REDUCTION OF SEISMIC RESPONSE OF BUILDING USING BASE ISOLATION

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ABSTRACT

The base isolation is aimed to attenuate the horizontal accelerations transmitted to the superstructure. The isolators attempt to decouple the superstructure from the strong components of horizontal ground motion. Isolators have low horizontal stiffness and they are placed between the structure and foundation. This makes the natural frequency of the structure of the order of 0.5 Hz of less, which enables the structure to experience low accelerations. Thus the structure along with the isolators acts like filter and will not respond to higher frequencies (> 0.5Hz). To study the behaviour of base isolated buildings under actual earthquakes, two numbers of three-storied RCC framed buildings have been constructed at IIT, Guwahati campus, one of the highest seismic zones (Zone-V) of India. Between two experimental buildings, one is on base isolator and other with conventional rigid foundation. Initially isolated building was constructed on Lead Plug Bearing (LPBs) and later LPBs were replaced by Laminated Rubber Bearing (LRBs) by lifting the building. Accelerometers are installed at first and third floors of both the buildings in order to record and compare the seismic responses of base isolated and conventional foundation buildings. The experimental buildings experienced actual earthquakes for both types of base isolators. A study has been made on the data recorded on both the buildings for both the cases of base isolation and the difference between recorded responses of isolated building using two different types of isolators have also been highlighted. Improvements required in the conventional analysis procedures are clearly brought out in this paper.

INTRODUCTION

The isolators attempt to decouple the building or structure from the horizontal components of the ground motion. Isolators have low horizontal stiffness and they are placed between the superstructure and foundation. This makes the natural frequency of the whole system including the structure to the order of 0.5 Hz of less, which eventually makes the structure to experience low accelerations as shown in Fig.1. Thus the structure along with the isolators acts like filter and will not respond to higher frequencies (> 0.5Hz).

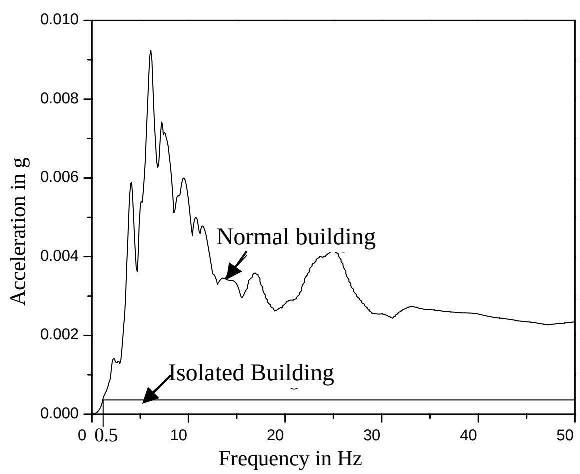

Fig. 1: Typical design response spectrum for normal and base isolated buildings

Recently Kelly compiled the literature in design, analysis, experiments and application of base isolators to structures and published a book [1]. From this book it is observed that there is no literature on behavior of base isolated structure subjected to real earthquake. In present work response of normal and isolated buildings have been recorded under real earthquakes, which would help to build more confidence in utilities and promote indigenous design, manufacturing and use of base isolation technique in India. To study the behavior of isolated building under actual earthquake scenario, two numbers of three-storeyed framed RCC buildings with similar construction, one building with conventional foundation (here onwards called as normal building) and other with base isolation as shown in Fig. 2(a), were-built at IIT, Guwahati campus. Guwahati is situated in the most severe seismic zone (Zone-V) of Northeast India. Northeast India is lying at the juncture of Himalayan arc to the north and Burmese arc to the east, and is one of the most seismically active regions of the world. Eighteen large earthquakes (M ≥7.0) including two great earthquakes (M ≥ 8.0) occurred in this region during the last 100 years [2]. The experimental building is 4.5mx3.3m area and the orientation of X and Z-axes of the buildings are shown in Fig. 2(c). The Y-axis is aligned with the height of the building. Initially for the base isolation, four numbers of Lead Plug Bearings (LPB) as shown in Fig. 2(b), with 50T vertical load capacity have been used under each column of the building and latter on these isolators were replaced by Laminated Rubber Bearings (LRBs) by lifting the building on hydraulic jacks and actual earthquake data were recorded on both the buildings. A twelve channel dynamic structural recording system has been employed for recording the seismic ground motion and structural response of normal and isolated buildings [3]. One tri-axial force balance accelerometer has been installed on the ground to capture earthquake induced ground motion and four numbers of accelerometers have been installed at 1st floor and 3rd floor of the buildings to record the bi-directional accelerations. Five numbers of actual earthquake data were recorded on experimental buildings with LPB isolation and further after replacement of LPBs by LRBs, seven numbers of real earthquake data have been recorded. The real earthquake data recorded with LPB isolation on November 06, 2006 and earthquake data with similar origin, depth and magnitude has been recorded on September, 03, 2009 with LRB isolation. A comparative study between recorded data has been made to investigate the effectiveness of two types of base isolation used separately. The magnitude of earthquake on November 06, 2006 was 5.2 on Richter scale with focal depth of 122.6 km (24.736^{o} N, 95.223^{o} E) and epicenter is in the Southeast to the site of the buildings, whereas the magnitude of earthquake on September, 03, 2009 was 5.9 on Richter scale with focal depth of 100 km (24.3^{0} N, 94.6^{0} E) and epicenter is in the Southeast of the site of buildings at Myanmar-India border. From the analysis and actual seismic records on experimental buildings, improvements required in the conventional analysis procedures are clearly brought out in this paper to obtain realistic structural seismic response.

