Earthquakes and Structures, *Vol. 4, No. 5 (2013) 471-487*
DOI: http://dx.doi.org/10.12989/eas.2013.4.5.471

Base isolated RC building – performance evaluation and numerical model updating using recorded earthquake response

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(Received January 6, 2012, Revised July 23, 2012, Accepted November 21, 2012)

Abstract. Performance of a prototype base isolated building located at Indian Institute of Technology, Guwahati (IITG) has been studied here. Two numbers of three storeyed single bay RCC framed prototype buildings were constructed for experimental purpose at IITG, one supported on conventional isolated footings and the other on a seismic isolation system, consisting of lead plug bearings. Force balance accelerometers and a 12 channel strong motion recorder have been used for recording building response during seismic events. Floor responses from these buildings show amplification for the conventional building while 60 to 70% reduction has been observed for the isolated building. Numerical models of both the buildings have been created in SAP2000 Nonlinear. Infill walls have been modeled as compression struts and have been incorporated into the 3D models using Gap elements. System identification of the recorded data has been carried out using Parametric State Space Modeling (N4SID) and the numerical models have been updated accordingly. The study demonstrates the effectiveness of base isolation systems in controlling seismic response of isolated buildings thereby leading to increased levels of seismic protection. The numerical models calibrated by relatively low level of earthquake shaking provides the starting point for modeling the non-linear response of the building when subjected to strong shaking.

Keywords: base isolation; lead rubber bearings; numerical models; system identification; N4SID

1. Introduction

Of all the destructive forces of nature, earthquake is perhaps one of the major causes of massive and widespread devastation of the natural as well as the built environment. Earthquakes become all the more destructive when they hit densely populated areas. As such, improved seismic performance of buildings has become one of the increasing demands that the construction industry has had to cater to in recent years. People now want a built environment, specifically buildings, which perform better in case of a large earthquake. Therefore, the criterion that a structure has to fulfill nowadays is an improved ability to minimize the damage caused by an earthquake to the maximum extent possible. It is here that base isolation devices such as lead rubber bearings (LRBs) and high damping rubber bearings (HDRBs) have come to the aid of buildings in enhancing their seismic performance. Skinner *et al.* (1991) presented the scenario of base isolation in New Zealand by citing examples of forty two base isolated bridges, three buildings, a tall chimney and

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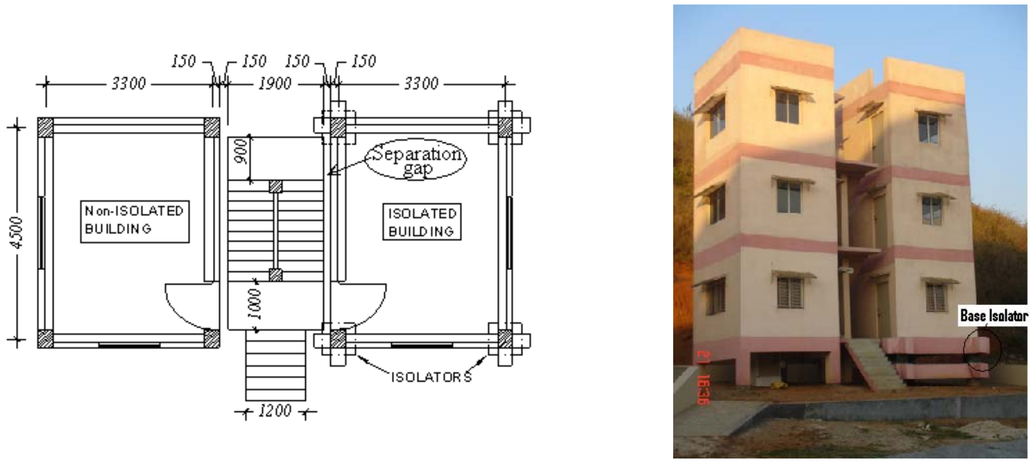
http://www.techno-press.org/?journal=eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

high-voltage capacitor banks. The study showed that besides enhancing the seismic performance of structures, cost savings of up to 10% of the structures' cost was possible by adopting base isolation techniques. The findings published by Moroni *et al.* (1998) about an experimental setup in Santiago, Chile where a four storeyed building supported on HDRBs and a conventional one was constructed, showed the effectiveness of base isolation devices in attenuating the horizontal acceleration transmitted to the superstructure. The enhanced performance of the base isolated USC Hospital building during the 1994 Northridge earthquake (Nagarajaiah and Xiaohong 2000) is well documented with the peak roof acceleration reduced to nearly 50% of the peak ground acceleration. Jangid and Kelly (2001) studied the effect of six pairs of near-fault motions on base isolated structures and found that the Electricité-de-France (EDF) type isolator was found to perform better when compared to LRBs and HDRBs. Wu and Samali (2002) conducted shake table testing of a five-storey steel frame along with numerical analysis of a five-storey benchmark model to study seismic characteristics of the same and evaluate the efficiency of the base isolation system consisting of rubber bearings. The enhanced seismic behavior of low-rise base isolated structures mounted on rubber bearings only, or with a hybrid isolation system of sliding bearings for isolation and steel rubber bearings to provide re-centering forces was studied by Braga and Laterza (2004) through a series of dynamic snap-back tests. Jangid and Matsagar (2004) studied the influence of isolator characteristics on the seismic response of multi-storey base-isolated structure by modelling the force-deformation behavior of isolators using two different mathematical models. The investigation of the seismic response of numerically simulated multi storey buildings isolated by lead rubber bearings under near-field motions (Jangid 2007) showed that LRBs with high yield displacement performed better than those with low yield displacement values. The performance of isolated steel-concrete composite structures under near-fault earthquake excitations was numerically studied by Providakis (2008) using pushover analysis on two five-storey three-dimensional models of buildings with steel columns and steel-composite slabs and beams. Providakis (2008) studied the effect of LRB isolators and supplemental viscous dampers on seismic isolated buildings under near-fault excitations by analyzing the seismic performances of two reinforced concrete (RC) buildings supported on various LRB isolation systems.

