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SEISMIC RESPONSE OF BUILDING BASE ISOLATED WITH FILLED RUBBER BEARINGS UNDER EARTHQUAKES OF DIFFERENT CHARACTERISTICS

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SUMMARY

Seismic base isolation is now an accepted practice, in many parts of the world, for protecting important buildings from earthquake forces. For low to moderate height buildings, natural rubber bearing has often been considered suitable because of its durability and easier fabrication. Many recent studies showed that low stiffness of base isolation systems could cause unacceptably large displacements of ground floor of the building necessitating substantial amount of damping in the isolation system. Later, use of certain filler materials in natural rubber have resulted in a breakthrough in the field of base isolation. These filler chemicals give better control over structural properties of natural rubber such as flexibility and damping. The bearings made up of these filled rubbers can fulfil all the requirements of an isolation system in single unit. In this analytical study, effect of earthquake characteristics on response reduction and effect of post-to-pre yield stiffness ratio & yield displacement of isolation system on equivalent viscous damping are studied for a six storey reinforced concrete building base isolated by filled rubber bearings. Five earthquakes, recorded at different sites in India, are considered in this study. It is observed that filled rubber bearings are effective isolation system against ground motions with high dominant frequencies. Besides other bearing parameters, the damping available from these bearings depends upon input ground motion also. The desired damping in filled rubber bearings for a given input motion can be achieved by controlling the value of yield force/displacement.

INTRODUCTION

The base isolation system consists in introducing low stiffness bearings and damper between foundation and superstructure. Bearings provide the needed flexibility to the combined system so as to shift its first mode natural frequency away from predominant frequency of the design earthquake motion. This results in the reduction of inertial forces and accelerations several times. The idea behind base isolation has been proposed again and again for atleast a century. Kawai in 1891, proposed a base isolated structure with timber logs placed in several layers in the longitudinal and transverse direction (Jurkovski, 1995). Almost a hundred similar proposals for aseismic systems were made prior to 1960, but none were ever built. The most probable reason was a lack of practicality and lesser confidence in their construction (Buckle, 1986). After 1960, several ideas like soft first storey, rollers, friction bearings, R-FBI system, EDF system, FPS system, SRF system etc. were proposed and used alongwith variety of dampers but due to one reason or other none could be used as frequent as the isolation system comprising of elastomeric laminated rubber bearings. Earlier the elastomeric bearings were made up of natural rubber, which possess very low energy dissipating capacity resulting in unacceptably high displacements at isolation level. Recent advances in rubber technology have enabled the manufacturers of these bearings to have better control over the structural properties of the rubber. This is achieved by mixing suitable amount of certain chemicals in the natural rubber. These filled rubbers can be used efficiently in the manufacture of isolation bearings. The laminated rubber bearings made by these filled rubbers have high initial stiffness, which reduces, at high level of shear strains. Therefore, behaviour of these bearings can be simulated by bilinear curve. The area of hysteretic loop i.e. damping for an earthquake event is controlled by yield force and post-to-pre yield stiffness ratio of the bearing which can be controlled by fillers. The purpose of this paper is to investigate the effectiveness of base isolation by filled rubber bearing and influence of bearing parameters viz. post-to-pre yield

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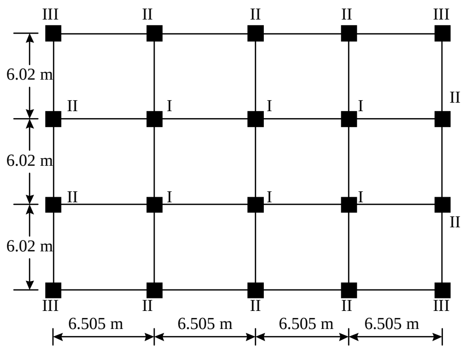
stiffness ratio and yield displacement on the isolation damping of a six storey reinforced concrete building excited unidirectionally with ground motions having different characteristics.

SIX STOREY R.C. FRAME BUILDING

The building considered for this analytical study is a six storey office building which is a reinforced concrete framed structure with masonry infilled walls (Jain, 1991). The floor plan is 26.02m x 18.06m and total height of the building is 17.8m (Fig. 1). Each floor consists of a solid slab 200mm thick. The distribution of the structural elements at each floor is symmetrical in both directions. The mass of the structure and the load carried by the building are assumed to be concentrated at the floor levels. Damping of superstructure is assumed to be 5% of critical damping in all the modes.



