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Seismic performance of secondary systems housed in isolated and non-isolated building

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Abstract. The concept of base isolation for equipment is well known. Its application in buildings and structures is rather challenging. Introduction of horizontal flexibility at the base helps in proper energy dissipation at the base level thus reducing the seismic demand of the super structure to be considered during design. The present study shows the results of a series of numerical simulation studies on seismic responses of secondary system (SS) housed in non-isolated and base-isolated primary structures (PS) including equipment-structure interactions. For this study the primary structure consists of two similar single bay three-store reinforced cement concrete (RCC) Frame building, one non-isolated with conventional foundation and another base isolated with Lead plug bearings (LPB) constructed at IIT Guwahati, while the secondary system is modeled as a steel frame. Time period of the base isolated building is higher than the fixed building. Due to the presence of isolator, Acceleration response is significantly reduced in both (*X* and *Y*) direction of Building. It have been found that when compared to fixed base building, the base isolated building gives better performance in high seismic prone areas.

Keywords: base isolation; equipment; primary structure; secondary structure; lead plug bearing; response spectra

1. Introduction

The goal of aseismic design is to protect the primary structure (PS), as well as the structural content housed inside a building. During an earthquake, equipment contained in a structure is excited by these floor motions and interacts with the primary structure. Due to tuning of natural frequency or near tuning, certain secondary systems may be damaged significantly even in a low intensity earthquake. There have been numerous cases where non-structural components experienced major damage while the structure itself survived the earthquake event. In earthquake resisting design of structures containing critical and/or expensive equipment such as nuclear power plants, hospitals, computer centres, and telecommunication buildings, protection of secondary systems is as important as the structure itself. In recent years, considerable attention has been paid to research and development of structural control devices with particular emphasis on mitigation of seismic response of buildings. Many vibration-control measures like active, passive, semi-active and hybrid vibration control methods have been developed. Passive vibration control system helps in keeping the building to remain elastic during large earthquakes and has fundamental frequency lower than both its fixed base frequency and the dominant frequencies of ground motion. Base isolation is one of the passive vibration control system. Various studies have shown drastic reduction in peak accelerations and deflections in structure by using properly designed base isolation systems (Kelly 1986). Several analytical and numerical schemes for calculating peak response of Secondary systems (SS) have been developed (Sackman and Kelly 1979, Singh 1980). A state of art review on response of secondary systems has been presented by Chen and Soong (Chen and Soong 1988).

From the literature it is evident that first base isolated system was proposed by Kawai in 1981 after Nobi Earthquake (M=8.0) (Izumi 1988). Fan and Ahmadi carried out a study of floor response spectra for a base-isolated multi-storey structure under sinusoidal and seismic ground excitations, using several isolation systems such as laminated rubber bearing, the pure-friction, the resilient-friction, the Électricité de France and the sliding resilient-friction systems. A sinusoidal ground acceleration and several earthquake accelerograms (including those of El Centro 1940, Pacoima Dam 1971 and Mexico City 1985) were used to evaluate the floor response spectra and compared with those for the fixed-base structure. The effectiveness of properly designed base isolation system is shown for the protection of the structural contents against earthquakes (Fan and Ahmadi 1992). A state of the art review on the theoretical aspects of the seismic base isolation was presented in 1992 highlighting the currently used devices and future research propositions. (Jangid and Datta 1995). Implicit-implicit partitioned Newmark's method in predictor-corrector form for direct integration of individual coupled equations of motion in staggered fashion has been used for obtaining seismic response of base isolated buildings by solution of equations of motions. In this study response of a three-storeyed building isolated by lead rubber bearings subjected to bi-directional Koyna

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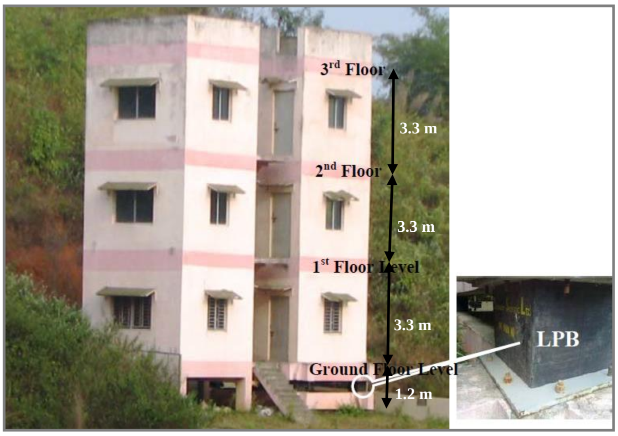
(1967) accelerograms (longitudinal and transverse components along *X* and *Y* direction of the building, respectively) are used (Deb *et al*. 1997). In 2004, 3-D nonlinear analysis for Seismic isolation was carried out and determined that it is suitable technology for protection of a variety of buildings that have the requisite dynamic characteristics (Deb 2004). Further, a procedure based on rigorous nonlinear analysis to an ensemble of ground motions representative of the spectrum was developed considering insensitivity of normalized deformations to ground motion intensity and hence minimizing the statistical variation of the normalized deformation to an ensemble of ground motions (Ryan and Chopra 2004). The influence of isolator characteristics on response of base isolated multi-storeyed building using bilinear hysteric and equivalent linear elastic plastic behaviours were compared and concluded that equivalent linear elastic plastic models for a bilinear hysteric model of the isolator underestimates the superstructure acceleration and over predicts the bearing displacements (Matsagar and Jangid 2004).

A number of experimental studies to illustrate the effectiveness of use of different types of base isolators for reducing the lateral-force demand for structures in areas of high seismicity are carried out. (Paulson *et al*. 1991, Aiken *et al*. 1993, Aiken 1996, Kikuchi and Aiken 1997). The performance of code designed fixed-base and base-isolated concrete frames were compared through time-history analyses conducted for three ensembles of recorded earthquakes. Analysis considered the nonlinear behaviour of the isolation system and superstructure. Base-isolated concrete moment frame designed to between 25% and 50% of the code-recommended base shear performed comparably to the fixed-base design, when based on, extent of superstructure yielding, average relative roof displacement, average first-story drift and average time of first yielding in the superstructure. (Shenton and Lin 1993). The numerical evaluation of the efficiency of anti-vibration mechanisms applied to typical frame structures under earthquake with and without anti-vibration mechanisms is compared, modelling the building structure by finite elements and placing the anti-vibration mechanism at the building base when subjected to an artificial earthquake equivalent to El Centro (Bezerra and Carneiro 2003).The seismic behaviour of four seismically isolated buildings from their recorded response for earthquakes producing various amplitudes and durations of shaking was studied considering the responses of multiple buildings to multiple earthquakes, using consistent procedures. The study evaluates soil-structure interaction effects, and achieves new insights into isolation system behaviour by examining temporal variations in system properties (Aiken 2003). The use of lead-rubber bearings (LRB) for isolation of building was investigated using the time-dependent equivalent linearization technique as the force-deformation behaviour of the LRB is highly nonlinear (Jangid 2010). Rao and Jangid (2001) carried out an experimental shake table study for the response of the structures supported on base isolation systems to determine the effectiveness of isolation in reducing response acceleration of the system.