The identification of modal parameters of a structural system using measured acceleration response from the structure has attracted the attention of researchers as this information can be used for assessing the health of the structure. The identified modal parameters can also be used for updating numerical models so as to closely simulate structural behavior on field. Out of the different methods available, parametric state space modeling algorithms like N4SID, introduced by Overschee and Boor (1993), has gained popularity among researchers in system identification for its advantages of being non-iterative with no nonlinear optimization part involved and the non-requirement of the initial condition to be zero for estimation of a state space system from measured data. Medhi *et al.* (2007) carried out identification on a numerically simulated shear building having standard floors (i.e., lumped masses at each floor being same) using N4SID algorithm. They evaluated modal as well as structural parameters of the simulated building subjected to seismic excitations. The cases of full and limited availability of sensors were also addressed for identification and localization of any damage in the structure. However, actual building structures generally do not possess standard floors and the issue of identification of modal and structural parameters needs to be addressed differently. Borsaikia *et al.* (2010) considered a non standard existing shear building for the evaluation of modal and structural parameters, with only few selected floors of the building equipped with accelerometers. Two earthquake excitations as experienced by the building were considered for the study. Modal parameters were evaluated



(a) (b)

Fig. 1 (a) Plan of conventional and isolated building showing position of isolators; (b) View of conventional building to the left and isolated building to the right

using N4SID in conjunction with an iterative approach to address the issue of limited sensors.

The number of base isolated buildings in India is very few and continuous effort is being taken to amalgamate this technology with popular structural design philosophies. Such an effort has been undertaken in IITG through a sponsored project wherein two numbers of three storeyed single bay RCC framed experimental buildings have been constructed. Of the twin buildings, one is supported on a conventional foundation system while the other has a seismic isolation system incorporated between the foundation and superstructure. Both buildings are identical in plan and elevation and have identical structural details. Instrumentation of the buildings has been done with uni-axial as well as tri-axial force balance accelerometers. Dynamic response data have been recorded using a 12 channel strong motion recorder. More than twenty five earthquakes measuring 4 to 5.4 on the Richter scale have been recorded till date with the first event on 10th September, 2006. The recorded events and the floor responses have been analyzed using parametric system identification technique for the evaluation of modal characteristics of the buildings. Numerical simulation of both the conventional as well as base isolated buildings has been carried out using SAP 2000 Nonlinear. While the simulated 3D model of conventional building could reproduce the dynamic response of the actual building quite well, the base isolated building needed some updating in terms of the stiffness values of base isolators. This paper is an attempt to bring forth a comparative study of the recorded acceleration response of the buildings and those obtained from the numerically simulated ones. From the comparison of the recorded and numerical responses as well as from identification of the system using N4SID, the numerical model of the base isolated building has been updated so that the model can represent the actual building system as close as possible. The updated model would be useful for nonlinear analysis to predict the highly nonlinear behavior of a base isolated building, if subjected to seismic excitation of larger magnitude.

2. Details of the sample buildings and the instrumentation system

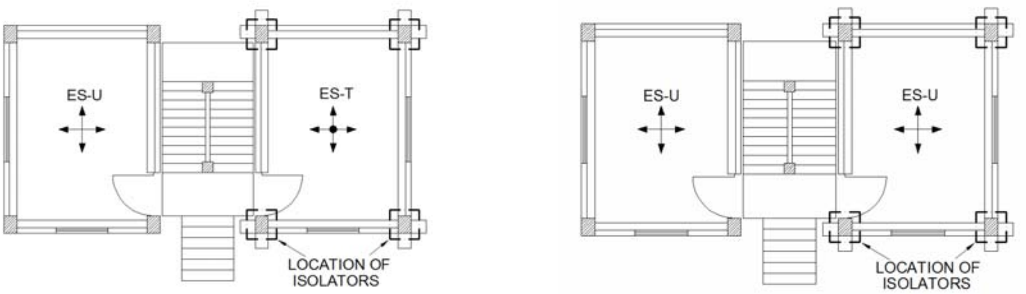
The prototype buildings were constructed and instrumented as a part of a sponsored project by

BRNS, Govt. of India, (Dubey *et al.* 2007). The main objective of the study is to evaluate the efficiency of the isolation system in protecting buildings and their contents from earthquake damage. IIT Guwahati is located in the highest seismic zone of India and hence the building experiences regular earthquakes, which have been utilized for the evaluation of seismic performance of the isolation system. Fig. 1 shows the plan of the prototype buildings with the position of the isolators marked in the isolated building and a view of the buildings at site. From Fig. 1(a), it can be seen that two buildings are having the same footprint and structural dimensions. While the building on the left is supported on conventional foundation, the building on the right is on seismic isolators. The isolators are placed between beams which separate the foundation from the superstructure. The location of the isolators is shown in Fig. 1(b). The staircase has been constructed such that it is structurally disconnected from the buildings on either side.

Surface mounted force balance accelerometers have been installed at site. Four uni-axial (ES-U) accelerometers are installed in the conventional building, two each at the 1st floor and roof level along the two orthogonal directions of the building. For the isolated building, 2 ES-U accelerometers have been installed at the roof level and 1 tri-axial (ES-T) accelerometer at the 1st floor level. For capturing ground motions, another ES-T accelerometer has been installed separately on the ground. The accelerometers are connected to a 12 channel strong motion recorder with a built-in GPS and expandable memory. Fig. 2 shows the accelerometers and strong motion recorder that have been used while Fig. 3 shows the position of the sensors (in plan) at the 1st floor and roof level of the prototype buildings.