I, II, III: Type of bearing
Fig. 1: Plan of six-storey building

FILLED RUBBER BEARINGS

The isolation system considered in this study is elastomeric bearing. The most common elastomers used in elastomeric bearings are natural rubber, neoprene rubber, butyl rubber and nitrile rubber. The mechanical properties of natural rubber are superior to those of most synthetic elastomers used for seismic isolation bearings. Therefore natural rubber is most frequently recommended material for use in elastomeric bearings followed by neoprene. Butyl rubbers are suitable for low temperature applications and nitrile rubber have limited application in offshore oil structure. High vertical stiffness of these bearings is achieved through the laminated construction of the bearing using steel plates (Fig. 2).

Fig. 2: Cross section of Elastomeric Bearing

The bonding of elastomer with steel plates is generally done by fully vulcanised process. In this process, the steel plates having adhesive coating are placed in a mould precisely at equal spacing with unvulcanised elastomer filling the space. The assembly is then treated at certain pressure and temperature condition. Earlier high horizontal stiffness at low lateral loads and hysteretic energy dissipation were achieved by providing the bearing with lead plug or by frictional elements. But later these properties are controlled to a large degree by the amount of filler agent used in compounding the elastomer. The proportion of filler agent can be put as much as the elastomer itself depending upon the requirement. A number of fillers are employed, such as metal oxides, clay, and cellulose, but the filler which is most commonly used in seismic isolation bearings, is carbon black (Taylor et al, 1992). For a given elastomer compound, increasing the proportion of carbon black filler generally enhances the effect of the shear strain amplitude. Vibrations of the building due to frequently occurring wind force or minor earthquakes are reduced by the higher modulus of the filled rubber at low value of shear strain. The lower modulus of the elastomer at the higher amplitude enables the bearings to have high flexibility for higher amplitude disturbance of a major earthquake. The addition of carbon black in elastomer has the effect of increasing the damping. Natural rubber is very versatile and can easily be compounded to obtain the desired damping over a wide range of hardness (Kadir, 1982).

DESIGN OF RUBBER BEARINGS

As shown in Fig. 3, an additional slab is provided at the base and the isolators are placed between the base slab and the foundation slab. One rubber bearing is provided under each column. The rubber bearings, 20 in number for this building are grouped into three categories (Fig. 1) based on the magnitude of the vertical load transferred from different columns. Provision is made for horizontal displacement at the level of isolation system, known as seismic gap. A reasonable seismic gap should be of the order of 50-400 mm (Skinner et. al., 1993).

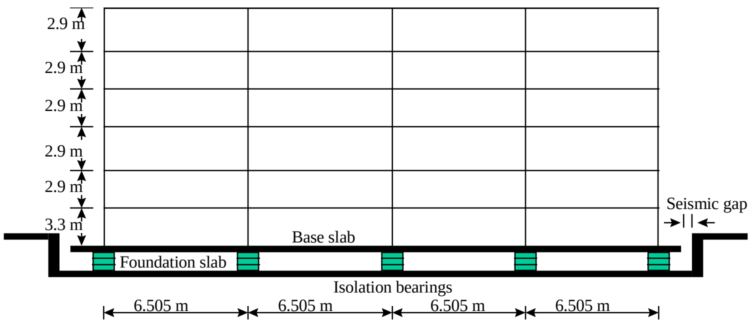


Fig.3: Elevation of Base Isolated Building

Filled rubber bearing show higher initial stiffness which decreases with increase in the shear strain. Several experimental tests showed strong non-linearities in shear force-displacement constitutive law, with considerable hardening at large strains (Kikuchi et al, 1997). In this study, these bearings are modelled by bilinear hysteretic model as shown in Fig. 4. The post yielding stiffness of the bearing is the most important parameter. This value decides the first natural frequency of the base isolated building. The value of post yielding stiffness is kept such that the value of time period for the six-storey building is shifted from 1.05 sec. to 1.85 sec. The design steps for determining the size of bearing, total thickness of rubber and number of layers are followed from Kelly (1997). Type and amount of fillers can control the values of pre-yielding stiffness and yield force. Details of design parameters of the bearings are given in Table 1.

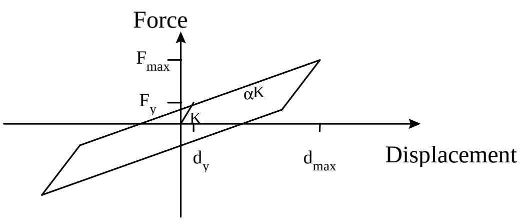


Fig. 4: Bilinear model for filled rubber bearing

Table 1: Design parameters of different isolation bearings in the building

BEARING TYPE	**I**	**II**	**III**
Design vertical load on bearing	4550 KN	2850 KN	1725 KN
Number of bearings	6	10	4
Size of bearing	1.0m x 1.0m	0.80m x 0.80m	0.62m x 0.62m
Height of bearing	0.163m	0.163m	0.163m
Number of rubber layers	7	7	7
Number of steel layers	6	6	6
Rubber layer thickness	19mm	19mm	19mm
Steel layer thickness	3mm	3mm	3mm
Ratio of vertical and horizontal stiffness	1149	751	448
Safety factor against buckling	17.00	10.87	6.53

EARTHQUAKE MOTIONS CONSIDERED

In order to study effect of earthquake characteristics, five earthquake motions recorded at different sites in India are considered in this study (Chandrasekaran et al, 1992). Fourier spectra for these ground motions, shown in Fig. 5, reveal that dominating frequencies covered by these ground motions ranges from 0.5 to 8.5 Hz. The salient features of these ground motions are shown in Table 2.