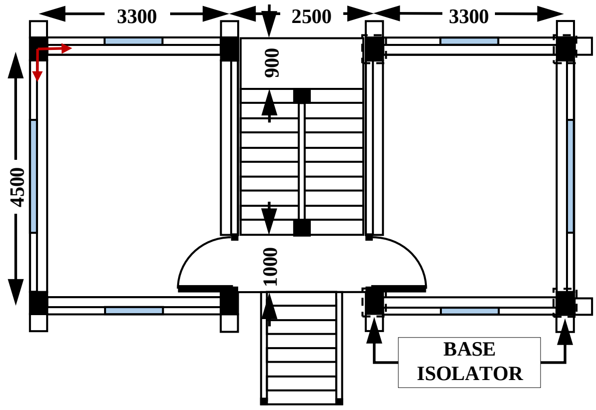
The studies on the secondary systems housed in isolated and non-isolated buildings have been reported. The evolution of the methods used to analyse the secondary systems are discussed. The developments starting with the direct generation of floor response spectra up to the recent introduction of the cross floor response spectra as the seismic inputs for the analysis of multiply supported secondary systems are discussed (Singh 1988). Another experimental study on the feasibility of base isolation for seismic protection of non-structural secondary system such as sensitive instrumentation, computer equipment, communication network, HVAC facilities, and power transmission systems housed in non-isolated primary structures is concluded by Khechfe *et al*. (2002). Rolling type base isolation systems have been proven to be very effective in improving the seismic performance of operational and functional components attached to the main structural system. Rolling type base isolation system called Tuned Configuration Rail (TCR) are successfully applied during the last few years in seismic base isolation of private housing, computer servers and more widely in museum showcases. It is a compact isolator that significantly reduces the acceleration response and can be easily installed underneath new or existing showcases, museum artifacts, preservation racks, shelves and statues (Mysliniaj *et al*. 2003).

The effectiveness of double concave Friction Pendulum Bearings and effect of soil-structure interaction for a building isolated with FPS was studied by Sevket (2012), Krishnamoorthy (2013) respectively. Various other systems with very particular characteristics, such as an elastomeric bearing with shape-memory alloy studied by Gur *et al*. (2013), a magneto-rheological elastomeric bearing developed by Li *et al*. (2013), hysteretic restoring force characteristics and analytical model of the Teflon-based lead rubber isolation bearings by Lu *et al*. (2013) and Cone-type Friction Pendulum Bearing System to control the acceleration delivered to a structure for prevention of the damage and degradation of critical communication equipment during earthquakes by Jeon *et al*. (2011, 2015). A numerical and experimental study for the validation of model of a building with and without roller seismic isolation bearings subjected to base excitations was carried out by Nelson *et al*. (2013). Other major breakthrough in the study of base isolation systems are reported for investigating seismic responses of a base-isolated nuclear power plant (BI-NPP) by Mohamed *et al*. (2015), for seismic mitigation system using connecting dampers to connect an existing building to a base-isolated building by Zhidong and Eddie (2015), and very recent study on behaviour of irregular building using two types of base isolation system ie hybrid base isolation system (HDRB+ FS) that is realized by a High Damping Rubber Bearing (HDRB) and hybrid base isolation system (LRB+FS) that is realized by a Lead Rubber Bearing (LRB) by Cancellara and Angelis (2016). Dynamic nonlinear analysis of hybrid base isolation systems has been investigated by, Cancellara and Angelis (2012, 2012)

In this paper, the effect of base isolation on secondary structures and comparison of its responses when housed in a fixed-base building frame and base isolated building frame



(a) Elevation of building



(b) Plan of building (All dimensions in mm)

Fig. 1 Layout of building

under seismic loading has been presented. In order to study the structural behaviour of isolated building under actual earthquake the full-scale prototype of two, three-storied framed RCC building with similar construction, one with conventional foundation and other with base isolation have been constructed at Indian Institute of Technology, Guwahati under a BRNS project (Dubey *et al*. 2007). The buildings are equipped with the response monitoring system consisting of accelerometers installed at various floor levels. These two structures have been considered as the Primary structure in the present study. Guwahati is situated in the most severe earthquake zone (Zone V) of North East part of India. North East India is lying at the juncture of Himalayan Arc to the North and Burmese Arc to the East and it is one of the most active regions of the world. Thus, this structure provides good opportunity to observe the performance of base isolated structure under the action of frequently occurring earthquakes in this region. The data recorded during an earthquake event on November 06, 2006 is used for study and validation purpose. The study aims at validation of design properties of the isolation system used and to formulate different kinds of guidelines for base isolated structures in Indian subcontinent. Fig. 1 shows the two prototype buildings along with base isolation system.

2. Details of structure

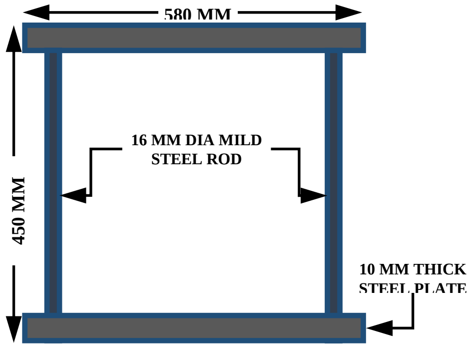


Fig. 2 View of considered secondary system

2.1 Primary structure

The selected primary structure is a three storey Reinforced Cement Concrete (RCC) frame building located at Indian Institute Technology Guwahati, left one with fixed-base and other on right with base Isolated. The plans of the both buildings are identical and symmetrical in plan dimensions as shown in the Fig. 2(b) with the position of base-isolators marked. Both buildings have a plan dimension of 4.5 m in longer span and 3.3 m in shorter span. The columns have a cross section of 400 mm x 300 mm with the longer dimension oriented along longer span of building. The beams have an equal width of 250 mm on both the direction of building and a depth of 450 mm along longer span and 350 mm along shorter span. The masonry infills are 250 mm thick and slab thickness is 150 mm. Both the buildings share a common staircase placed between them. The staircase is built separately, completely disconnected from two buildings with some gap such that it does not modify or affect the dynamic characteristics of both the buildings.

2.2 Secondary structure

As shown in the Fig. 2, the secondary system comprising of two square plates of 580 mm sides, supported at the corners with the help of 16 mm diameter mild steel rods has been considered. The square plates at top and bottom had a uniform thickness of 10 mm.

3. Mathematical and numerical formulation

Elastomeric bearings are most commonly used as base isolator by various researchers and engineers. These are composed of alternating layers of steel and hard rubber and, for this reason, it is also known as the laminated rubber bearings. These types of bearings have sufficient stiffness to sustain the vertical loads, yet flexible under the lateral forces. The ability to deform horizontally enables the bearing to reduce significantly the structural base shear transmitted from the ground. Major function of elastomeric bearings is to reduce the transmission of shear forces to the superstructure by lengthening the vibration period of the entire system, while maintaining sufficient vertical stiffness to the structure.

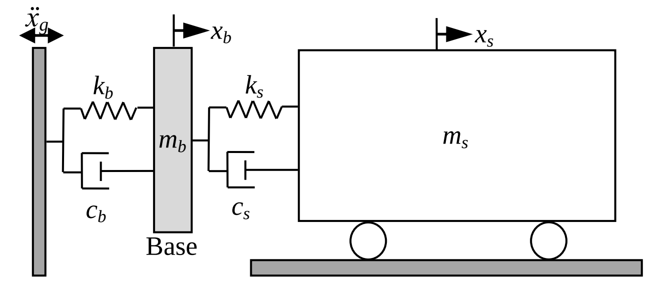


Fig. 3 Mathematical model of base-isolated primary system

In reality, the reduction in the seismic forces transmitted to a superstructure through the installation of laminated rubber bearings is achieved at the expense of large relative displacements across the bearings. If substantial damping can be introduced into the bearings or the isolation system, then the problem of large displacements can be alleviated. It is for this reason that the laminated rubber bearing with a central lead plug inserted has been devised. To simulate the dynamic properties of the lead plug bearing (LPB) system, an equivalent bi-linear system has been proposed. Fig. 3 shows the mathematical model of base isolated primary system which is subjected to support acceleration $\ddot{x}_g$. By representing the isolated structure as a single - DOF system, based on the assumption that the superstructure is rigid in comparison with the stiffness of the lead plug bearings, the equation of motion for the entire system can be written as

$$\begin{bmatrix} m_s & 0 \\ 0 & m_b \end{bmatrix} \begin{Bmatrix} \ddot{x}_s \\ \ddot{x}_b \end{Bmatrix} + \begin{bmatrix} c_s & -c_s \\ -c_s & c_b + c_s \end{bmatrix} \begin{Bmatrix} \dot{x}_s \\ \dot{x}_b \end{Bmatrix} + \begin{bmatrix} k_s & -k_s \\ -k_s & k_b + k_s \end{bmatrix} \begin{Bmatrix} x_s \\ x_b \end{Bmatrix} = -\begin{Bmatrix} m_s \ddot{x}_s \\ m_b \ddot{x}_b \end{Bmatrix} \tag{1}$$

where m_s, c_s and k_s denote the mass, damping and stiffness of the super structure (i.e., primary structure), respectively, m_b, c_b and k_b denote the mass, damping and stiffness of the base. x_s and x_b denote the displacement of superstructure and base, respectively.