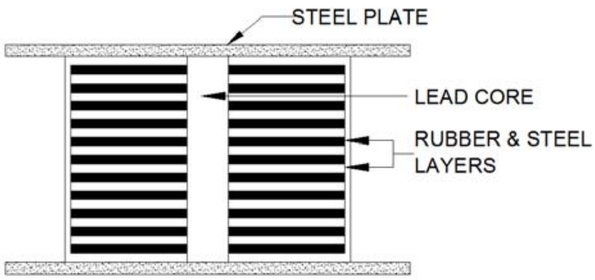
(a) (b) (c)

Fig. 2 Accelerometers and recorder used in the buildings; (a) EpiSensor Uni-Axial (ES-U); (b) EpiSensor Tri-Axial (ES-T) and (c) Strong motion recorder Altus-K2



(a) (b)

Fig. 3 Position of accelerometers in the prototype conventional and isolated buildings: (a) 1^{st} floor level and (b) Roof level



(a) (b)

Fig. 4 (a) Cross section of LRB used at site and (b) LRB connected with bolts to prototype isolated building

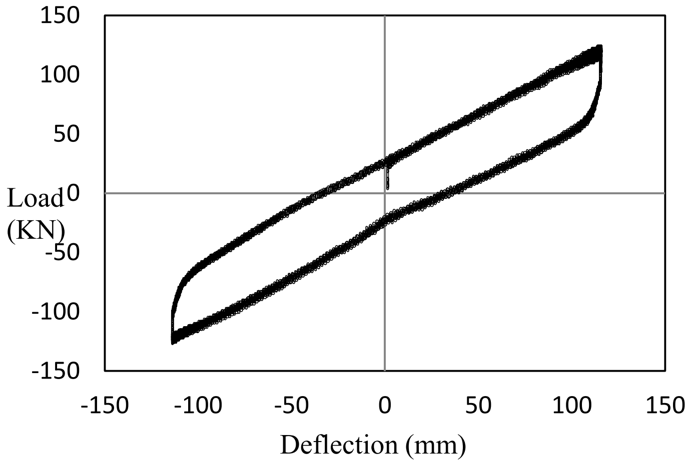


Fig. 5 Cyclic load displacement characteristic of lead plug bearing

3. Description of the isolation systems

Lead plug bearings (LPBs) have been used in this project. The bearings consist of alternate layers of rubber and steel shims with a central lead core. Each bearing has a vertical stiffness of 188960 KN/m with a vertical load carrying capacity of 50 tonnes (Dubey *et al.* 2007). The first event was recorded on the 10th September, 2006. A cross-section of the LPB isolator is shown in Fig. 4 along with the installed isolators at site.

4. Isolation system characteristics

The LPBs have been tested by the manufacturer to record their load-displacement characteristics. A typical load displacement characteristic as obtained from cyclic load testing is shown Fig. 5. The important parameters such as the post-yielding stiffness K2, defined as the ratio of maximum load to maximum deflection, the pre-yielding stiffness K1, yield force Q defined as the intercept of the load-deflection curve on the load axis, the effective stiffness of the bearing K_{eff} and the effective damping β_{eff} (Naeim and Kelly 1999) are obtained from the load-displacement

Table 1 Details of sources of seismic events recorded with LRBs

Date	Magnitude (*Mw*)	Epicentre	Focal depth (km)	PGA at site (g)		Region
				Longer	Shorter	
10-09-2006	4.0	24.6^0 N, 94.6^0 E	84.8	0.0022	0.0029	India (Manipur) - Myanmar Border
06-11-2006	5.0	25.0^0 N, 95.0^0 E	123	0.0021	0.003	Myanmar
10-11-2006	5.0	24.6^0 N, 92.2^0 E	33	0.0038	0.0047	Bangladesh-India (Assam) Border Region
11-05-2012	5.4	26.6^0 N, 93.0^0 E	20	0.1018	0.0741	Assam

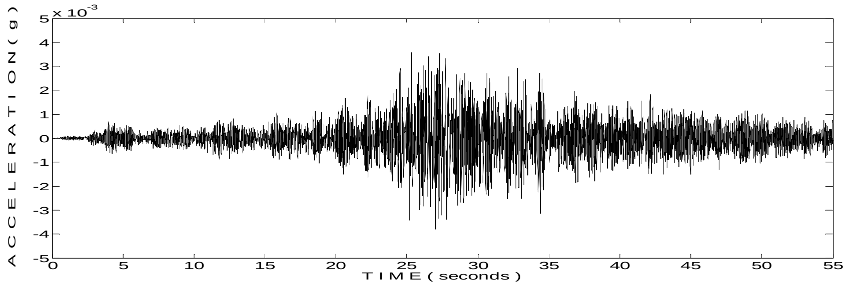
hysteresis loop. These parameters have been calculated for the isolation system from the load-displacement curves and incorporated in the numerical model introduced in a later section.