Table 2: Characteristics of the earthquake motions

Earthquake Date	**M**	**Station**	**Component**	**PGA (m/s/s)**	**Underlying strata**	**Dominant frequencies**
Dharamshala April 26, 1986	5.7	Shahpur	N15W	2.43	Soil	2.0 - 5.0 Hz
Koyna Dec.12, 1967	6.5	Koyna dam	Longitudinal	6.19	Rock	2.5 - 8.5 Hz
NE(India) Aug. 6, 1988	6.8	Berlongfer	N14W	3.37	Sandy soil	1.5 - 3.0 Hz
NE(India) Aug. 6, 1988	6.8	Silchar	S30E	0.89	Alluvium	0.5 - 2.5 Hz
Uttarkashi Oct. 20, 1991	6.5	Uttarkashi	N15W	2.37	Rock	2.5 - 6.5 Hz

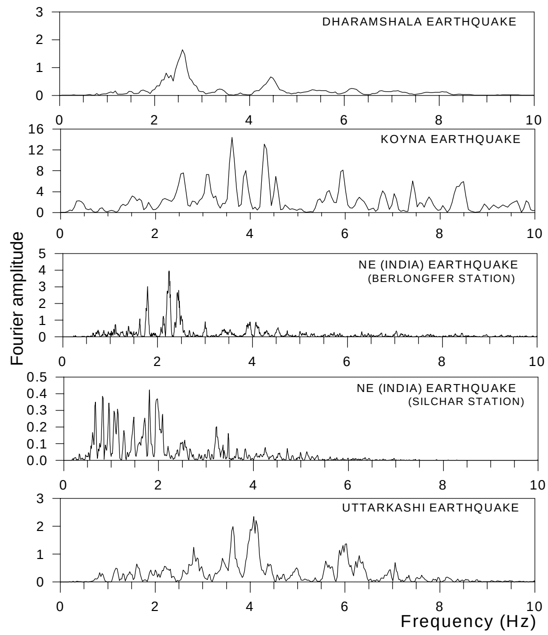


Fig. 5 : Fourier spectra for different earthquake motions

METHOD OF ANALYSIS OF BASE ISOLATED BUILDING

The time history analysis of the base isolated building is carried out using the computer program 3D-BASIS-TABS. A full three-dimensional representation of the structure is used in time history analysis of the base isolated buildings. The isolation system is modelled as a bilinear hysteretic element. The details of method of analysis are described by Reinhorn et al. (1994). Following assumptions are made for the analysis of base isolated building:

- The superstructure is elastic at all time and the non-linear behaviour is restricted in isolators only.
- All frame substructures are connected at each floor level by a diaphragm, which is infinitely rigid in its own plane.
- Each floor has three degrees of freedom (two translations and one rotation) attached to the centre of mass of each floor.
- The isolation devices are rigid in the vertical direction and each has negligible torsion resistance.
- Effect of infilled walls on stiffness of the structure is negligible. These are considered in computation of mass only.

DISCUSSION OF RESULTS

The seismic response of the base isolated building is obtained from 3D-BASIS-TABS computer program (Reinhorn et al, 1994). For evaluating the seismic response of fixed base building, software STAAD III is used. The building is excited unidirectionally along the longitudinal direction by five earthquake motions described in Table 2. The equivalent viscous damping of the system (in percent of critical damping) is calculated from maximum base displacement using expression (Stanton et al, 1991):

$$\zeta = \frac{2}{\pi}\left[\frac{F_y}{\left\{F_y + \left(d_{\max} - d_y\right)\alpha K\right\}} - \frac{d_y}{d_{\max}}\right] \times 100 \qquad (1)$$

where all the variables used in the expression are defined in Fig. 4.