Fig. 4 shows the mathematical formulation for the structure-equipment isolation system. The governing equation of motion for base isolated primary structure housing secondary system when subjected to ground accelerations $\ddot{x}_g$ is given by

$$\begin{bmatrix} m_e \ddot{x}_e \\ m_s \ddot{x}_s \\ m_b \ddot{x}_b \end{bmatrix} + \begin{bmatrix} c_e & -c_e & 0 \\ -c_e & c_s + c_e & -c_s \\ 0 & -c_s & c_s + c_b \end{bmatrix} \begin{Bmatrix} \dot{x}_e \\ \dot{x}_s \\ \dot{x}_b \end{Bmatrix} + \begin{bmatrix} k_e & -k_e & 0 \\ -k_e & k_s + k_e & -c_s \\ 0 & -k_s & k_s + k_b \end{bmatrix} \begin{Bmatrix} x_e \\ x_s \\ x_b \end{Bmatrix} = -\begin{Bmatrix} m_e \\ m_s \\ m_b \end{Bmatrix} \ddot{x}_g \tag{2}$$

The equation of motion for the base mass under seismic excitation is given by

$$m_b \ddot{x}_b + F_b - kx - c\dot{x} = -m_b \ddot{x}_g \tag{3}$$

where F_b is the restoring force of the base isolator given by

$$F_b = c_b \dot{x}_b + k_b x_b \tag{4}$$

The response of the base-isolated building can be obtained by solving the above equations using the step-by-step Hilber-Hughes-Taylor method.

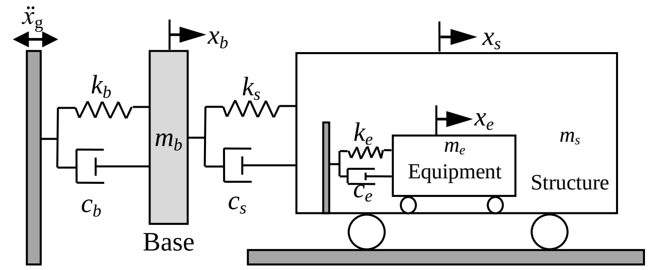


Fig. 4 Mathematical model of structure-equipment isolation system

Table 1 Parameters of Isolator used in primary and secondary structure

Model	Property	Value
Primary System	Mass	0.5 T
	Vertical Stiffness	188960 kN/m
	Post Yield Stiffness	796 kN/m
	Ratio of Post to Pre yield stiffness	0.0463
	Effective Damping	0.1056
	Yield Strength	25.38 kN
	Effective Horizontal Stiffness	1292.085 kN/m
Secondary System	Vertical Stiffness	1089.40 kN/m
	Effective Horizontal Stiffness	46.8 kN/m
	Effective Damping	0.05

Lead plug bearings, which were installed in primary structures, consists of alternate layers of rubber and steel shims with a lead core at the centre. Each isolator has a vertical stiffness of 188960 kN/m with a vertical load carrying capacity of 50 tonnes (Kikuchi and Aiken 1997). The bearings are 480 mm in both length and breadth and 345 mm in height. A steel plate, 20 mm thick and 68 cm in length and breadth is attached to the bearings at top and bottom for fastening the same to the beams of the building. Elastomeric bearings, installed in secondary structure, have a vertical stiffness of 1089.40 kN/m. The bearings are 80 mm in both length and breadth and 36 mm in height. A steel square plate, 12 mm thick and 110 mm in length and breadth is attached to the bearings at top and bottom for fastening the same to the beams of the building.

3.2 Numerical model of primary and secondary system

The numerical modelling and simulation of the primary and secondary model is carried out in SAP2000. For this purpose 3-Dimensional models of the structure were created in the software to the full scale and the parameters like material properties, loads and support conditions were assigned in a reliable way to predict actual seismic behaviour of the structure. All the materials used in the structure are modeled as per relevant Indian standards using the material properties specification used in the construction of buildings.

3.3 Modeling of structural members

The modeling of different structural members is carried out with the help of SAP2000. In order to simulate the actual behaviour of the structure different members are modeled with same loading conditions, dimensions, isolator character and boundary conditions.

Beams and columns of the structure are modeled as frame elements with same dimensions and reinforcement as provided in the actual building. The columns are assigned fixidity at the foundation level. The self-weight of the structure is automatically taken in account by the software from the dimensions and material properties assigned to different structural members of building. The load from the walls and parapet is considered as uniformly distributed on the beams. The slabs are modeled as the four noded area elements with diaphragm constraints assigned to each node in order to ensure a rigid diaphragm action at each floor level. The steel plates are assigned rigid diaphragm constraints, since, the structure is analysed only for horizontal component of earthquake. Thus rigid diaphragm assumption may be used in the plane of floor and effect of vibration mode of floor is considered insignificant for lateral component of earthquake. On the floor carrying the secondary structure extra nodes are created at appropriate position to study the interaction effect of primary and secondary structure by attaching the secondary structure to these nodes with different boundary conditions. The dead load and live load on of the slab is transferred to the beams in the form of triangular and trapezoidal loadings.

Steel plates of secondary structure are modeled as shell element with appropriate dimensions and material properties. The steel plates are modeled on top and bottom of steel rods as a frame. Self-weight of steel plates and columns are automatically taken into account.

3.4 Modeling of infill walls

Equivalent diagonal strut method is used for modeling the brick infill wall to easily represent the effect of inplane walls during lateral load. In SAP 2000 diagonal strut is modeled as cross-braces with no tension assigned to the members using gap element. Calculations for equivalent diagonal strut width for full infill are performed as follows.

The following Eq. (5) is used to calculate the effective width of diagonal compression strut. The geometric properties of the diagonal strut have been derived from the geometric properties of brick walls using procedures given in FEMA 306.

$$Effective\ width\ (a) = 0.175(\lambda_1 h_{col})^{-0.4}.r_{inf} \qquad (5)$$

where

h_{col}=Column height in inch

r_{inf}=Diagonal length of Masonry Infill panel in inch as shown in Fig. 5.

λ_1 is given by

$$\lambda_1 = \left[\frac{E_{me} t_{inf} Sin\ 2\theta}{4E_{fe} I_{col} h_{inf}}\right]^{0.25} \qquad (6)$$

where, E_{me} and E_{fe} are expected modulus of elasticity of masonry (secant modulus of elasticity between 5% and 33% of masonry prism strength) and frame material, respectively.

t_{inf} =Actual thickness of Masonry Infill in contact with frame

θ =Iinclination of diagonal strut with horizontal

I_{col}=Moment of inertia of column

h_{inf}=Height of Masonry Infill panel

Thickness of equivalent diagonal strut is taken equal to actual thickness of the wall. Various parameters for the building being analysed are given in Table 2 below:

Fig. 5 shows the diagrammatic representation of the representation of equivalent diagonal strut model of masonry wall.