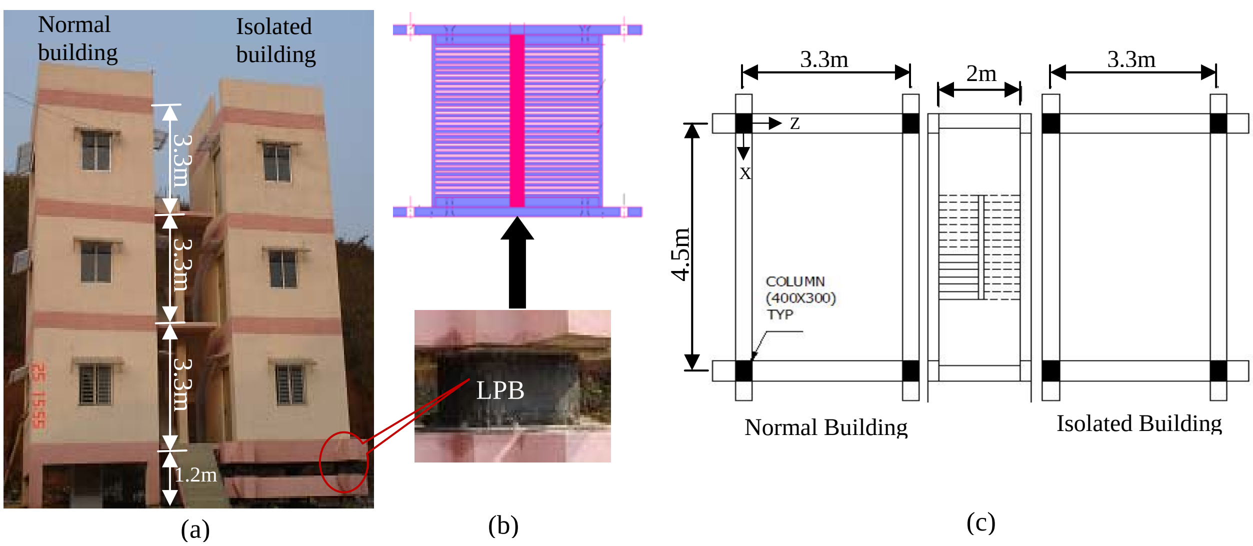

Fig. 2: (a) Experimental buildings at IIT, Guwahati; (b) Lead plug bearing (c) Plan view of the buildings

SEISMIC BASE ISOLATORS

Base isolation is a technique to reduce the acceleration transferred to structure from the ground and hence prevent the damage to buildings during an earthquake. Use of base isolation technique is very common in New Zealand, Japan, Italy and USA, however use of same is very limited in India. Commonly two types of base isolators are used viz. laminated rubber bearing and lead plug bearing. The lead plug bearing consists of alternate layers of metal and rubber with central lead plug as shown in Fig. 3(a), to control the lateral displacement by hysteretic deformation of lead. The re-crystallization temperature of lead is 25^{0}F, therefore lead can plastically deform under earthquake forces and regain its original shape when forces are removed and also it can take large numbers of load reversal cycles of plastic deformation without losing strength [4]. The laminated rubber bearing is similar as lead plug bearing without central lead plug as shown in Fig. 3(b). The central lead plug in LPB absorbs the seismic energy by hysteretic deformation of lead hence lesser seismic response however in case of LRBs more lateral displacements can be expected. Both the base isolators used for base isolation of experimental building are consisting of 28 numbers of 4mm thick steel shims and 29 numbers of 7 mm thick rubber layers with 460 mm diameter and 355 mm height. The diameter of central lead plug in LPB is 40mm.

