floor acceleration for without impact and with impact responses are listed in table 2, 3 and 4 for SLE, DBE and MCE earthquake.

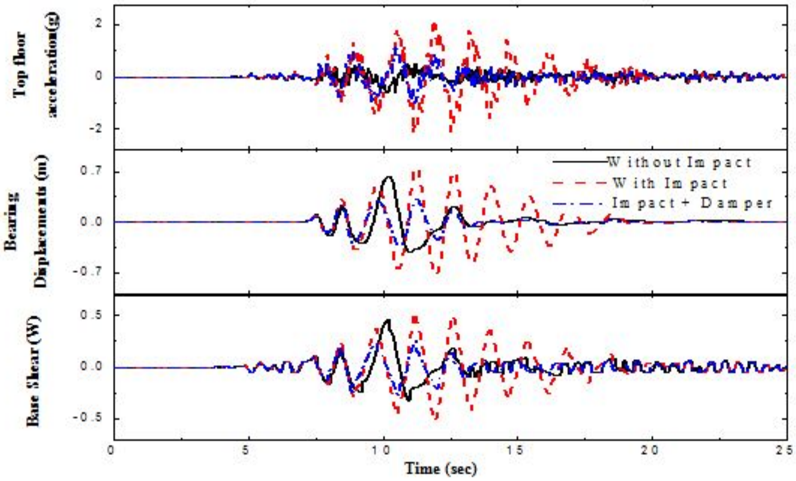

Figure 6 Time variation of top floor acceleration, isolator displacement and base shear of five storey building isolated by FPS isolator subjected to 1995 Kobe earthquake

Figure 7

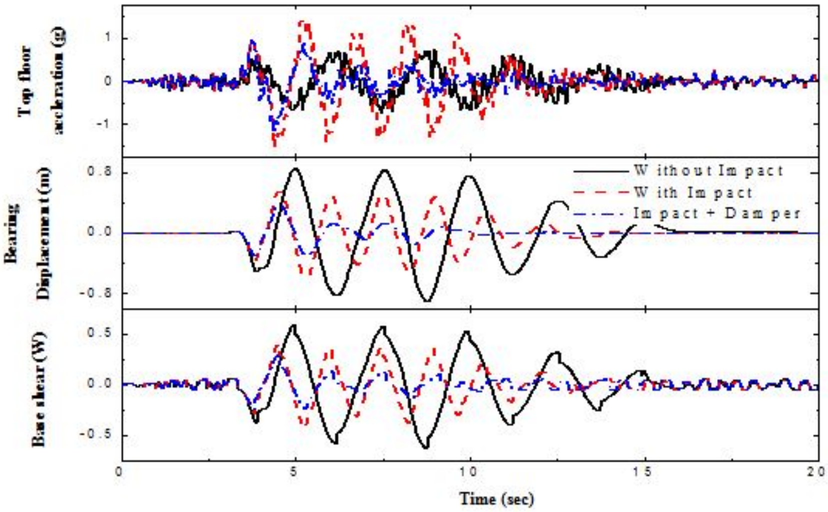

Figure 8 Time variation of top floor acceleration, isolator displacement and base shear of five storey building isolated by FPS isolator subjected to 1994 Northridge earthquake

TABLE IV. Peak Responses of five storey isolated building for MCE ground motions by FPS

Earthquake	Top Floor Acceleration(g)			Bearing Displacements (cm)		
Label No.	Without Impact	With impact	Impact + Damper	Without Impact	With impact	Impact + Damper
LA21	0.62	2.05	0.985	43.8	67.72	30.28
LA22	0.644	1.535	1.196	48.21	54.98	34.87
LA23	0.689	1.19	0.88	89.36	37.83	23.94
LA24	0.735	1.793	1.08	83.67	62.06	32.39
LA25	1.307	1.89	1.338	169.08	0.683	48.37
LA26	1.35	1.792	1.328	180.3	70.09	49.68
LA27	0.941	1.248	0.952	110.86	45.43	33.58
LA28	1.15	1.592	1.214	152.18	58.56	45.05
LA29	0.391	0.843	0.647	33.65	29.58	19.62
LA30	0.959	1.65	1.04	117.04	60.99	40.1
LA31	0.608	2.18	1.21	63.66	75.43	34.22
LA32	0.742	0.977	0.85	45.77	25.99	23.29
LA33	0.452	0.89	0.605	27.13	23.46	12.02
LA34	0.777	1.572	0.951	83.94	60.78	30.31
LA35	0.496	1.1	0.968	39.72	41.85	29.09
LA36	0.606	1.519	1.252	70.52	52.18	37.19
LA37	0.967	1.072	0.855	100.61	32.61	24.98
LA38	0.719	1.524	1.184	89.69	0.586	37.3
LA39	0.614	0.869	0.665	20.96	17.76	11.4
LA40	0.745	0.824	0.838	55.34	23.84	22.55

