PERFORMANCE OF LEAD-RUBBER BASE ISOLATED BUILDING STRUCTURE IN HIGH SEISMIC PRONE REGION

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INTRODUCTION

Seismic isolation mitigates earthquake induced responses based on the concept of reducing the seismic demand by shifting the primary period of the structure rather than increasing the earthquake resistance capacity of structure. [1] The isolation technique can be adopted to improve the seismic performance of strategically important buildings such as schools, hospital, industrial structures, government office buildings etc. The goal is to simultaneously reduce inter-storey drifts and floor accelerations to limit or avoid damage, not only to the structure but also to its foundation, in a cost-effective manner. The main feature of the base-isolation technology is that it introduces between superstructure and its foundation a properly chosen flexible layer in order to shift the natural period of structure away from the dominant period of earthquake ground motion and thus to avoid the destructive effects given by the system resonance. [2-3] Based on the content of control to be achieved over the seismic response, the choice of the isolation system varies and thereupon its design is done to suit the requirements of use of the structure.

In seismically base-isolated systems, the superstructure is decoupled from the earthquake ground motion by introducing a flexible interface between the foundation and the base of the structure. Thereby, the isolation system shifts the fundamental time period of the structure to a large and dissipates the energy in damping, limiting the amount of force that can be transferred to the superstructure such that inter-storey drift and floor acceleration and reduce drastically. It is very essential to understand the various characteristics affecting the response of fixed and base-isolated structure when used for seismic protection of the structures. Moreover, the performance of base isolated structure also reportedly depends on superstructure stiffness, damping and flexibility of the isolation system. [4-5] The intense research activity in the field of seismic isolation has led to the development of a variety of base isolation system, which have been tested and implemented in many countries with very encouraging result. Various types of isolation system enormously and effectively implemented all over the world for seismic protection, where elastomeric rubber bearing, lead-rubber bearing and sliding bearing are most widely used. Thus, in this paper parametric characteristics have been evaluated for lead rubber bearing for different time period, bearing damping and its performance on building structural response. The bilinear model, used to express the relation between the shear force and the lateral displacement, can be defined by three parameters: initial stiffness, post-yield stiffness, and characteristic strength. The characteristic strength, Q, is usually utilized to estimate the stability of hysteretic behavior when the bearing experiences many loading cycles. For this study 10 storey RCC hospital

It is very essential to understand the various characteristics affecting the response of fixed and base-isolated structure.

building taken and modeled in ETABS program for the region IV, as per Indian code and site soil condition. The model has been analyzed by non-linear time history analysis have been performed on the set of different mathematical models, with time period T=2, 2.5, 3, 3.5 sec & bearing damping value, ξ=0.10, 0.15, 0.20, 0.25, 0.30. The spectral matching procedure for real accelerograms is summarized and applied to a target earthquake response spectrum given in IS: 1893-2016, for type-I site soil. Matching technique in based on scaling of selected time history in time domain. The specific objectives of this study are: (i) to investigate the effects of increase of initial stiffness on structural response, (ii) to analyze the effect of isolation period on structural response and, (iii) to investigate the effects of characteristic strength ratio of isolator on structural response.

1. To evaluate the parameters of lead rubber isolator as per the variation of effective time of isolation and damping of the isolator.
2. To study the parametric analysis and compare the seismic response of fixed base with base isolated building.
3. To evaluate the building floor spectra.

MATHEMATIC FORMULATION

The Building Description

For comparative parametric analysis typical floor plan and elevation of RCC building, with 2 basements + ground floor + 10 storeys above ground level is considered as shown in Fig. 1 and Fig. 2. The building comprises with four bays in X-direction, having 8 m each length, whereas, five bays in Y-direction, having 5 m for middle and 4 m for both external ends. The dimension of building at ground floor and basement is 40x31 m.

The spectral matching procedure for real accelerograms is summarized and applied to a target earthquake response spectrum given in IS: 1893-2016, for type-I site soil.