Effectiveness of base isolation

The comparison of seismic response of the six storey fixed base building to that of base isolated building is made for base isolation system given in Table 1. The yield force for the isolators is considered as 4.5% of vertical load carried by it (Reinhorn et al, 1994). The yield displacement of the bearings is assumed such that value of α is 0.15. It is observed from Table 3 that there is a general reduction in seismic response for four earthquake motions. The reduction in maximum shear and roof acceleration is maximum for Koyna earthquake. The maximum shear of the base isolated building is reduced to as much as 0.28 times the maximum shear of the corresponding six storey fixed base building. In case of NE India earthquake recorded at Silchar station, the values of maximum shear and roof acceleration are more or less same for fixed base and base isolated buildings. For the remaining three ground motions, the reduction in maximum shear is substantial but roof acceleration is not so much reduced. This shows that this isolation system is very effective when the ground motion has dominant frequencies far away from that of first natural frequency of base isolated building which is 0.54 Hz (Koyna, Uttarkashi, NE India (Berlongfer Stn.) and Dharamshala) but is not suitable for ground motions such as NE India (Silchar Stn.), having dominant frequencies close to fundamental frequency of the base isolated building. Maximum storey drift also reduces for all ground motions except the NE India earthquake motion recorded at Silchar station.

Table 3: Effectiveness of base isolation system for different Indian earthquakes

Earthquake	**Base Shear (KN)**		**Roof Acceleration (m/s/s)**		**Max. Storey Drift (%)**	
(As recorded)	*Fixed base*	*Base isolated*	*Fixed base*	*Base isolated*	*Fixed base*	*Base isolated*
NE India (Berlongfer Stn.)	8758	4366	3.94	3.11	0.46	0.33
Dharamshala	4604	2631	2.07	2.35	0.24	0.20
Koyna	15085	4311	6.81	2.38	0.78	0.28
NE India (Silchar Stn.)	3358	3325	1.51	1.47	0.17	0.24
Uttarkashi	8546	3931	3.86	2.21	0.44	0.29

Effect of α on isolation damping

In order to study the influence of α on energy dissipation at isolation level the value of α is varied from 0.05 to 0.25, keeping *Fy* and *dy* as constant and same as above. Equivalent viscous damping of isolation system is computed by expression (1). It can be observed from Table 4 that for α varying from 0.05 to 0.25, there is no significant change in equivalent viscous damping for all the five earthquake motions. The maximum percentage change in the equivalent viscous damping is found to be only 7.6%. Therefore value of α can be kept as low as 0.05 for achieving lower seismic response. Table 4 shows that for same bearing parameters, the achieved damping of isolation bearings depends upon the characteristics of input ground motion. The maximum percent change in equivalent viscous damping achieved for different earthquake motions varies from 17 to 28.8%.

Effect of *dy* on isolation damping

The value of yield force and yield displacement can be controlled by fillers. The effect of these values on damping of isolation system is studied by changing the value of yield displacement from 0.002m to 0.10m. The value of *Fy* is kept such that initial stiffness of the bearing remains constant for all the values of *dy*. α is assumed as 0.15 which results in constant fundamental period of 1.85 sec for the base isolated building. It is observed from Table 5, that change in yield level of bearings results in significant variation in their damping. Therefore yield displacement can be considered as an important parameter for achieving the desired damping. Table 5 also shows that besides yield displacement, equivalent viscous damping provided by the isolation bearings depends upon characteristics of input ground motion.

Table 4: Variation of equivalent viscous damping (%) with α

Earthquake	**Post to pre yielding stiffness ratio (α)**				
(As recorded)	*0.05*	*0.10*	*0.15*	*0.20*	*0.25*
NE India (Berlognfer Stn.)	26.0	26.2	26.8	27.0	26.8
Dharamshala	21.3	19.3	21.3	21.3	23.0
Koyna	25.4	25.8	26.8	27.2	27.5
NE India (Silchar Stn.)	27.5	27.1	27.1	26.6	26.6
Uttarkashi	28.1	28.0	28.0	27.9	27.7

Table 5: Variation of equivalent viscous damping (%) with yield displacement

Earthquake	**Yield displacement (*dy*) in metre**				
(As recorded)	*0.002*	*0.004*	*0.006*	*0.008*	*0.010*
NE India (Berlognfer Stn.)	13.3	21.8	26.0	27.8	27.7
Dharamshala	37.3	44.0	23.5	16.8	8.8
Koyna	5.9	15.8	25.3	28.1	27.4
NE India (Silchar Stn.)	16.6	26.1	27.9	23.5	14.6
Uttarkashi	19.7	26.1	28.1	26.5	22.6

CONCLUSIONS

Filled rubber bearings are suitable for ground motions having high dominating frequencies but is not effective for ground motions whose dominant frequencies are close to natural frequency of base isolated structure. The fundamental period for a bearing is unique for given bearing parameters but the damping is found to be dependent upon the characteristics of input ground motion also. The increase in the value of α beyond 0.05 do not substantially increase the damping of the bearing and therefore it should be kept low to minimise the storey shears. Yield displacement can be used as an important parameter for controlling damping in order to achieve desired base displacement.

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