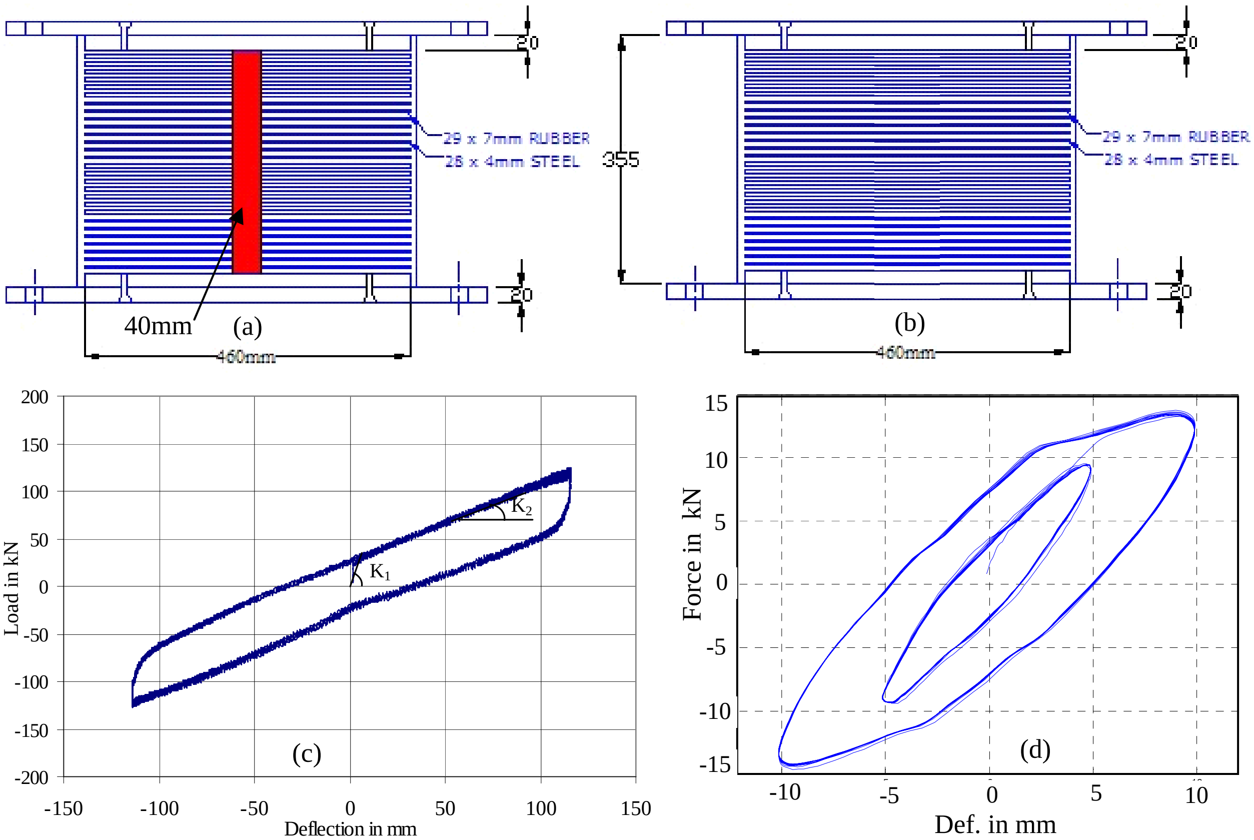

Fig. 3: (a) Dimensions of LPB; (b) Dimensions of LRB; (c) Cyclic load-deflection curve for LPB; (d) Cyclic load-deflection curve for LRB

The vertical stiffness of single LPB is 806.64 kN/mm and horizontal stiffness of isolator considering the first slope (K_1) is 17.18 kN/mm and 0.7968kN/mm for second slope (K_2) as shown in Fig. 2(c). The vertical stiffness of other type of isolator used i.e. LRB is 753kN/mm and experimentally derived horizontal stiffness from cyclic force-displacement curve as shown in Fig. 3(d), is 2.0kN/mm.