The heights of basement floors are 3.6 m and 3.5 m for typical floors. Total height of building from Ground floor is 35 m. Concrete grade taken as M30 for beam and floor element, whereas for column M50 grade is used. Structural member sizing considered as mentioned as below:

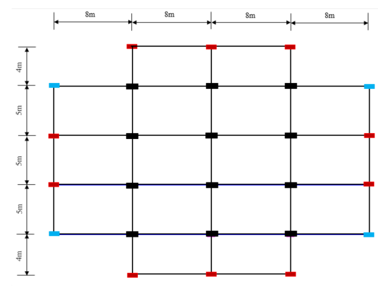


Fig 1. Typical Floor Plan

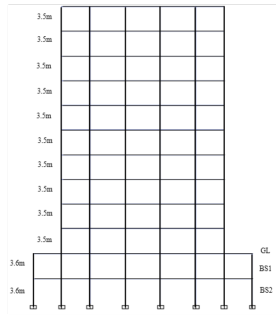


Fig 2. Longitudinal Section

Column	
Group-1	C 600x800 mm
Group-2	C 350x800 mm
Group-3	C 350x600 mm
Beam	B 300x700 mm
Slab	175 mm

Table 1: Structural Elements

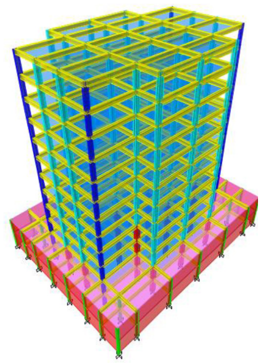


Fig 3. ETABS analysis model

Sample Earthquake used in the Analysis and Scaling

In this study, ground motion record has been selected from PEER Strong Ground Motion Database. [6] The Details of earthquake record as mentioned in Table 2.

Location	Imperial Valley-02
Date	19-May-40
Magnitude (M)	6.95
Station	El-centro Array #9
Closes to fault Rupture (km)	6.09
PGA (g)	0.28
PGV (cm/sec)	30.95
PGD (cm)	8.76

Table 2: Time History Record

In order to obtain a design earthquake compatible with the local seismicity, an earthquake signal treatment was performed consisting baseline correction, filtering and spectral matching in time domain, using computational program SeismoMatch - 2018. [7] The objective of