5. Earthquake events recorded with LPB isolation system

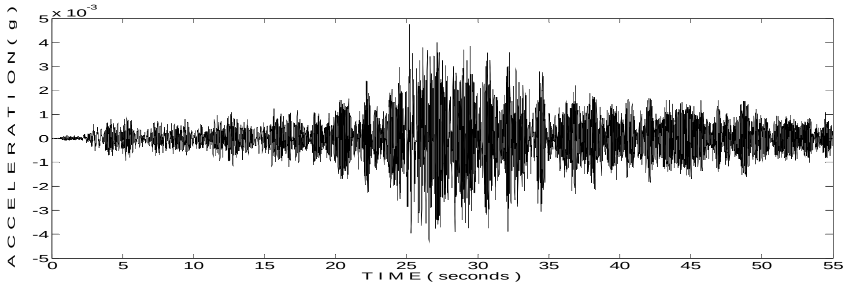
As mentioned earlier, the prototype buildings have been instrumented with floor mounted force balance accelerometers. The limiting value of these accelerometers is ±2.0 g with automatic triggering at 0.005% of the full range. The sampling frequency of the recording system has been set at 200 Hz. More than 25 events have been recorded so far at the site since 2006 till date. The first seismic event recorded with the LPB isolation system in the building was on 10th September, 2006. The event, measuring 4.0 on the Richter scale, had its epicenter at latitude 24.6°N and longitude 94.6°E in the India (Manipur) - Myanmar border region and its focal depth was 84.8 km. The peak ground acceleration (PGA) recorded at site in the longer direction of the building was 0.0022 g while that in the shorter direction was 0.0029 g. Table 1 gives the details of the sources of four events recorded with the LPB isolation system along with the PGA at site. The plots of the earthquake induced ground acceleration recorded on 10th November, 2006 are shown here in Fig. 6.

5.1 Comparison of Floor Responses of Conventional and Isolated Buildings

Observation of the floor responses of both the buildings corresponding to the earthquake on 10th November, 2006 shows magnification in the response for the conventional building while significant reduction in response has been observed for the base isolated building. Fig. 7 shows the roof response of the conventional building for both the longer and shorter direction for the event on 10th November. It is seen from Fig. 7 that there is magnification in the conventional building roof response when compared to the PGA. On the other hand, considerable reduction in the roof response in both directions has been observed for the isolated building as evident from Fig. 8. The PGA, peak roof response of both buildings and the corresponding percent reduction in isolated



(a)



(b)

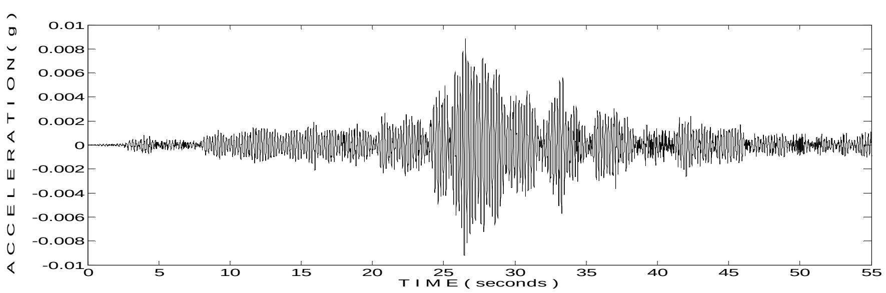
Fig. 6 Ground history plots for event on 10th November, 2006: (a) Longer direction - peak 0.0038 g and (b) Shorter direction – peak 0.0047g

Table 2 PGA, conventional and isolated building roof response and percentage reduction in roof acceleration for isolated building

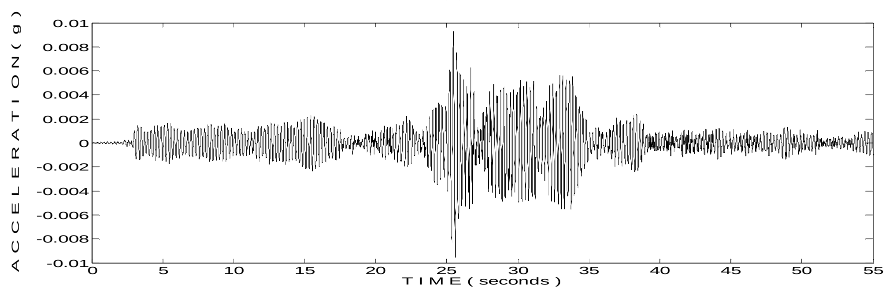
Event date	PGA (g)		Roof acceleration (g)					
			Conventional building		Isolated building			
	Longer	Shorter	Longer	Shorter	Longer	Shorter	Reduction (%)	
							Longer	Shorter
10-09-2006	0.0022	0.0029	0.0048	0.0074	0.00069	0.0011	68.64	62.07
06-11-2006	0.0021	0.003	0.0065	0.0094	0.0014	0.0017	33.33	43.33
10-11-2006	0.0038	0.0047	0.0092	0.0096	0.0013	0.0019	65.79	59.57
11-05-2012	0.1018	0.0741	0.4063	0.2408	0.0425	0.0253	58.25	65.85

building response for the selected four events are shown in Table 2.

From Table 2 and from Fig. 8, it is evident that the LPB isolation system has been very effective in reducing the response of the base isolated building with reduction of about 68% in comparison to PGA. On the other hand for the conventional building, it is seen from Table 2 and Fig. 7, that the peak roof acceleration is two to three times more than the PGA. Hence, isolated buildings can be designed for much lesser magnitude of earthquake forces compared to the conventional buildings. Table 3 shows displacement at isolator level as well as the inter-storey drifts. It may be seen that the magnitudes of inter-storey drifts are very small and hence indicates



(a)



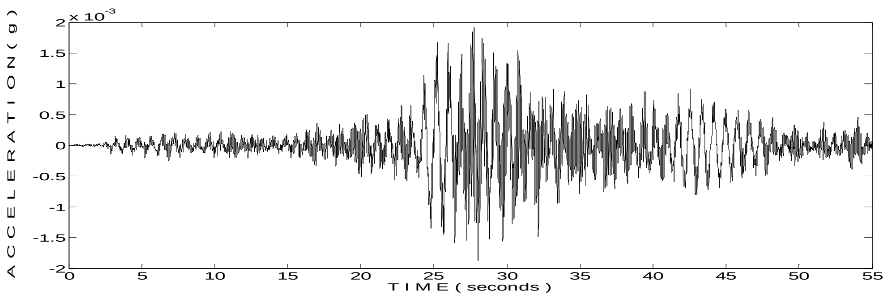
(b)