RECORDED RESPONSE OF THE BUILDINGS UNDER ACTUAL EARTHQUAKE

Among twelve recorded actual earthquakes, the earthquake data on November 06, 2006 with LPB isolation and September, 03, 2009 with LRB isolation on experimental buildings along with ground motion records have been discussed under following headings.

Recorded Response with LPB Isolator

The recorded response on 1st and 3rd floors in Z-direction of normal and base isolated buildings with LPBs have been plotted in Figs. 4 & 5 and corresponding ground motion record has also been plotted in Fig. 6. It can be observed from Figs. 4(a) & (b), that there is 4.8 times reduction in seismic response at 3rd floor of base isolated building as compared to normal building. Similarly 2.6 times reduction can also be observed from Figs. 5(a) & (b), at 1st floor of the isolated building as compared to normal building. The recorded response of isolated building is lesser than the response of normal building and ground motion records, which depicts the effectiveness of base isolation. There is amplification of response from ground to 3rd floor of the normal building, whereas almost same response can be observed at 1st and 3rd floor of isolated building, which is a desired characteristic of base isolated system.

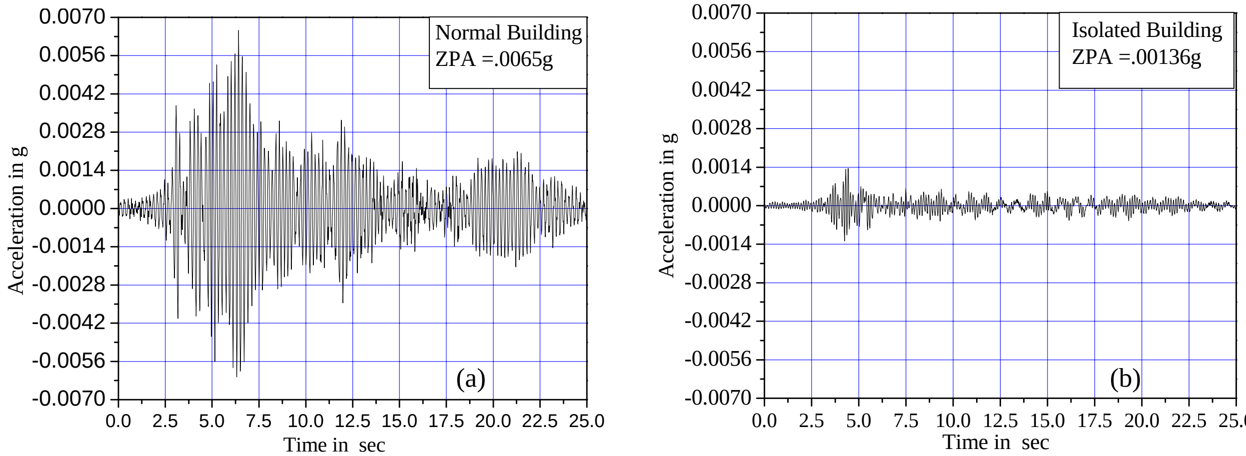

Fig. 4: Recorded response at 3rd floor in Z-direction, (a) Normal building; (b) Isolated building with LPB