6.1 Reduction in Response

To reduce the impact effect one viscous damper is used. It is observed that the employment of viscous damper makes and efficient output in a way to reduce the impact response. The response is tabulated in table 2, 3 and 4 for SLE, DBE and MCE respectively. There is a considerable reduction in top floor acceleration and isolator displacements. In some of the SLE level earthquake ground motions the Impact problem has totally resolved.

7 Effect of Gap size and Adjacent structure Stiffness

The normalization of gap is carried out with respect to maximum gap distance beyond which there was no impact observed. It is observed that top floor acceleration increases up to a certain value of normalized gap distance and it decreases with further increase in the normalized gap distance for SLE and DBE level earthquake ground motions. For MCE level earthquake ground motions, the gradual increase in top floor acceleration with respect to normalized gap is noted from the results. The maximum increase in top floor acceleration in for intermediate gap distance is due to the increased velocity of superstructure at the time of impact.

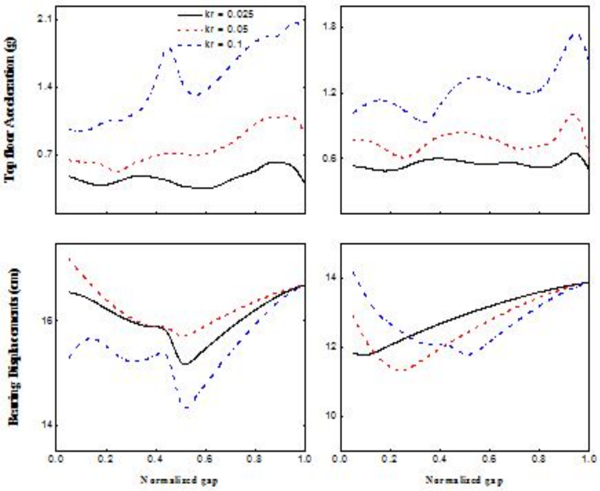

Figure 9 Effect of gap distance on top floor acceleration and bearing displacement for five storey isolated building using FPS system for SLE earthquake ground motions

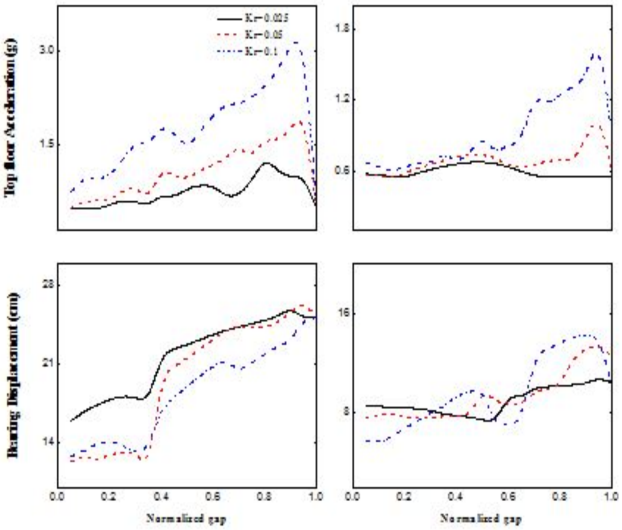

Figure 10 Effect of gap distance on top floor acceleration and bearing displacement for five storey isolated building using FPS system for SLE earthquake ground motions