Fig. 7 Roof acceleration history - Conventional bldg. - 10th November, 2006 event (a) Longer direction - peak 0.0092 g and (b) Shorter direction – peak 0.0096 g

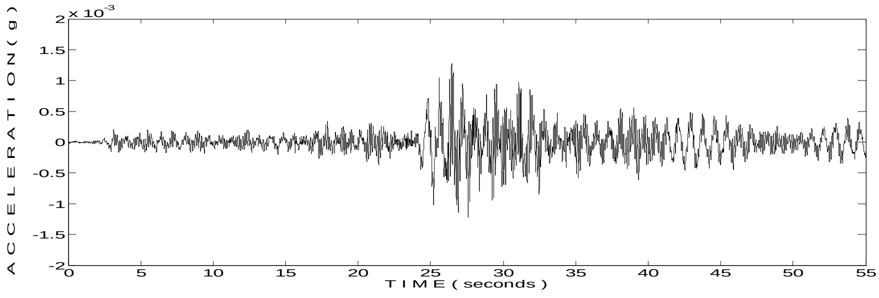
Table 3 Displacement at different floor levels of isolated building

Event date	Isolator displacement (mm)		Inter-storey drift (mm)					
	Shorter direction	Longer direction	Shorter direction			Longer direction		
			1st floor	2nd floor	Roof	1st floor	2nd floor	Roof
10th September, 2006	1.522 x 10^{-3}	1.292 x 10^{-3}	0.112 x 10^{-3}	0.12 x 10^{-3}	0.107x 10^{-3}	0.054 x 10^{-3}	0.052 x 10^{-3}	0.044x 10^{-3}
6th November, 2006	5.076 x 10^{-3}	4.977 x 10^{-3}	0.32 x 10^{-3}	0.321x 10^{-3}	0.284x 10^{-3}	0.18x 10^{-3}	0.167x 10^{-3}	0.141x 10^{-3}
10th November, 2006	1.981 x 10^{-2}	9.403 x 10^{-3}	0.038 x 10^{-2}	0.06x 10^{-2}	0.051x 10^{-2}	.0597 x 10^{-2}	0.06x 10^{-2}	0.054x 10^{-2}
11th May, 2012	0.2630	0.4168	0.0137	0.0128	0.0114	0.0136	0.0124	0.0104

the effectiveness of the isolation system. The values indicate almost rigid body motion of the isolated building above the level of isolators. Further, the isolator displacements are also quite small, the maximum value for the largest recorded earthquake is even less than 0.5 mm. Thus, it is



(a)



(b)

Fig. 8 Roof acceleration history - Base Isolated bldg. - 10th November, 2006 event (a) Shorter direction - peak 0.0019 g and (b) Longer direction – peak 0.0013 g

quite unlikely that the isolators would show any nonlinear behavior under all the considered earthquakes in the present study.

6. Numerical models

Numerical simulation of the prototype buildings has been done using SAP2000 Nonlinear. Beams and columns have been modeled as frame elements with appropriate geometric properties. Slabs have been modeled as area elements with diaphragm constraints to simulate the rigid diaphragm action of slabs. Fig. 9 shows the numerical models of the prototype buildings as created in SAP2000. Isolators have been modeled as link elements (CSI 2009) with the link type kept as rubber isolator. The biaxial hysteretic behavior of the isolators is based on the proposals by Wen (1976) and Park, Wen and Ang (1986). For the six deformation degrees of freedom (DOFs) the biaxial hysteretic isolator has coupled plasticity properties for two shear deformations and linear effective stiffness properties for the remaining four deformations.

The two shear DOFs, if nonlinear are characterized by coupled force deformation relationships given by

$$f_{s1} = r_1 k_1 d_{s1} + (1 - r_1) y_1 z_1 \tag{1}$$

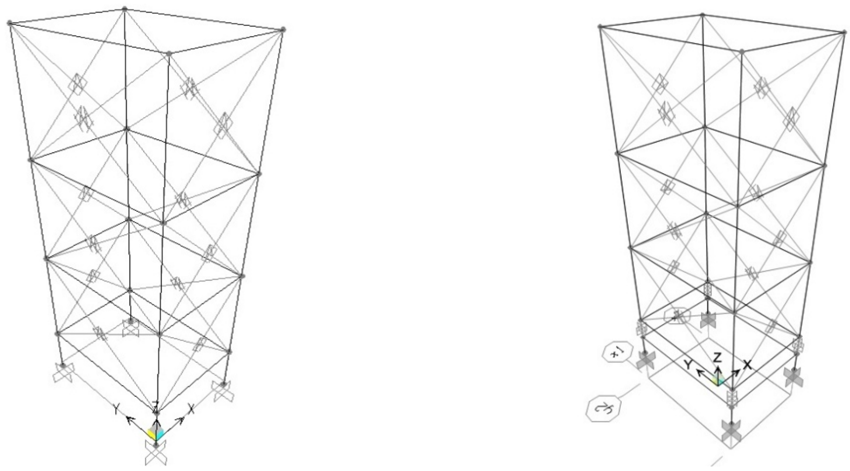


Fig. 9 3D SAP models of (a) Building with conventional foundation and (b) Building on seismic isolator

$$f_{s2} = r_2 k_2 d_{s2} + (1 - r_2) y_2 z_2 \tag{2}$$

where f_{s1}, f_{s2}, d_{s1}, d_{s2} are force and deformation in shear direction 1 and 2 respectively, r_1 and r_2 are the ratios of post yield stiffness to elastic stiffness, k_1 and k_2 are elastic spring constants, y_1 and y_2 are yield forces in shear direction 1 and 2 respectively. z_1 and z_2 are internal hysteretic variables.