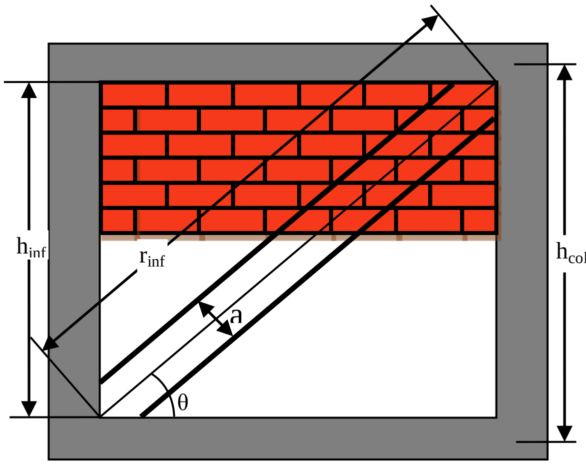


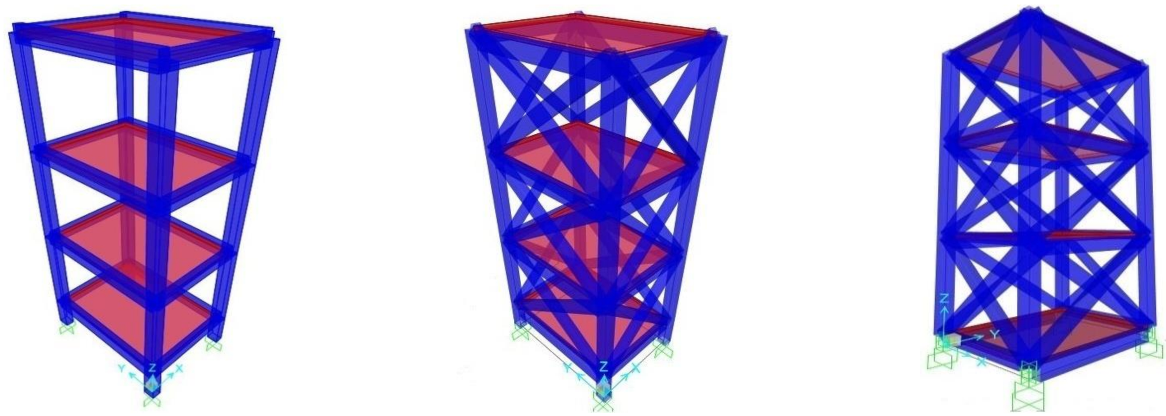
Fig. 5 Diagonal strut model of masonry infill

Table 2 Parameters of building for calculation of diagonal strut

Parameter	Dimension
h_{inf}	130 inch
h_{col}	130 inch
r_{inf}	219.698 inch (longer side) 183.73 inch (shorter side)
θ	θ=36° (longer side) θ=45° (shorter side)
I_{col}	3.85×103 inch^4 (longer side) 2.162×103 inch^4 (shorter side)
λ_1	0.08238 0.09637
Effective Width (a)	0.3783 m for longer side 0.2971 m for shorter side

4. Validation of model

Verification and validation of computer simulated model is conducted during the development of simulation model with the ultimate goal of producing an accurate credible model. The reliability of a numerical simulation depends upon the accuracy of modeling. Numerical simulations are increasingly relied upon for making critical engineering decisions. Thus, it becomes important that the generated model should yield accurate simulation results, which are



Fixed base building without infill   Fixed base building with infill   Base-Isolated building with infill

Fig. 6 Models of the buildings with fixed base and with base isolation

close to real system. The modal analysis of primary structure is carried with SAP 2000 and the results thus obtained are cross verified with the results of modal analysis performed (Dubey *et al*. 2007). In order to validate the seismic behavior of simulation model under applied earthquake ground motion, the simulated Time-History response at different floors of modeled building (Fixed and Base Isolated) are compared with the actual field recorded values during considered earthquake event. The mass of the normal building is estimated around 120.44 Ton which is 3.75 Ton greater than estimated by Dubey *et al*. (2007). The Fig. 6 shows the model of fixed base building with and without infill. The model generated considering the stiffness of infill gives much realistic results than the model without considering infill. The masonry infills are modeled as the equivalent diagonal strut with no tension assigned to it and the geometric and material properties of strut have been taken from geometry of brick (FEMA-306). The struts are aligned diagonally along both the direction of building and the Thickness of strut is taken equal to thickness of masonry infill. Fig. 6 shows the view of base isolated building modeled in SAP 2000. The secondary structure considered is an arbitrary structure considered for the purpose of study. The validation and verification of the secondary structure is not included in this study. However, if a validated model equivalent to an artifact is simulated the, the results if available for such a secondary structure can also be validated.

5. Results and discussion

5.1 Modal mass participation and frequencies of building

Modal analysis of normal building (without infill and with infill) and base isolated building is carried out in SAP2000 to obtain fundamental natural frequencies and modal mass participation. Various results obtained are tabulated below and a comparison has been made with Dubey *et al*. (2007).

From Table 3 and 4 it can be seen that frequencies and mass participation obtained are matching. From the two cases it can be clearly observed that there is about three times hike in fundamental frequencies of normal building when the stiffness of infill walls are considered and mass participation in higher modes are insignificant.

Table 3 Modal mass and mass participation of normal building without infill

Without Infill [SAP2000]				
Mode	Frequency (Hz)	Mass participation (Kg)		
		M(*x*)	*M*(*y*)	*M*(*z*)
1	1.25	83103	0	0
2	1.54	0	83103	0
4	3.90	9635	0	0
5	4.88	0	10011	0
10	13.44	0	0	66242
11	15.67	0	0	9635

Table 4 Modal mass and mass participation of normal building with infill

With Infill [SAP2000]				
Mode	Frequency (Hz)	Mass participation (Kg)		
		M(*x*)	*M*(*y*)	*M*(*z*)
1	4.66	98760	0	0
2	6.12	0	98760	0
4	12.17	20474	0	0
5	14.58	0	0	62628
6	15.65	0	20474	0
7	16.04	0	0	9665

Table 5 Modal mass and mass participation of base isolated building

Isolated Building [SAP2000]				
Mode	Frequency (Hz)	Mass participation (Kg)		
		M(*x*)	*M*(*y*)	*M*(*z*)
1	2.08	97750	0	0
2	2.43	0	104650	0
4	6.00	17250	0	0
5	6.73	0	9200	0
6	8.98	0	0	111550

Table 6 Acceleration response of normal building at different floor level

Parameter	Normal Building Recorded PGA (Dubey *et al*. 2007)	Normal Building (without Infill) PGA, SAP 2000	Normal Building (with Infill) PGA, SAP 2000
Response at Third Floor, *Y*-Direction	0.00653	0.00269	0.00549
Response at First Floor, *X*-Direction	0.00411	0.00266	0.00517
Response at Third Floor, *X*-Direction	0.00942	0.00274	0.00928

Table 7 Acceleration response of base isolated building at different floor level

Parameter	Isolated Building Recorded PGA (Dubey *et al*. 2007)	Isolated Building PGA, SAP 2000
Response at Third Floor, *Y*-Direction	0.00168	0.00167
Response at First Floor, *X*-Direction	0.00163	0.00163
Response at Third Floor, *X*-Direction	0.00137	0.00136

From Table 5, it can be observed that about 85% mass participation takes place in 1st and 2nd modes in *X* and *Y* direction whereas 6th mode is in *Z* direction with 92.6%. In base isolated building maximum mass is getting participated in 1st mode in each direction whereas in normal building it is distributed to higher modes also.