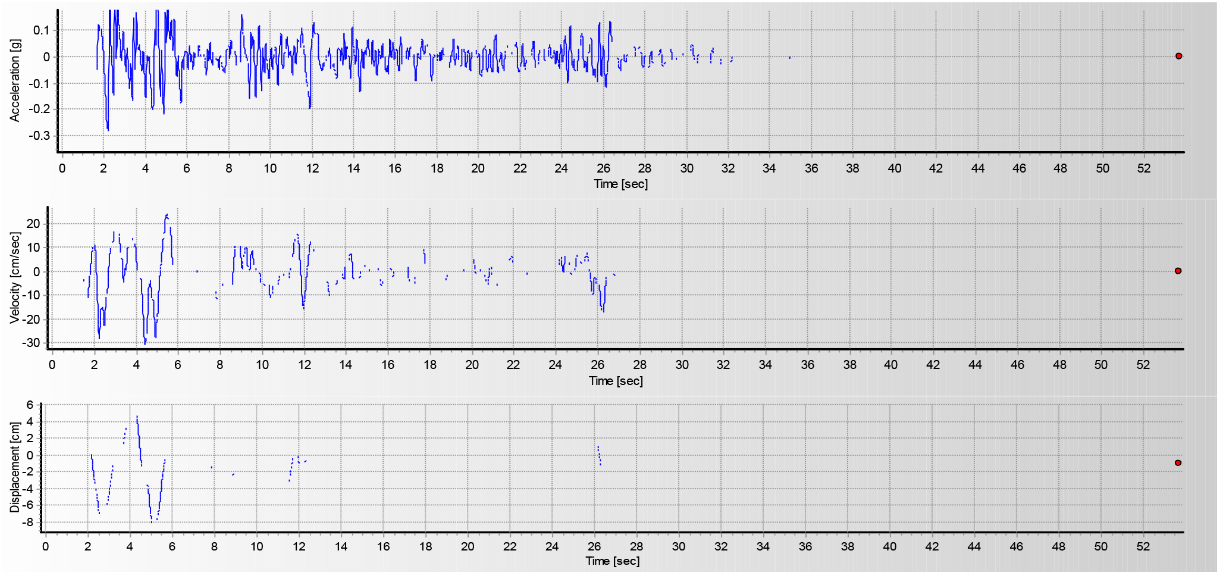


Fig 4. Imperial Valley-02-Time History Plot for Acceleration, Velocity and Displacement.

the spectral matching is to correct the actual acceleration record, compatible of standard target response spectrum properties as per IS1893-2016, for hard soil. [8] The principal goal of scaling accelerograms records is to obtain a design acceleration time history that will have a response spectrum as close as desired to the predetermined codal target spectrum. After matching the time history data is examined to ensure that the acceleration, velocity and displacement time histories should be reasonably close to the target codal spectrum.

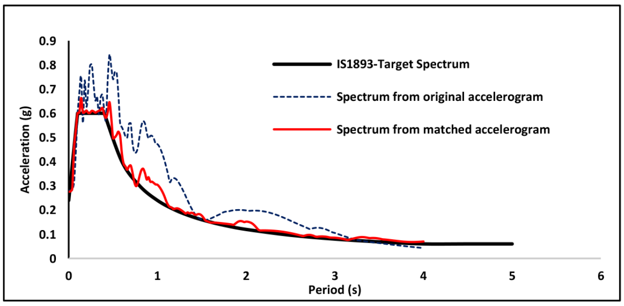


Fig 5: Scaled Spectra compatible to IS1893:2016

basement floors and dissipate earthquake shocks. Lead-rubber bearing were first introduced and used in New Zealand in late 1970s.[9] Since then, lead-rubber bearings were widely used all around the world for effective seismic isolation including USA and Japan. The lead-rubber bearing is similar to the elastomeric rubber bearing from construction perspective, except the additional lead-plug in central part of bearing. The lead plug has a property to deform plastically under shear deformation, thereof enhancing the energy dissipation compatibility in comparison to elastomeric bearing.