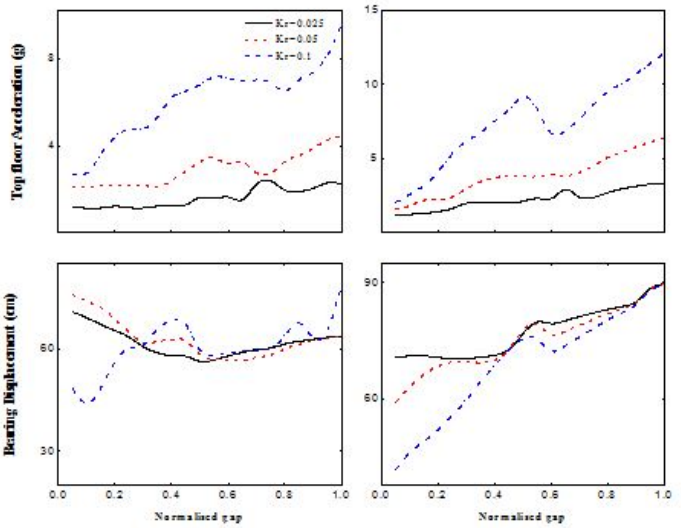

Figure 11 Effect of gap distance on top floor acceleration and bearing displacement for five storey isolated building using FPS system for MCE earthquake ground motions

The effect of variation in separation gap distance on superstructure acceleration and bearing displacements for are studied under different level earthquake ground motions for the five storey building isolated by FPS as shown in Figs. 8, 9 and 10 respectively. The responses are calculated by varying the separation gap and plotted against normalized gap distance under various earthquake ground motions.

8 CONCLUSION

Seismic response of base isolated building by FPS during impact with adjacent structure is investigated. From the results, following conclusions are derived.

- Superstructure acceleration of base isolated building increases due to impact upon adjacent structure during earthquake
- The bearing displacement is reduced after having impact with adjacent structures.
- The employment of damper shows considerable reduction in bearing displacement, base shear and impact force for DBE and MCE.
- As the Seismic gap between the structure increases, top floor acceleration increases up to certain limit and decreases with more increase in gap distance for SLE and DBE earthquake motions, while for MCE earthquake motions the top floor acceleration increases gradually with the increase in seismic gap.
- The stiffness of adjacent structure shows significant effect on the impact response of isolated building. As the stiffness of adjacent structure increases the top floor acceleration increases.
- The bearing displacements of isolated building increases with the increase in seismic gap and decreases with the increase in stiffness of adjacent structure.

References

[1] P. Malhotra, "Dynamics of seismic impacts in base-isolated buildings." Earthquake Engineering and Structural Dynamics, vol. 26, pp.797–813, 1997.
[2] S. Nagarajaiah and X. Sun, "Base isolated FCC building: Impact response in Northridge earthquake", Journal of Structural Engineering, ASCE, vol. 29(2), pp. 1063-1075, 2001.
[3] V. Matsagar, R. Jangid, "Seismic response of base-isolated structures during impact with adjacent structures." Engineering Structures; vol. 25, pp.1311-1323, 2003.
[4] V. Matsagar and R. Jangid, "Impact Response of Torsionally Coupled Base-isolated Structures". Journal of vibration and control, vol. 16, No. 11, pp. 1623-1649, 2008.
[5] P. Polycarpou and P. Komodromos, "Earthquake-induced poundings of a seismically isolated building with adjacent structures", Engineering Structures, vol. 32, pp. 1937-1951, 2010.
[6] V. Agarwal, J. Niedzwecki and J. Lindt, "Earthquake induced pounding in friction varying base isolated buildings", Engineering Structures, vol. 2007, pp. 2825-2832, 2007.
[7] VA Zayas, SS Low, and SA. Mahin, "A simple pendulum technique for achieving seismic isolation", Earthquake Spectra, vol. 6(2), pp. 317-333, 1990.
[8] YK. Wen, "Method for random vibrations of hysteretic systems", Journal of Engineering Mechanics Division, ASCE, vol. 102, pp. 249-263, 1976.
[9] B. Soneji and R. Jangid, "Passive hybrid system for earthquake protection of cable-stayed bridge", Engineering Structures, vol. 29, pp. 57-70, 2007.