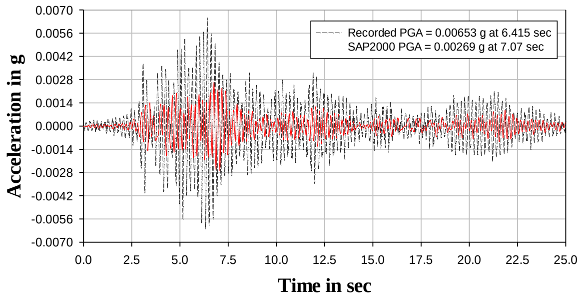
5.2 Comparison of simulation result of floor response of normal building and base isolated building with recorded data

Time history analysis is performed on the buildings using the available known time history and the maximum absolute acceleration of different floors in *X* and *Y* direction are tabulated and compared with the recorded values at field during specified seismic event. From the result obtained in Table 6, it can be clearly observed that the presence of infill walls greatly affect the dynamic characteristics of a building and much better results are obtained when stiffness of wall is taken into account. Thus while analyzing a building proper care should be taken to account for infill walls. In general, while performing the static analysis of a building the building frame is analysed as a bare frame and the infill walls are only incorporated as a dead loads. Thus, it is necessary to account for the stiffness of infill as they significantly affect the dynamic response of a structure. Table 7 shows the result of acceleration response of base isolated structure.

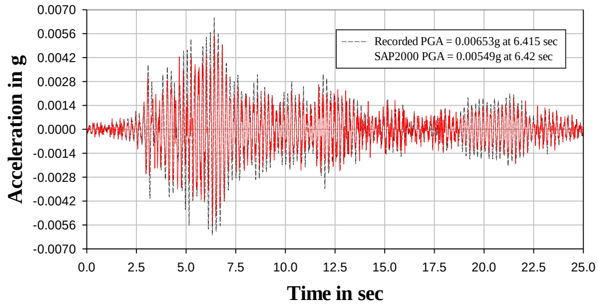
The graphical comparisons of time histories of different floors of building are represented in the figures below.

5.3 Floor response spectra for normal building and base isolated building

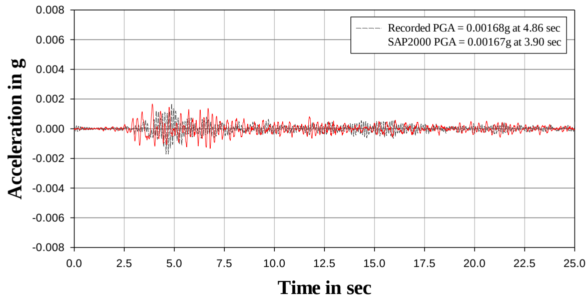
From the floor time histories of normal building, floor response spectra at 5% damping have been generated and shown in Fig. 7(a), (b) and (c), at 3rd floor *Y*-direction, 1st and 3rd floor in *X*-direction respectively. From Fig. 7(a), (b) and (c), it can be observed that spectral peaks of recorded response and analysis response are matching and occurring at almost same frequency, when stiffness of infill walls are considered in the analysis and are differing when infill walls are not considered.



(a) Normal building (without infill)



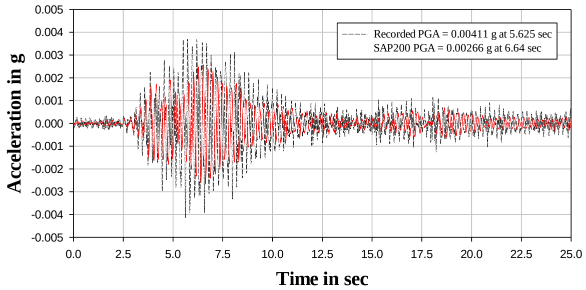
(b) Normal building (with infill)



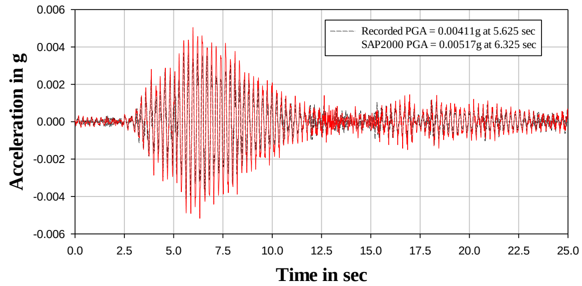
(c) Isolated building (bi-linear)

Fig. 7 Response of building in 3rd floor *Y*-direction

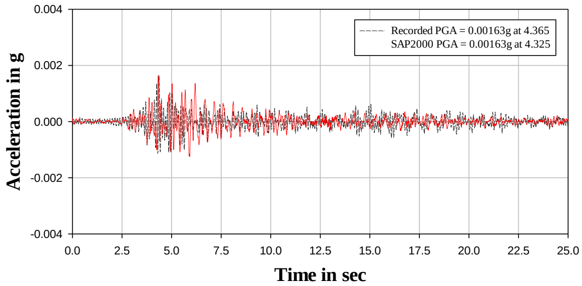
From Figs. 8(a), (b) and (c) and 9(a), (b) and (c) similar pattern is observed. For the base isolated building assuming bilinear hysteric model of the isolator. The floor response spectra at 5% damping for 3rd floor *Y*-direction, 1st and 3rd floor in *X*-direction respectively have been generated and shown in Fig. 10 (a), (b) and (c) for normal building and Fig. 11 (a), (b) and (c) for base isolated building. From Fig. 10 and Fig. 11, it can be observed that peak of recorded response and simulated response are almost matching and occurring at same frequency. The response acceleration of both normal as well as isolated building when considered with infill are nearer to the recorded values. However the peaks are occurring at same frequency as frequency at peak acceleration of structure is function of ground motion characteristics. From the above ground spectra of earthquake time history it may be noted that maximum peak acceleration takes place at near 25 Hz which is far away from fundamental frequencies of both structure (with infill



(a) Normal building (without infill)

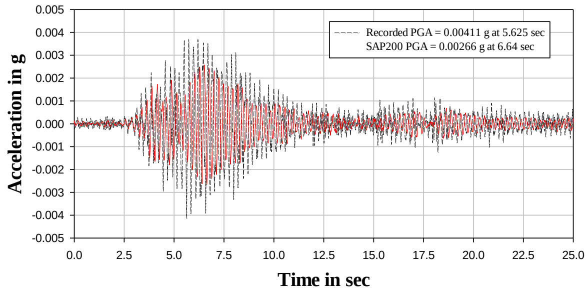


(b) Normal building (with infill)

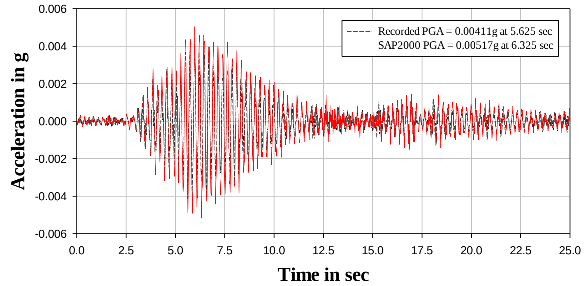


(c) Isolated building (bi-linear)

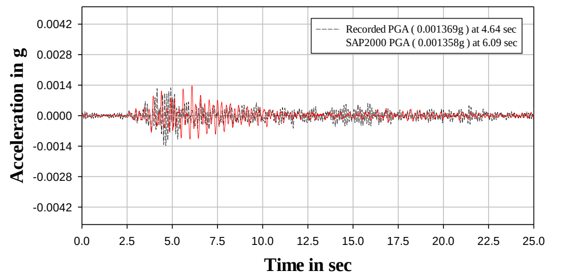
Fig. 8 Response of building in 1st Floor *X*-direction



(a) Normal building (without infill)

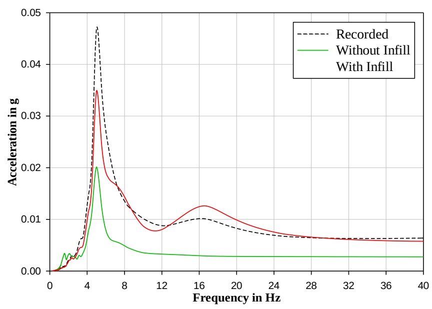


(b) Normal building (with infill)