The directional properties of the isolators, namely the two horizontal linear and non linear stiffness values K_1 and K_2 respectively, the effective stiffness K_{eff} , the yield strength Q and effective damping β_{eff} have been calculated from the load-deflection curves and the same have been used to characterize these link elements as isolators. Further, masonry infills in the structure have been modeled as compression struts using GAP element (CSI 2009). The stiffness contributed by walls to RC frames is an important factor to be taken into consideration in the modeling of a structure with infill walls. The wall stiffness has been calculated based on the equivalent strut method as enumerated in Jain and Murty (2006).

For this, the modulus of elasticity of masonry E_m is calculated as

$$E_m = 550 f_m \tag{3}$$

where f_m, the compressive strength of masonry prism is given by

$$f_m = K f_b^{\alpha} f_i^{\beta} \tag{4}$$

Here, K, α and β are constants and f_b and f_j are the compressive strengths of brick and mortar respectively (Kaushik *et al.* 2007).

7. System identification and numerical model updating

System identification techniques have emerged as effective tools for the evaluation of modal parameters of any structural system. System input and output are utilized to develop a mathematical model, which is utilized for the extraction of modal parameters such as natural frequencies, mode shapes and damping ratios. As such, modal parameter estimation by system identification has become very popular among researchers in the field of structural health monitoring. In this study, system identification by *Parametric State Space Modeling (N4SID)* has been employed for parameter identification of both conventional and base isolated buildings. The ground acceleration data at the building site is taken as input while acceleration responses from different floors of the actual structure are considered as output in the adopted identification strategy. The details of the adopted methodology may be seen in Medhi *et al.* (2007). However, a brief description of the strategy is presented below for ready reference.

7.1 Parametric state space modeling

The equation of motion for a finite dimensional linear dynamic system with **M**, ξ and **K** as mass, damping and stiffness matrices respectively can be expressed by the state equation as

$$\mathbf{M}\ddot{a} + \xi\dot{a} + \mathbf{K}a = f(a,t) \tag{5}$$

Where $\ddot{a}$, $\dot{a}$ and a are the vectors of acceleration, velocity and displacement respectively and $f(a,t)$ is the forcing function at any time t over a specific location. The system defined by Eq. (5) can be represented in State Space form as

$$\dot{x}(t) = \mathbf{A}x(t) + \mathbf{B}u(t) \tag{6}$$

where
$$A = \begin{bmatrix} 0 & I \\ -M^{-1}K & -M^{-1}\xi \end{bmatrix};$$

$$x = \begin{bmatrix} a \\ \dot{a} \end{bmatrix};$$

$$\mathbf{B} = \begin{bmatrix} 0 \\ \mathbf{M}^{-1}\mathbf{B}_2 \end{bmatrix}$$

And $f(a,t) = \mathbf{B}_2 u(t)$ and $u(t)$ are the inputs of the State Space Model.

The response of the dynamic system has been measured by output quantities using accelerometers and can be written as

$$y(t) = \mathbf{C}x(t) + \mathbf{D}u(t) \tag{7}$$

where
$$C = [-C_a M^{-1}K \quad -C_a M^{-1}\xi];$$

$$D = C_a M^{-1} B_2$$

As modern data acquisition systems used for collection of output response are generally digital, Eqs. (6) and (7) must be represented in discrete time. Thus, considering the discrete form and applying Z- transform, we get

$$Y(z) = H(z)u(z) \tag{8}$$

where $H(z)$ is the system transfer function relating the input and output. The detailed derivation has been given in Medhi *et al.* (2007). The values of z for which $H(z)$ is infinity are called poles. For a stable system, all poles must have a magnitude < 1 and should be located within the unit circle. The j^{th} pole of the system is given by

$$z_j = e^{(-\xi_j\omega_j \pm i\omega_j\sqrt{1-\xi_j^2})\Delta t} \tag{9}$$

where ξ_j and ω_j are damping ratio and frequency of the j^{th} mode of vibration. The frequency and damping ratio can be determined as follows

$$\omega_j = \frac{1}{\Delta t}\sqrt{\ln^2 r_j + \theta_j^2};\ \ \xi_j = -\frac{\ln r_j}{\sqrt{\ln^2 r_j + \theta_j^2}} \tag{10}$$

where $r_j = |z_j|$, the magnitude; and $\theta_j = \tan^{-1}[\mathrm{Im}g(z_j)/\mathrm{Re}(z_j)]$, the phase angle of the j^{th} pole.

The evaluated system matrix A has been utilized for the evaluation of Eigenvalues (λ) and their corresponding eigenvectors (φ). However, the modal matrix $(\mathbf{\Phi})$ corresponds to the non-physical state of the structure and hence, the C matrix is used to transform the computed eigenvector from the non physical state to the mode shape vector at the structural floor level, where the response data have been measured. Thus, the modal displacement vector for the structure corresponding to all the modes can be calculated as