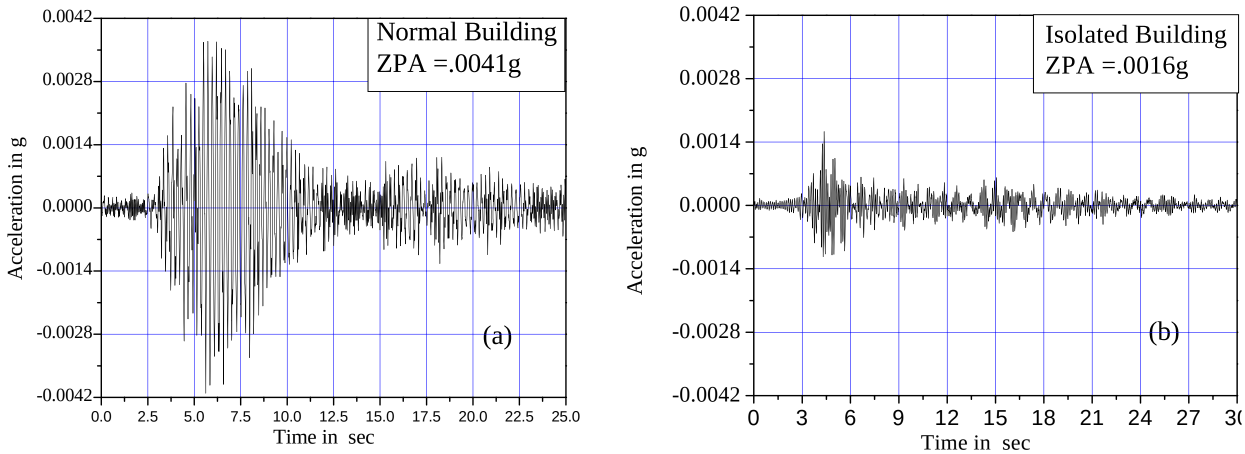

Fig. 5: Recorded response at 1st floor in Z-direction, (a) Normal building; (b) Isolated building with LPB

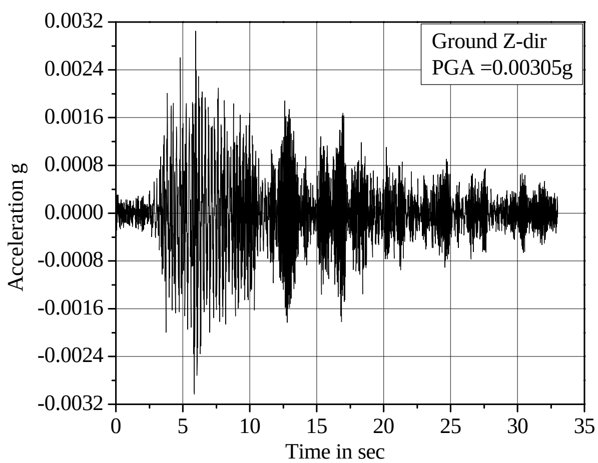

Fig. 6: Recorded ground motion acceleration in Z-direction on Nov 06, 2006

Recorded Response with LRB Isolator

The recorded response on 1st and 3rd floors in Z-direction of normal and base isolated buildings with LRBs have been plotted in Figs. 7 & 8 and corresponding ground motion record has also been plotted in Fig. 9. It can be observed from Figs. 7(a) & (b), that there is 2.3 times reduction in seismic response at 3rd floor of base isolated building as compared to normal building. Similarly 1.8 times reduction as shown in Figs. 8 (a) & (b) can also be observed at 1st floor of the isolated building as compared to normal building. The recorded response of isolated building is lesser than normal building similar to previous case, which depicts the effectiveness of base isolation using LRBs. The response of isolated building is more uniform from 1st floor to 3rd floor as compared to previous case. The earthquake occurred on September 03, 2009 was of higher magnitude even then the percentage reduction in seismic response is more in case of LPB isolators.

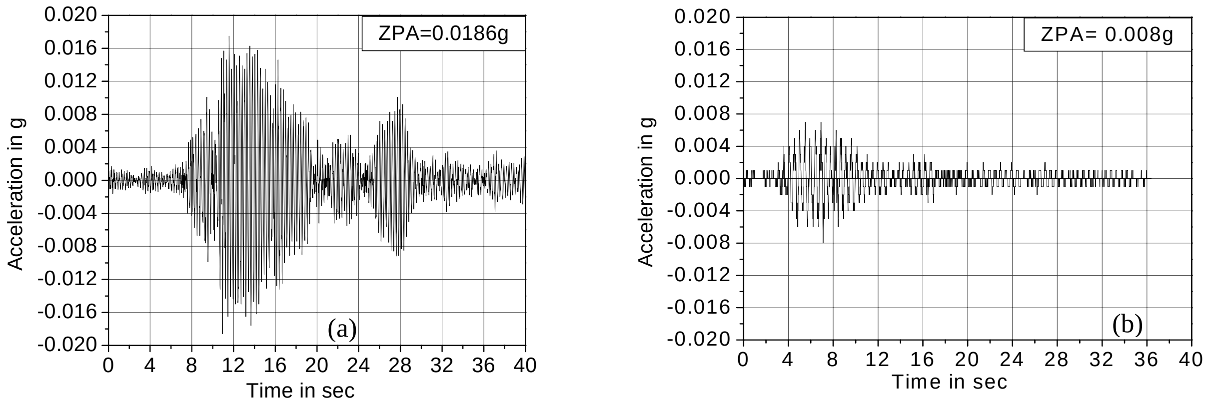

Fig. 7: Recorded response at 1st floor in Z-direction, (a) Normal building; (b) Isolated building with LRB