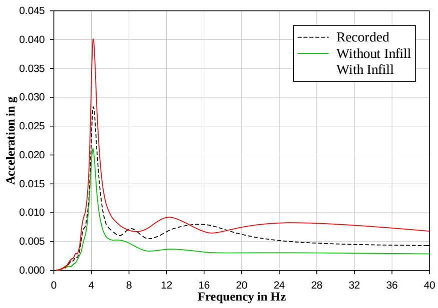


(c) Isolated building (bi-linear)

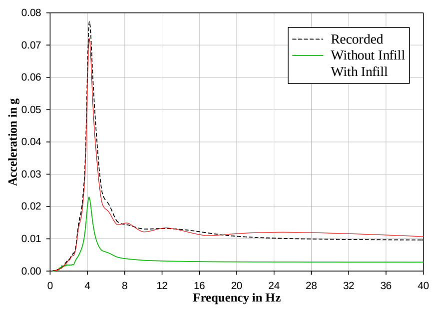
Fig. 9 Response of building in3rd floor *X*-direction



(a) At 3rd Floor in *Y*- Direction



(b) At 1st Floor in X- Direction



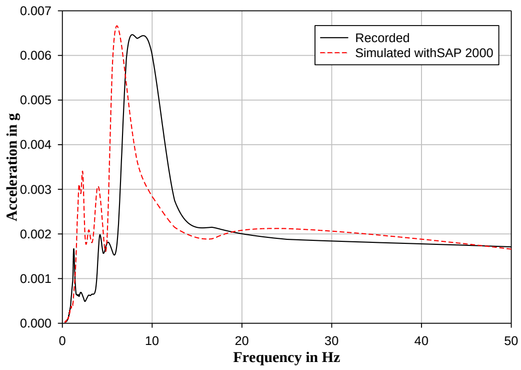
(c) At 3rd Floor in X- Direction

Fig. 10 Response spectra at 5% damping for normal building

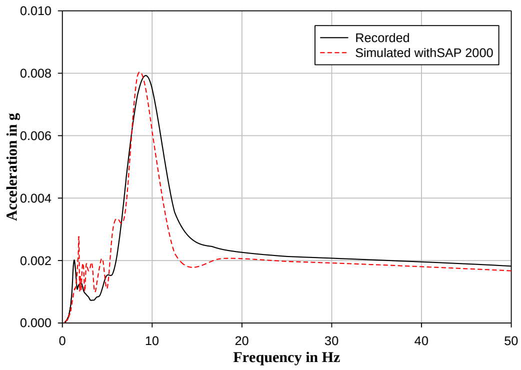
and without infill). But the fundamental frequencies of building with infill (1st mode) and without infill (4th mode) are much closer to the Peak ground acceleration of 4Hz-5Hz. Thus it may be concluded that the peak acceleration of both structures takes place at same frequency but at different modes of vibrations.

5.4 Simulation models developed

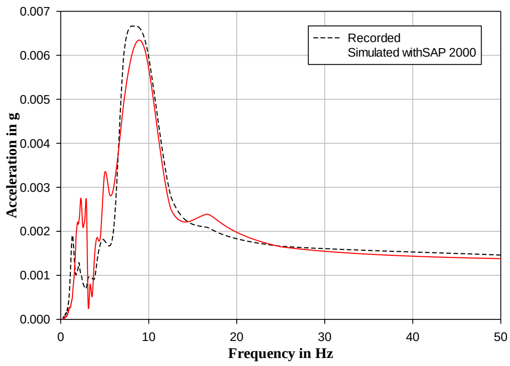
In order to study the dynamic response of the secondary system housed in a primary structure subjected to near-fault ground motions, a numerical investigation is carried out by developing various simulation models of the normal as well as base isolated building in SAP 2000. Fig. 12 (a) shows the simulation model of fixed base secondary system housed at various floors of fixed base primary structure. Fig. 12(b) shows the base isolated secondary system housed in a fixed base building. Fig. 12(c) illustrates the base isolated primary structure with base isolators incorporated between foundation and super structure and fixed base secondary structure installed at various floor levels. Fig. 12(d) and Fig. 12(e) shows the fixed base secondary system and base isolated secondary system modeled separately when Primary-Secondary interactions are not taken into



(a) At 3rd Floor in *Y*- Direction



(b)At 1st Floor in *X*- Direction



(c) At 3rd Floor in *X*- Direction

Fig. 11 Response spectra at 5% damping for isolated building

Table 6 Details of earthquake event recorded

Event Date	Magnitude on Richter Scale	Epicenter	Focal Depth (km)	PGA in units of g		Region
				Shorter direction	Longer direction	
06/Nov/2006	5.2	24.736°N 95.223°E	122.6	0.003	0.0021	Myanmar

consideration.

5.5 Comparison of floor response of primary and secondary system under different cases

The time history records of Guwahati region Earthquake (November 06, 2006) data recorded at Indian Institute of Technology, Guwahati is used for the time history analysis (Dubey *et al*. 2007). This earthquake had a magnitude of 6.2 on the Richter scale and its epicenter was reported at latitude 24.736°N and longitude 95.223°E in Myanmar border region with focal depth around 122.6 km. Table 9 gives the details of seismic event recorded at site. From the available time history functions two records along the horizontal directions of building are chosen for analyses which are shown in Fig. 13 (a) and (b) for shorter and longer direction respectively. Each record is divided into 5000 points of acceleration data equally spaced at an interval of 0.005 sec. (In Units of acceleration due to g).

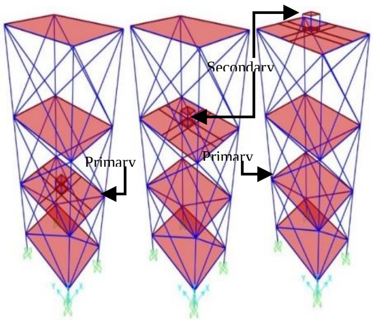
An analysis of acceleration response of secondary system for the chosen time history shows the magnification in acceleration response for fixed base secondary structure while significant reduction of acceleration response has been observed for the isolated secondary structure. It is evident from the results obtained that base isolation technology helps in significantly reducing the response of secondary system attached to primary structure. Table represents the relative performance of base isolation system used under different cases.

Maximum absolute displacement, velocity and acceleration of the frame subjected to time history analysis are recorded at each floor in both *X*-direction and *Y*-direction. No displacement is recorded at the base since the base is in the fixed condition. Storey displacements are plotted graphically as shown in Fig. 15(a).Displacement of the frame in each floor in *Y*-direction is found to be very less as compared to the displacement of the frame in the *X*-direction when it is subjected to time history force and this is due to higher stiffness in *Y*-direction. The building shows soft storey behaviour at the bottom 1.2 meter due to lack of infill walls at this portion. From Fig. 15(b) it is clear that slope of the storey velocity graph gets steeper for the successive upper stories as compared to lower storey, which indicates that storey velocity is more in the lower storey and it goes on decreasing in the successive upper stories. As the floors are assumed to be rigid in its plane, and the mass is assumed to be lumped at each floor level, thus the storey velocity and storey acceleration are the peak velocity and acceleration of respective floors/storey. Figure 15(c) indicates that slope of the storey acceleration graph gets steeper for the successive upper stories as compared to lower storey, which indicates storey acceleration is more in the lower storey and it goes on decreasing in the successive upper stories.

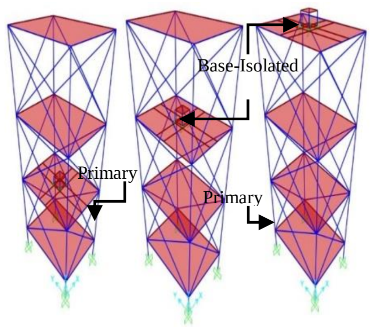
Response of fixed base secondary system placed on different floors of fixed base primary structure is studied under both the conditions while considering interaction and without considering interaction between them.