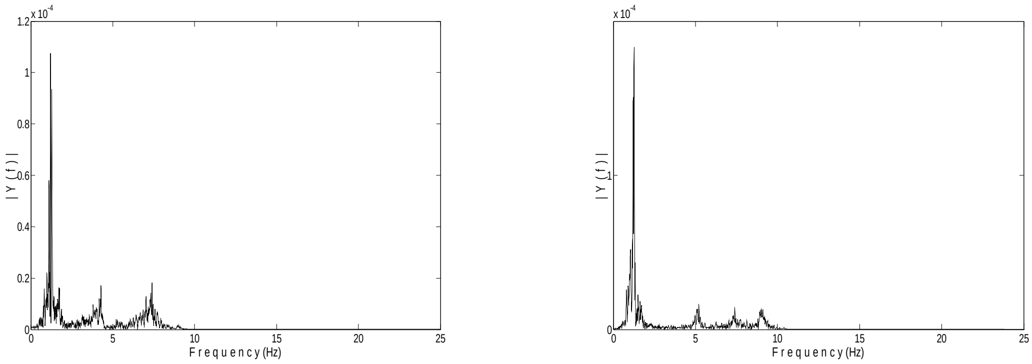
$$\Gamma = C\Phi \tag{11}$$

7.2 System identification of prototype conventional building

In order to demonstrate the effectiveness of the adopted system identification technique, the acceleration data from the conventional building were used first. The identified frequencies based on data corresponding to six earthquakes and those corresponding to the modal analysis of the 3D

Table 4 Natural frequencies of conventional building

Event date	Frequencies for conventional building (Hz)			
	Identified		SAP model	
	Shorter	Longer	Shorter	Longer
10th September, 2006	4.69	5.85	4.59	5.85
6th November, 2006	4.66	5.83		
10th November, 2006	4.71	5.91		
11th May, 2012	4.58	5.84		



(a) (b)

Fig. 10 FFT plot of recorded roof response of isolated building - Event - 10th November, 2006 (a) SHORTER direction, Peak at 1.209 Hz and (b) LONGER direction, Peak at 1.27 Hz

Table 5 Identified and modal frequencies from updated LRB model

<table>
<tr><th rowspan="3">Event date</th><th colspan="4">Frequencies for isolated building (Hz)</th></tr>
<tr><th colspan="2">Identified</th><th colspan="2">SAP model</th></tr>
<tr><th>Shorter</th><th>Longer</th><th>Shorter</th><th>Longer</th></tr>
<tr><td>10th September, 2006</td><td>1.23</td><td>1.24</td><td rowspan="4">1.245</td><td rowspan="4">1.273</td></tr>
<tr><td>6th November, 2006</td><td>1.25</td><td>1.28</td></tr>
<tr><td>10th November, 2006</td><td>1.21</td><td>1.22</td></tr>
<tr><td>11th May, 2012</td><td>1.24</td><td>1.27</td></tr>
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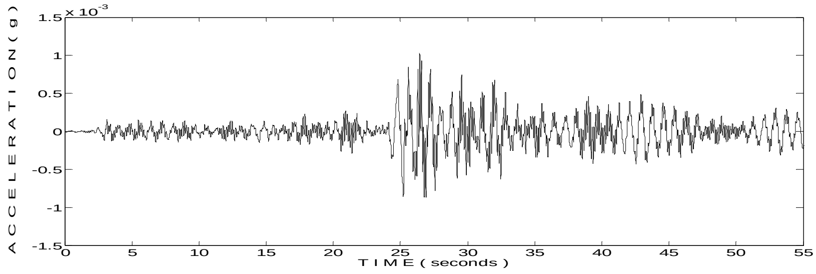
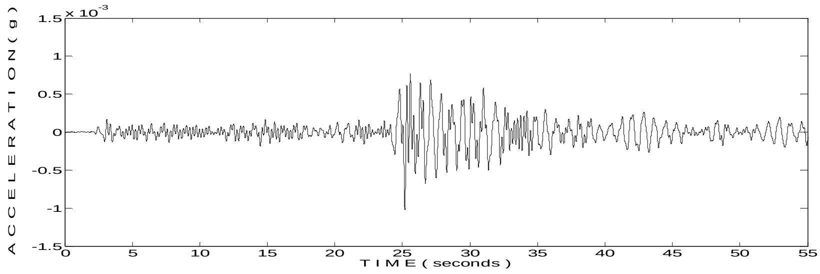
finite element model in SAP2000 are shown in Table 4. A very good agreement may be seen, which indicates the efficacy of the methodology.

7.3 System identification of LPB base isolated building

The identified frequencies obtained from the four considered earthquake records, namely the events on 10th September, 6th November, 10th November, 2006 and 11th May, 2012 for the base isolated building with LPBs have shown very good consistency as presented in Table 5. Fourier transforms of the recorded data corresponding to the earthquake event on10th November, 2006 are shown in Fig. 10 and it can be observed that the natural frequency of the isolated building obtained from identification and as the characteristic peaks of the Fourier transform are in good agreement with each other. Although these frequencies are different from the target value of 0.94 Hz considered in the design phase, it agrees with the low intensities of the events considered for the identification studies and absence of any live load on different floors of the building. Further, the natural frequencies obtained from the numerically simulated model of the base isolated building in SAP2000 without any live load on floors are observed to have some mismatch with the identified frequencies obtained from the recorded data. The fundamental frequencies as obtained from modal

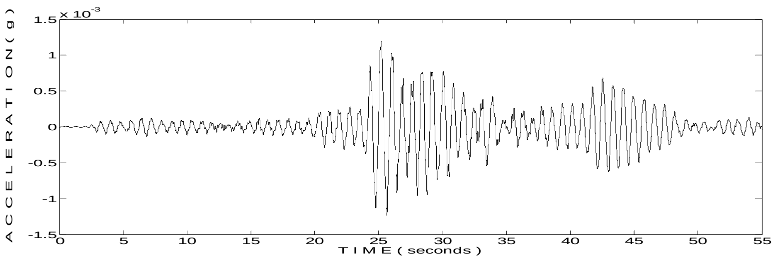


(a)