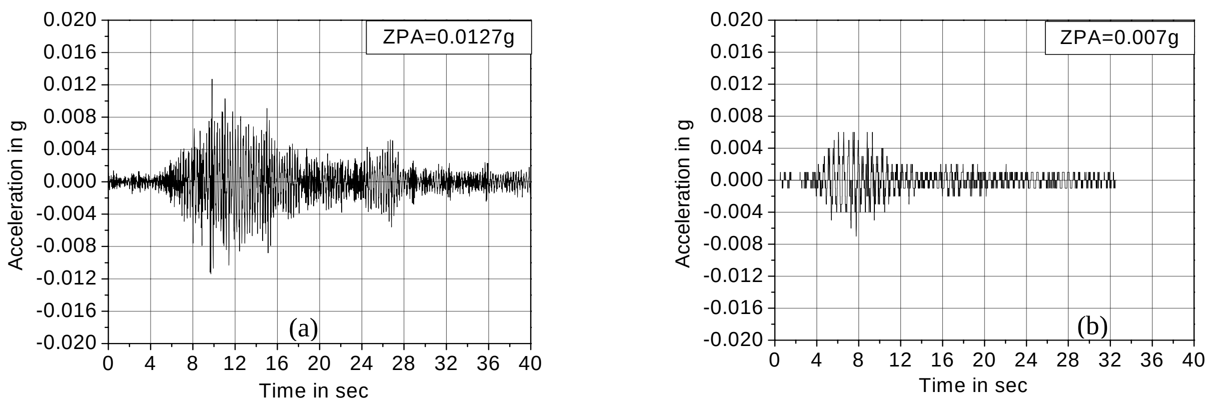

Fig. 8: Recorded response at 1st floor in Z-direction, (a) Normal building; (b) Isolated building with LRB

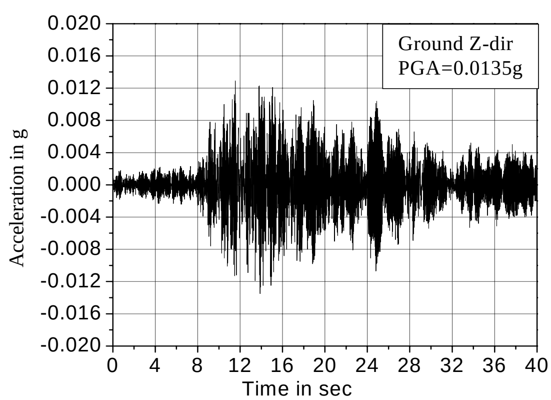

Fig. 9: Recorded ground motion acceleration in Z-direction on Sept 03, 2009

FREE VIBRATION ANALYSIS OF EXPERIMENTAL BUILDINGS

Analysis of Normal Building

Using conventional design approach, analysis of normal building has been performed by ignoring the stiffness of the in-fills walls and only considering the masses of the in-fill walls. The masses of infill walls have been lumped at the nodes of respective floor beams as shown in Fig. 10 (a). The first mode frequencies obtained in Z and X-directions are 1.25Hz and 1.54Hz respectively with 76% mass participation. Free vibration analysis is also performed considering frequency independent soil springs, whose properties are obtained using the formulae given in ASCE 4-98 [5] and from the analysis it is found the effect of soil springs are insignificant and frequencies and participation factors were unaltered.