For the first case, without considering interaction between fixed base secondary structure (SS) and fixed base primary structure (PS) the earthquake ground accelerations are applied at the base of PS and output floor response are taken at different floor levels of building. From this analysis, the responses obtained at different floors of PS are applied to the base of SS modeled separately to achieve the response without interaction.

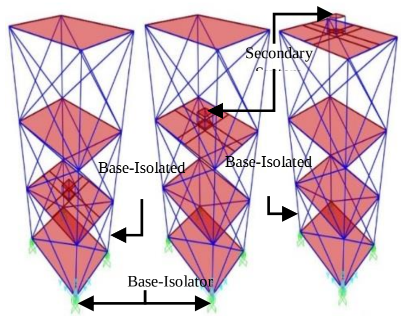
For the second case considering interaction, the fixed base SS and fixed base PS are modeled together (i.e. SS is attached to the required floor of PS) and the earthquake ground accelerations are applied at the base of PS. In this case the interactions between primary and secondary



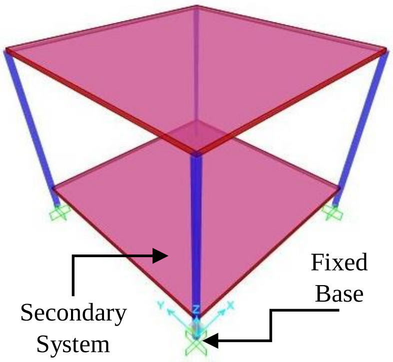
(a) Fixed base secondary system with fixed base primary structure



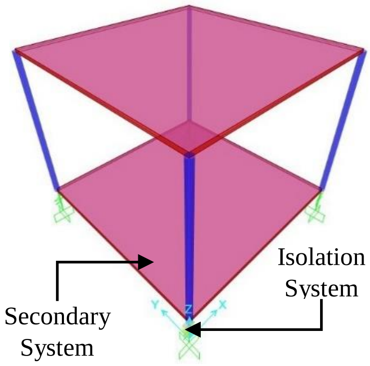
(b) Base-isolated secondary system with fixed base primary structure



(c) Base-isolated secondary system with base-isolated primary structure

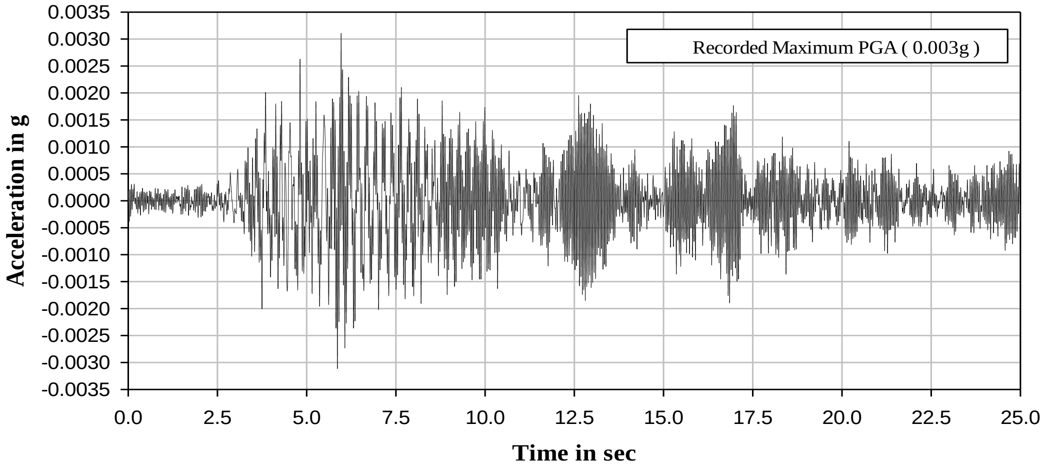


(d) Fixed Base Secondary System

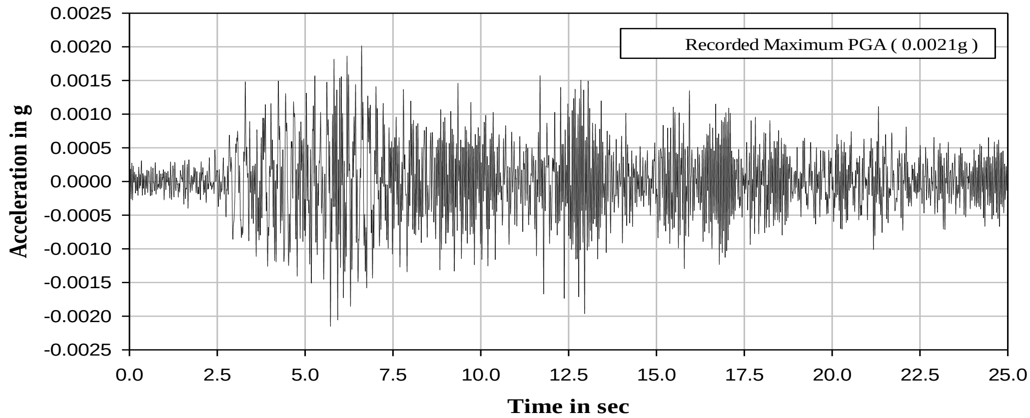


(e) Base-Isolated Secondary System

Fig. 12 Various simulation models of the normal as well as base isolated building

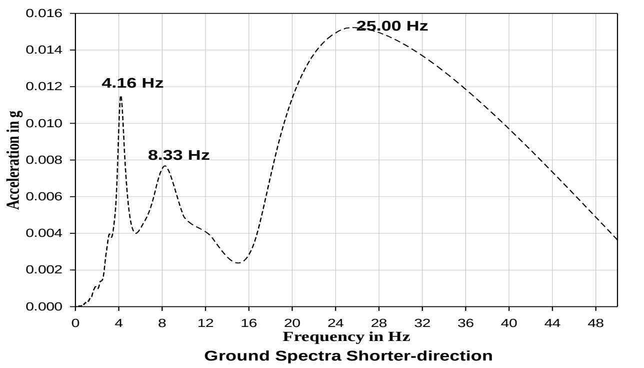


(a) Shorter direction of building

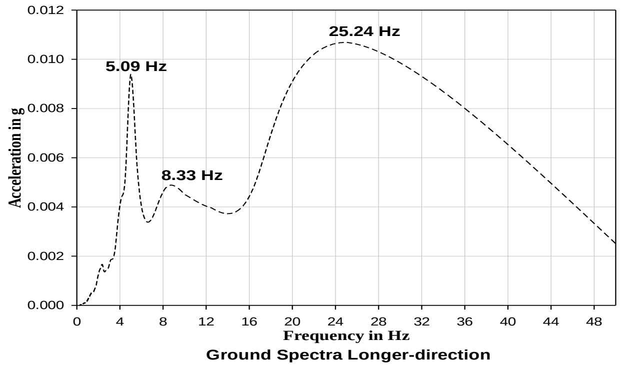


(b) Longer direction of building

Fig. 13 Time history function record of Guwahati region Earthquake (November 06, 2006) (Dubey *et al*. 2007)



(a) Ground acceleration spectra in shorter direction of building



(b) Ground acceleration spectra in longer direction of building

Fig. 14 Ground acceleration spectra of building in Guwahati region Earthquake (November 06, 2006)

structures are automatically taken into consideration. However, this depends upon fixity of secondary system (SS) with primary system (PS). Figure 16(a) below shows the comparison of acceleration time history of fixed base SS placed on different floor of fixed base PS while considering and without considering interaction between them.

Response of base isolated SS modeled in fixed base PS is studied by considering and without considering the interaction effect between them. The plots of acceleration time history at different floor levels are shown in Figure 16(b). For providing base isolation, SS is provided with elastomeric bearings at its base. Similar types of presentations are shown in Figure 16(c) for fixed base SS and base isolated PS at different floors considering and not considering the interaction.