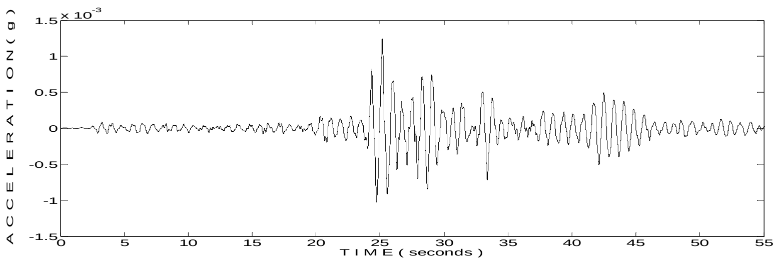


(b)

Fig. 11 Roof response of isolated building - LONGER direction; Event - 10th November, 2006; (a) Recorded response, Peak = 0.001021 g and (b) SAP response, Peak = 0.001011 g

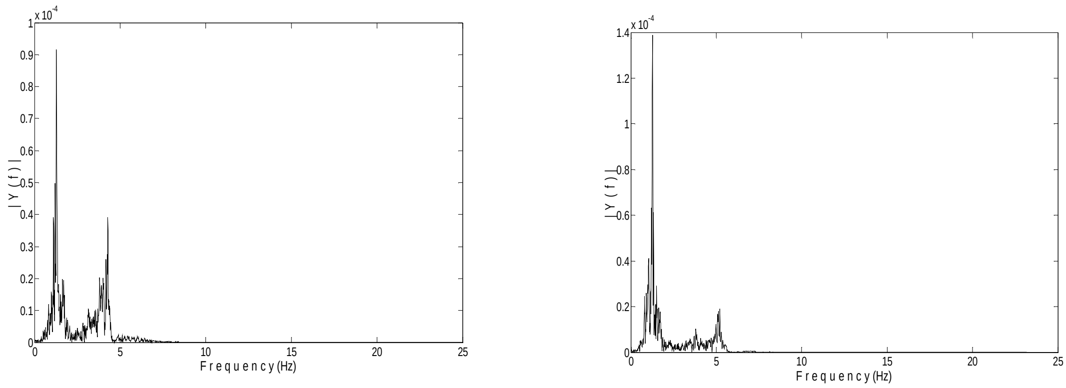


(a)



(b)

Fig. 12 Roof response of isolated building - SHORTER direction; Event - 10th November, 2006; (a) Recorded response, Peak = 0.001238 g and (b) SAP response, Peak = 0.001241 g



(a) (b)

Fig. 13 FFT plot of SAP roof response of isolated building - Event - 10th November, 2006; (a) SHORTER direction, Peak at 1.282 Hz and (b) LONGER direction, Peak at 1.27 Hz

analysis in SAP2000 are 0.98 Hz in the shorter direction and 0.99 Hz in the longer direction of the building. Hence, numerical model updating has been carried out. The bearing stiffness values have been selected to match the fundamental periods obtained from the identification technique as well as from the acceleration spectra. The stiffness of LPB isolators has been changed from 1072.85 KN/m assumed at the design phase to 1800 KN/m and represents much lesser deformation at the isolator level. With respect to damping, equivalent ratio of 10.5% has been used for the isolators, while superstructure modal damping has been set at 5% in each mode. The updated natural frequencies in the shorter and longer direction have been obtained as 1.245 Hz and 1.273 Hz respectively. These frequencies are observed as a close match with the frequencies obtained from identification and Fourier transforms of the recorded data. The modal frequencies from the updated numerical model in SAP2000 are also shown in Table 5.

Further, time history analysis of the updated LPB model of the isolated building has been carried out using Newmark's direct integration method. The ground motion history of 10th November, 2006 event has been used as time history input function and floor responses at every level have been obtained. A comparison of these numerically simulated responses with the recorded ones (Figs. 11-12) show that the simulated models have been able to represent the measured response from the actual building with good accuracy. Fig. 13 shows the FFTs of the roof responses of the SAP model. By examining Figs. 10 and 13 as well as Table 5, it can be stated that the updated numerically simulated model of the isolated building is a very good representation of the actual LPB isolated structure at site. The dominant frequencies as observed from the FFTs of the responses from the numerical model are in good agreement with both the identified frequencies as well as the FFTs of recorded response.

8. Conclusions

In the present study, the performance of two prototype buildings - a conventional structure and a base isolated one has been investigated. The buildings have been instrumented with force balance accelerometers. The ground motions and structural responses have been recorded at the site by a strong motion recorder. These data have been analyzed and have also been used for system identification studies. While the conventional prototype building has shown amplification in structural response, significant reductions (60 to 70%) in the floor responses of the isolated building have been observed. SAP2000 has been used to simulate numerical models of both the conventional as well as the base isolated building. On the basis of the results of system identification of the recorded data, the numerical models have been updated. Time history analysis of the updated LPB model has been performed and the results obtained have been found to be in good agreement with the recorded data. Fourier transforms of the numerically obtained time history results are also found to be in conformity with the Fourier transforms of the recorded data. The numerical models so developed can thus be said to be updated to a good degree and can be taken up as effective tools for taking this study to the next phase which may include nonlinear analysis and nonlinear system identification of the base isolated model.

The conclusions drawn from the present study can be enumerated as follows:

●As much as 60 to 70% reduction in the roof acceleration as compared to the ground motion has been observed for the isolation systems.

●Even though the seismic events registered are mostly of relatively low intensity, the isolation systems have been effective in reducing structural response of the isolated structure.

●The fundamental frequencies of the isolated building are quite different than the target value of 0.94 Hz as considered in the design phase. This may be attributed to the relatively low intensity of the seismic events which has not really excited the isolation systems to the nonlinear stage as well as due to the absence of live load on floors.

●The numerical models that have been created and updated have been able to represent the modal and dynamic characteristics of the actual buildings quite well.

●The LPB model seems to be functioning perfectly with a good degree of reliability.

The said models can further be employed as effective tools for nonlinear analysis and nonlinear system identification of the prototype buildings.

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