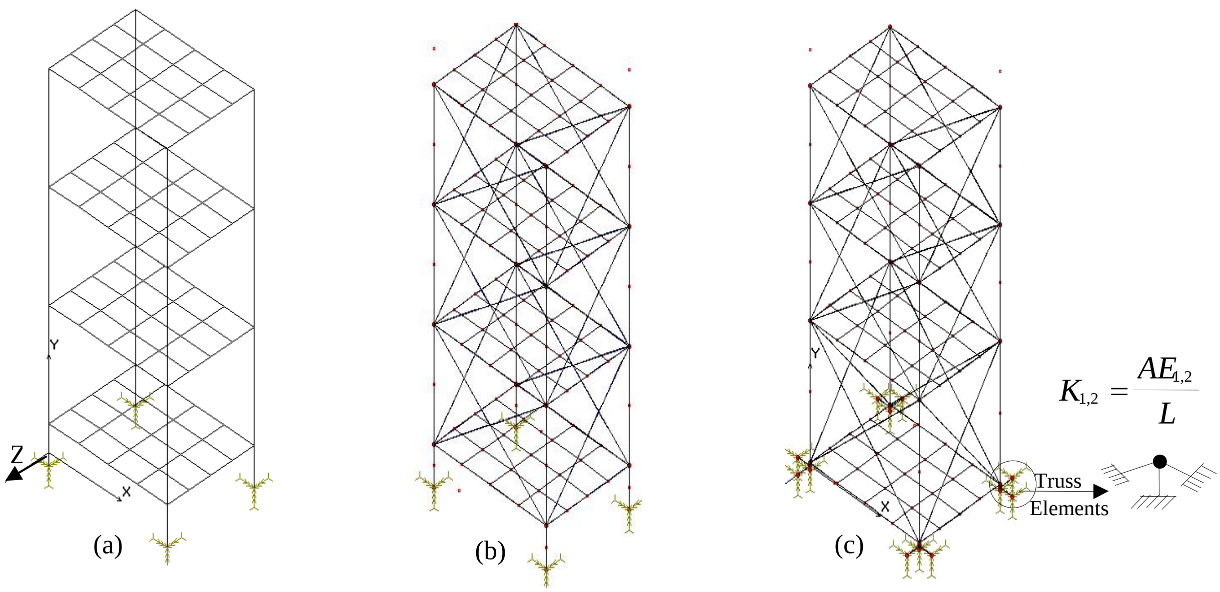

Fig. 10: (a) FE model of normal building without infill wall; (b) FE model of normal building with in-fill wall as equivalent strut; (c) FE model of isolated building

Later to investigate the effect of infill walls on natural free vibration characteristics of normal building, stiffness of infill walls have been modelled as equivalent diagonal struts [6] as shown in Fig.10 (b), and equivalent struts geometric parameters have been calculated from the geometry of the brick wall using the procedures explained in reference [7]. The first fundamental frequencies in Z and X-directions are 4.42Hz and 5.65 Hz with 81% and 82% mass participations respectively. It is clearly understood from this analysis that there is significant contribution of infill walls in increasing the fundamental frequency of normal building.

Analysis of Isolated Building

Isolated building has been FE modelled same as normal building and initially LPB isolators were modelled with second slope stiffness (K_2), where yielding of lead was assumed, however later it was realised that the seismic excitation is very low to cause any yielding in central lead plug. Hence the modal frequencies thus obtained were very low as compared to modal peaks in the recorded data. Later the isolators have been modelled as nonlinear truss elements as shown in Fig. 10 (c). The first lateral stiffness (K_1) of LPB isolator corresponding to un-yielded lead and the 2^{nd} lateral stiffness (K_2) of LPB corresponding to nonlinearly deforming lead plug as shown in Fig. 3(c), have been modelled using Eq. (1).

$$K_{1,2} = (AE_{1,2})/L \tag{1}$$

Where E_1 and E_2 are the elastic modulus corresponding to first and second stiffness as discussed above.
A, L= area and length of truss element respectively.

It can be observed from the analysis results listed in Table-1, that there is significant mass participation in 2nd modes in horizontal direction considering the duel slope model of isolators, whereas total mass was participated in 1st mode when second slope was only considered for modelling the isolators. Non-yielding of lead plug due to low earthquake excitation imparts higher stiffness to isolators and hence frequency of isolated building is higher in this situation.