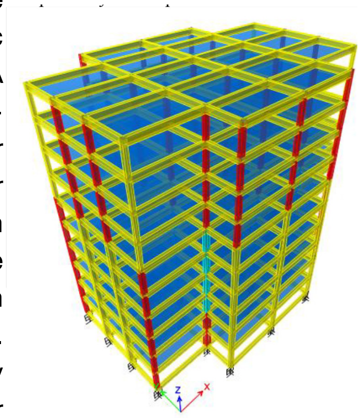


Fig 7: Building 3D model with base isolator

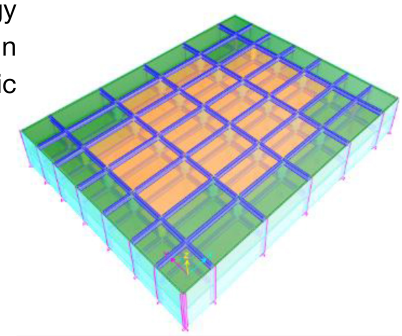


Fig 8: Building podium substructure

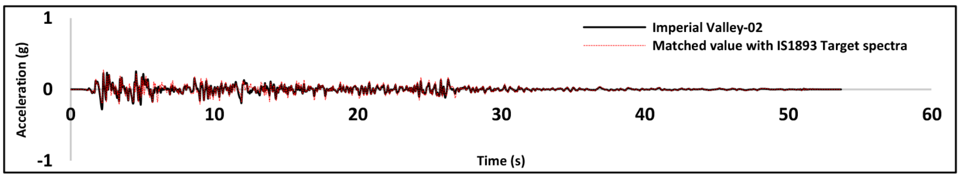


Fig 6: Scaled Time History compatible to IS1893:2016

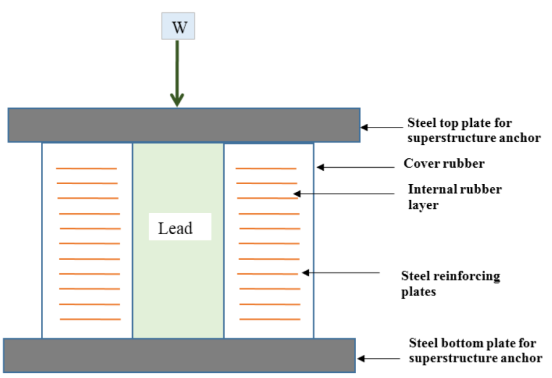
Design of Isolator

Analysis model developed, analyzed and maximum vertical load on each column have been carried out. The lead-rubber isolator has been designed to mount at ground floor to decouple the superstructure from

In practice lead-rubber isolator characterized and modeled by bilinear behavior with force-deformation relationship. This relationship, termed the hysteresis loop, defines the average stiffness at a specified displacement (Effective stiffness)

Accelerogram	Original Accelerogram	Matched Accelerogram
Max Acceleration (g)	0.280	0.276
ax. Velocity (cm/sec)	30.939	20.867
Max Displacement (cm)	86.6	83.9

Table 3: Ground Motion Parameter



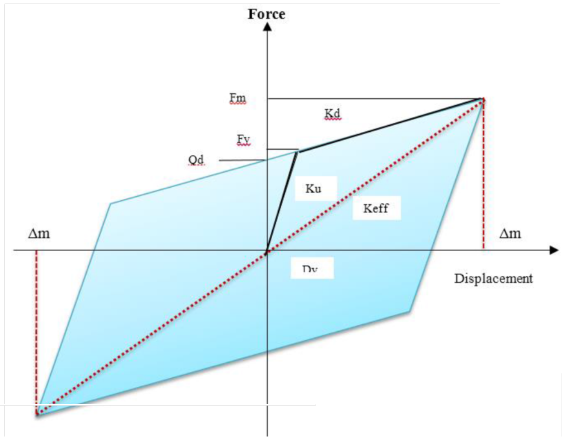


Fig 9: Bilinear Force-Deformation relationship of lead-rubber isolator.

and hysteretic damping provided by the system. A typical hysteresis for a lead rubber bearing is shown in Fig. 9. For design and analysis this shape represented as bilinear behavior mainly based on three parameters initial/elastic stiffness (K_u), post yield stiffness (K_d) and zero-displacement force intercept (Q_d). The characteristic strength of lead rubber bearing is controlled by the yield strength of the lead in shear, бy, and the cross-sectional area of the lead-plug, A*L* as:

$$Q_d = б_L\ A_L \qquad (1)$$

Post yield stiffness, K_d, is equal to the shear stiffness of the elastomeric bearing alone:

$$K_d = \frac{G_y\ A_r}{T_r} \qquad (2)$$

The shear modulus G_y=0.35 MPa, for a high damping rubber bearing is a function of shear ϒ. The unloading elastic stiffness for lead-rubber bearing is defined as:

$$K_u = 6.5K_r\left(1 + \frac{12A_{pl}}{A_r}\right) \qquad (3)$$

The second-slope stiffness, K_d, is the stiffness of elastomeric component of the bearing which can be calculated by the equation:

$$K_{eff} = \frac{Q_d}{\Delta} + K_d \qquad (4)$$

The isolator displacement can be calculated from the effective period, equivalent viscous damping and spectral acceleration as:

$$D_D = \left(\frac{g}{4\pi^2}\right)\frac{C_v}{B}\ T \qquad (5)$$

Where,

$C_v = \frac{S_a}{g}$ Spectral acceleration value for T = 1sec

T = Target design period of isolated building

B = Damping coefficient corresponding to the effective damping ratio. The relation between B and ξ expressed in here. [10]

$$\frac{1}{B} = 0.25(1 - In\ \xi) \qquad (5a)$$

Effective damping ξeff is given by

$$\xi_{eff} = \frac{1}{4\pi}\frac{E_D}{E_{so}} \qquad (6)$$

Where, E_{so} = Energy stored

$$E_{so} = \frac{1}{2}K_{eff}\ D^2 \qquad (6a)$$

As we put eq. (6a) in eq (6) it becomes

$$E_D = 2\pi\xi_{eff}K_{eff}D^2 \qquad (7)$$

E_D = Energy dissipated in one cycle which is equal to the area of the hysteresis loop.

For dynamic analysis code permits, furthermore reduction of target displacement which can be expressed as:

$$D'_D = \frac{D}{\sqrt{1+\left(\frac{T}{T_M}\right)^2}} \qquad (8)$$

Numerical Study

Mathematical Modeling of Building –

In this paper, mathematical models were defined for fixed base building and base isolated with lead rubber bearing. Building models were analyzed with scaled actual time history analysis building was analyzed. Analysis details of the building as shown in table: [11]

Description		Remark
No storey	10 storey+2 basement	
Type	RCC	Use as-Hospital building
Analysis used	Time history analysis	EQ-Imperial Valley-02
Scale History	Target response spectrum for hard soil	Code-IS1893-2016
Response reduction factor	4	
Seismic Zone Zone Factor	IV 0.24	Zone classified as per-IS1893-2016
Soil type	Hard	Type-I-IS1893-2016
Time Period	Tx = 0.60 S=sec.	Used formula as per-IS1893-2016
	Ty = 0.72 sec	

Table 4: Building Analysis Details

Seismic Isolation System –

In this study, dynamic building analysis has been performed by ETABS (Nonlinear version 16.2.0). Dynamic axial loads under each column at calculated for calculating parametric mechanical properties of lead-rubber bearing. As the structure got decoupled from the basement podium and mounted isolator at ground level. Nonlinear dynamic history analysis has been performed, to give a more accurate picture of the contribution of the base isolation system to the total seismic forces that are developed at the superstructure during a seismic excitation. It must be noted here that the response of the superstructure is elastic, while the response of the seismic isolation bearings is inelastic.

- Specification of Target Displacement - The target displacement of an isolator calculated from the expression given in Eq. 5. Design deflection governed by spectral 5% damped acceleration, Sd1 and time period, T, shown in Fig. 10.

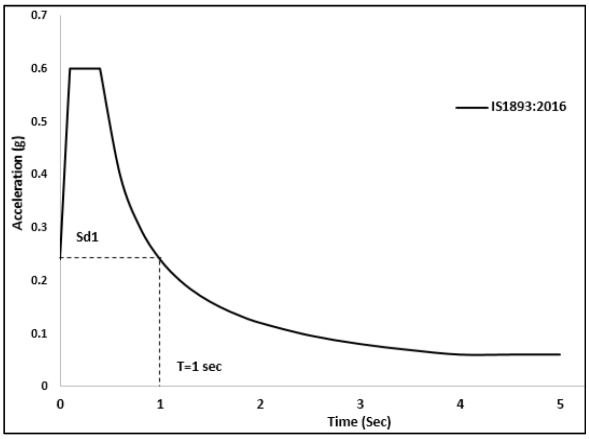


Fig.10-Codal horizontal response spectra for hard soil.