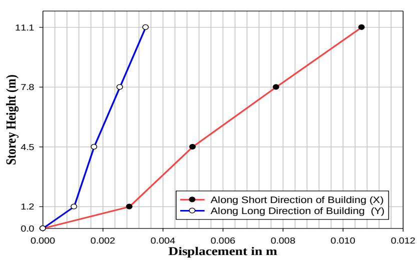
The values of peak response of secondary system (SS) in g (PGA) with and without interaction along with the effect of use of base isolation are given in Table 10. From Table 10, it can be observed that base isolation of secondary system with elastomeric bearing is more effective than base isolation of primary structure with LPB. The effectiveness of base isolation in both the cases increases with the height of building. It can be also observed that the effect of primary-secondary interaction is significant when secondary system is base isolated and it does not have much effect when the primary structure is isolated.

However, as the secondary structure is considered arbitrary, and no preliminary study is included on it in this limited study, the effect of resonance on the structure have not been carried out.

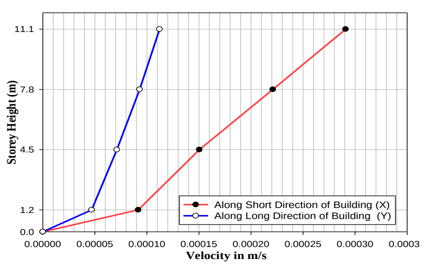
6. Conclusions

The results are obtained with an aim at develop a greater understanding of the dynamic behavior of (SS) secondary systems in a seismic environment and in developing practical criteria and procedures for the analysis and design of SS. From the series of numerical simulation using SAP 2000 and the result obtained thereof, it is concluded that:

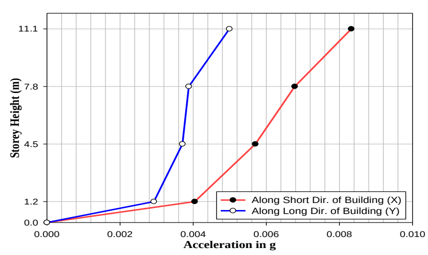
- Base isolation of the structure proves to be one of the most reliable techniques for seismic protection of SS housed in a PS.
- Use of base isolation shows the drastic reduction of peak acceleration response of both PS and SS.
- Local isolation of secondary system with elastomeric bearing provides better results than global isolation of the whole structure, but it also depends upon relative characteristics of both the isolators.
- The base isolation decouples the building from earthquake induced loads, and maintain longer fundamental lateral period than that of fixed base.
- There is significant contribution of infill walls in the dynamic characteristic of the buildings. The frequency shift is more than three times that of normal building without infill walls.
- Including the stiffness of the infill walls in the analysis, leads to better matching of the analytical spectral peaks with the recorded data. Therefore,



(a) Variation of absolute displacement with height of normal building

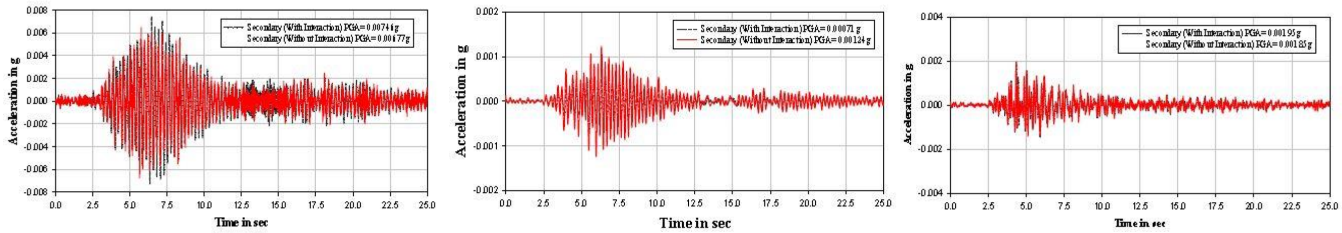


(b) Variation of absolute velocity with height of normal building

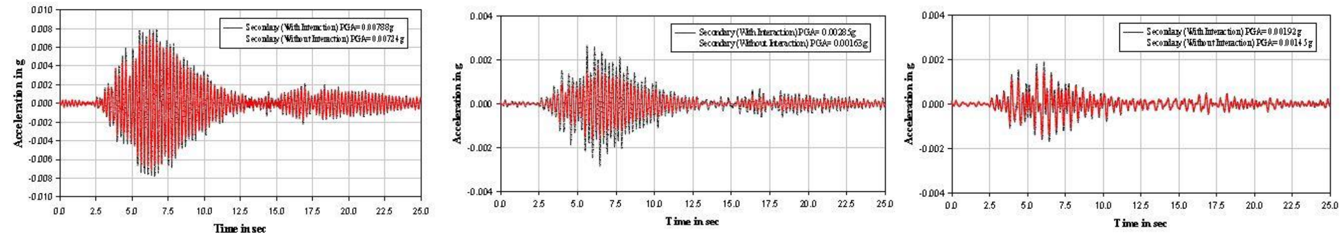


(c) Variation of absolute acceleration with height of normal building

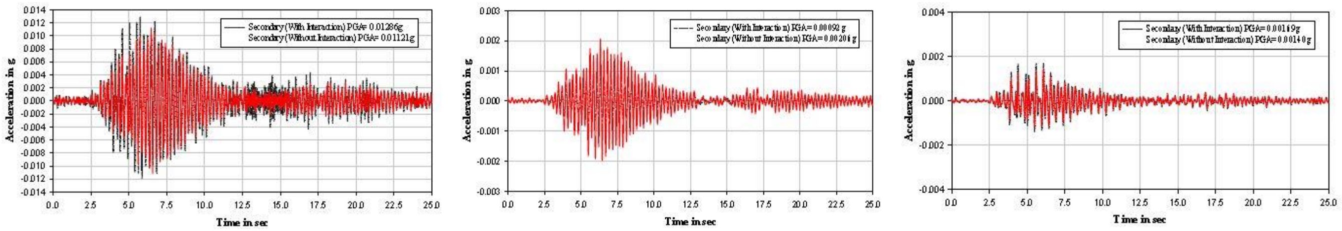
Fig. 15 Various simulation models of the normal as well as base isolated building



First Floor First Floor First Floor



Second Floor Second Floor Second Floor



Third Floor Third Floor Third Floor

(a) Fixed base SS with fixed base PS (b) Base isolated SS and Fixed base PS (c) Fixed base SS and base isolated PS

Fig. 16 Acceleration time history of while considering and without considering interaction

Table 10 Absolute peak acceleration of secondary structure under different cases

S. No.	Case	Peak Response of Secondary system in g		Percentage reduction	
		With Interaction	Without Interaction	With Interaction	Without Interaction
	Fixed primary system and fixed secondary system				
1	First Floor	0.00746	0.00677	-	-
	Second Floor	0.00788	0.00724	-	-
	Third Floor	0.01286	0.01121	-	-
	Fixed primary system and base isolated secondary system				
2	First Floor	0.00064	0.00129	91.42	80.94
	Second Floor	0.00078	0.00169	90.10	76.65
	Third Floor	0.00081	0.0021	93.70	81.26
	Base isolated primary system and base isolated secondary system				
3	First Floor	0.00195	0.00185	73.87	72.68
	Second Floor	0.00192	0.00145	75.64	79.98
	Third Floor	0.00169	0.00140	86.86	87.52

inclusion of stiffness of infill walls leads to more realistic response.

• It is evident from the analysis that, local isolation of equipment with elastomeric bearing show a response reduction of about 90% when interaction effect are considered and about 75-80% when interaction effect are ignored.

• Similarly, the provision of base isolation to primary system with LPB shows about 75% reduction in peak response and the interaction effect does not has any significant effect on the analysis.

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