Table 1: Modal frequencies and mass participation of isolated building

Dual Slope					2nd Slope				
Mode No	Freq (Hz)	Mass Participation in kg			Mode	Freq (Hz)	Mass Participation in kg		
		M_x	M_y	M_z			M_x	M_y	M_z
1 (Z-dir)	2.07	0	0	98718	1 (X-dir)	0.796	0	0	116000
2 (X-dir)	2.53	104000	0	0	2 (Z-dir)	0.812	116000	0	0
4 (Z-dir)	7.58	0	0	17367	6 (Y-dir)	10.10	0	112000	0
5 (X-dir)	8.42	12211	0	0					

Time history analysis has also been performed for above two cases using recorded ground time history on November 06, 2006 as base excitation to isolated building and the corresponding response spectrum have been plotted in Figs. 11(a) & (b). It can be observed that in case of dual stiffness modelling of isolator the analytical spectral peaks are more close to recorded spectral peaks as compared to single stiffness i.e. in 2nd slope case. This analysis also depicts that for small input excitations the deflection of the isolator is small to cause yielding in lead plug and hence natural vibration characteristic is governed by the elastic slope (K_1) and higher.

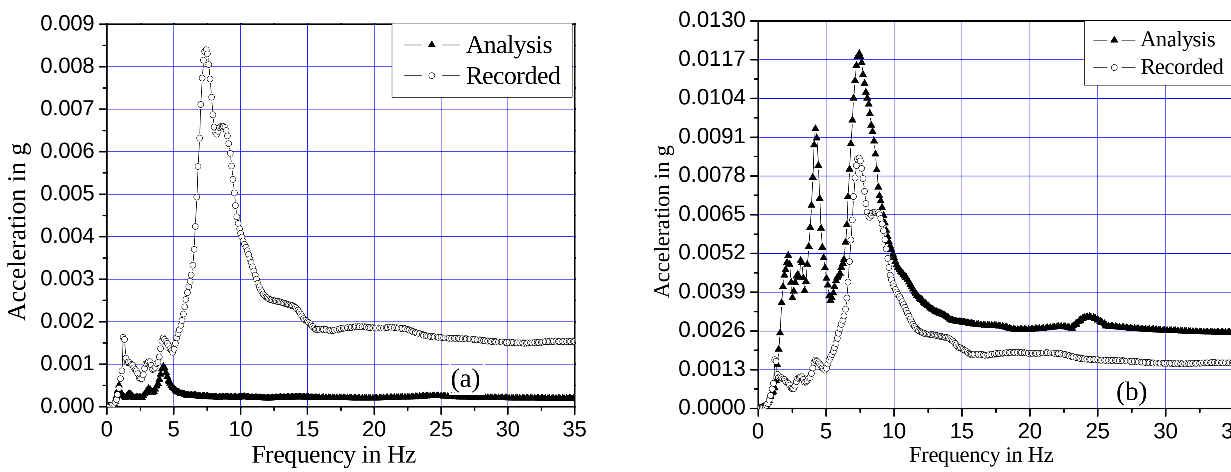

Fig. 11: (a) Recorded and analysis response spectrum corresponding to 2nd slope of isolator; (b) Recorded and analysis response spectrum corresponding to dual slope of isolator.

CONCLUSION

From the FE analysis of normal building it is observed that there is significant contribution of in-fill walls in the dynamic characteristic of the normal building, whereas effect of same is insignificant in case of isolated building because of rigid body motion of the structure above the isolator. The recorded response of isolated building using two types of base isolators is much lesser than the response of normal building, which depicts the effectiveness of base isolation. The percentage reduction in seismic response is higher in case of base isolation using lead plug bearing. The input seismic excitation is very low to cause yielding of lead plug and therefore frequency of isolated building is higher in this situation. The initial stiffness (un-yielded lead plug) of LPB is higher that can provide rigidity under lateral service loads such as wind loads. The spectral peaks are more close to recorded response when LPB isolators are modelled as dual slope nonlinear truss element as compared to single slope model.

Since there is significant contribution of infill walls on dynamic characteristics of normal building, the structural members should be designed for two levels of earthquakes, one low level earthquake at which infill walls are intact and other high level (design) earthquake at which infill walls are failed, because the acceleration corresponding to increased frequency due to infill walls may be higher than acceleration at lower frequency in design spectrum. Similarly in case of isolated building, modal frequencies are higher in case of un-yielded lead plug condition at low level of earthquakes, which may correspond to higher acceleration than design spectrum. Therefore structural members of isolated building needs to be checked for a limiting earthquake level at which lead core is un-yielded otherwise isolated building may attract higher acceleration corresponding to un-yielded lead plug frequency, which is higher than the design frequency. The deformations may exceed the design value at an earthquake which is lower than the design earthquake.

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