- Parametric Study for Mechanical Properties of LRB - In this paper, iterative LRB properties have been evaluate for different vertical loading on the column. As per the maximum vertical seismic loads on each column three column grouping are made for the building shown in Table 1. For these column groups, different LRB properties have been worked out to make economical design and thereby reduce the cost of the isolation. Parametric study carried out for target time period Tb=2.0, 2.5, 3.0 and 3 sec. corresponding effective damping, ξb=0.10, 0.15, 0.20, 0.25, 0.30. For each loading group, parametric iteration of LRB properties have been evaluated which are mentioned in table 5.

RESULT AND DISCUSSION

Comparison between Design and Time History Analysis Procedure

To investigate the effectiveness of base isolated building, time history analysis has been perform on both the model. The isolator performance parameters are the shear force coefficient, C, (the maximum isolator force normalized by the weight of structure) and the isolator displacement, DD. The ratios of the displacements and shear coefficient from the time history analysis to the values predicted by the design procedure are plotted in Table 6. In this study all twenty cases analyzed to work out the optimum case in each assumed time period.

Comparison between LRB and Fixed Structure

Table 6 shows the performance result of all LRB parameter for Tb=2.0, 2.5, 3, 3.5 sec.

with respect to the LRB damping 0.10, 0.15, 0.20, 0.25, 0.30. All four LRB system time history analysis, optimum performance of isolator have been worked out for these damping values.

11Sr no	Tb Sec	ξeff	S_{d1}	B	D_D (m)	$D_{D'}$ (m)	Dy (mm)	K_U (kN/mm)	K_{eff} (kN/mm)	K_V (kN/mm)	Q_D (kN)	Fy (kN)
1	2	0.1	0.24	1.21	0.099	0.094	5.57	6.45	0.863	1301	30.79	35.92
2	2	0.15	0.24	1.38	0.086	0.083	7.52	5.9	0.845	1067	38.23	44.4
3	2	0.2	0.24	1.53	0.078	0.074	8.52	5.47	0.828	880	40.21	46.67
4	2	0.25	0.24	1.67	0.071	0.068	12.13	5.73	1.167	874	60.34	69.48
5	2	0.3	0.24	1.814	0.066	0.063	15.77	6.02	1.594	867	83.1	94.92
6	2.5	0.1	0.24	1.21	0.123	0.12	5.67	6.33	0.754	1309	30.79	35.92
7	2.5	0.15	0.24	1.21	0.108	0.105	7.52	5.9	0.749	1067	38.23	44.4
8	2.5	0.2	0.24	1.53	0.097	0.095	10.62	6.16	0.977	1061	40.21	46.67
9	2.5	0.25	0.24	1.67	0.089	0.087	14.56	6.52	1.329	1052	60.34	69.48
10	2.5	0.3	0.24	1.814	0.082	0.08	15.77	6.02	1.313	867	83.1	94.92
11	3	0.1	0.24	1.21	0.148	0.145	5.67	6.33	0.71	1309	30.79	35.87
12	3	0.15	0.24	1.38	0.13	0.127	8.53	6.6	0.876	1302	48.66	56.28
13	3	0.2	0.24	1.53	0.117	0.115	10.62	6.16	0.873	1061	56.71	65.38
14	3	0.25	0.24	1.67	0.107	0.105	13.95	6.46	1.126	1053	78.82	90.16
15	3	0.3	0.24	1.814	0.099	0.097	15.77	6.02	1.131	867	83.1	94.92
16	3.5	0.1	0.24	1.21	0.173	0.17	5.67	6.33	0.679	1309	30.79	35.87
17	3.5	0.15	0.24	1.38	0.151	0.149	7.52	5.9	0.641	1067	38.23	44.4
18	3.5	0.2	0.24	1.53	0.136	0.134	10.62	6.16	0.803	1061	56.71	65.38
19	3.5	0.25	0.24	1.67	0.125	0.123	13.95	6.46	1.016	1053	78.82	90.16
20	3.5	0.3	0.24	1.814	0.155	0.113	15.77	6.02	1.01	867	83.1	94.92

Table 5: Parametric Properties of LRB for Group 1 Column Loading

							Design Procedure			Time History Analysis			
No	System	Seismic Weight (W)	Qd (kN)	Variation	Tb (Sec)	ξeff	DD	Vs=K.Δ	C=Vs/W	DD	BS	C=BS/W	Accel
1	LRB	75399	30.79	0.04	2	0.10	94	832.2	0.011	69	1298	0.017	0.830
		75399	38.23	0.05	2	0.15	83	734.8	0.010	72	1310	0.017	0.940
		75399	40.21	0.05	2	0.20	74	655.1	0.009	82	983	0.013	0.750
		75399	60.34	0.08	2	0.25	68	602.0	0.008	87	786	0.010	0.720
		75399	83.1	0.11	2	0.30	63	557.7	0.007	85	764	0.010	0.680
2	LRB	75399	30.79	0.04	2.5	0.10	120	679.2	0.009	62	1686	0.022	1.100
		75399	38.23	0.05	2.5	0.15	105	594.3	0.008	64	1686	0.019	1.030
		75399	40.21	0.05	2.5	0.20	95	1273.5	0.017	73	1012	0.013	0.870
		75399	60.34	0.08	2.5	0.25	87	492.4	0.007	82	830	0.011	0.740
		75399	83.1	0.11	2.5	0.30	80	452.8	0.006	88	726	0.010	0.690
3	LRB	75399	30.79	0.04	3.0	0.10	145	517.7	0.007	67	1329	0.018	1.050
		75399	48.66	0.06	3.0	0.15	127	453.4	0.006	65	1329	0.017	1.020
		75399	56.71	0.08	3.0	0.20	115	410.6	0.005	76	894	0.012	0.840
		75399	78.82	0.10	3.0	0.25	105	374.9	0.005	75	825	0.011	0.770
		75399	83.1	0.11	3.0	0.30	97	346.3	0.005	88	698	0.009	0.690
4	LRB	75399	24.15	30.79	3.5	0.10	170	491.3	0.007	62	1435	0.019	1.120
		75399	30.79	38.23	3.5	0.15	149	430.6	0.006	65	1220	0.016	1.030
		75399	35.34	56.71	3.5	0.20	134	387.3	0.005	71	977	0.013	0.900
		75399	50.89	78.82	3.5	0.25	123	355.5	0.005	84	716	0.009	0.730
		75399	69.27	83.10	3.5	0.30	113	326.6	0.004	88	679	0.009	0.690

Table 6: LRB Isolation System Performance

Sr. No	Tb (Sec)	ξ	BI		Fixed	
			Db (mm)	Ac (m/sec²)	Db (mm)	Ac (m/sec²)
1	3.5	10	62	1.12		
2	2.5	15	64	1.03		
3	2.5	20	73	0.87	5.7	2.48
4	2	25	87	0.72		
5	2	30	65	0.68		

Table 6: LRB Isolation System Performance

Floor Spectra Plot Variation

Response spectrum is the curve showing the maximum response versus the structural frequency relationship. [11] A study of floor response spectra for a base-isolated multi-storey structure under seismic ground excitations is carried out. All the LRB systems studied in Table 6 have been considered An El-Centro earthquake accelerogram is used to evaluate the floor response spectra. The characteristics of the spectra generated by different base isolation systems are studied, and the variation of all twenty LRB System plotted on a single graph. [13] The results are compared with those for the fixed-base structure. Fig.11 shows the plotting of floor acceleration spectra at top floor of the building. All optimum design cases are shown in dark line. For all the cases (ξ=0.10, Tb= 3.5 S, ξ=0.15, Tb=2.5 S, ξ=0.20, Tb= 2.5 S, ξ=0.25, Tb=2.0 S ξ=0.30, Tb= 2.0 S) maximum peak ordinate occur at the time period of 0.8 sec. and gradually lower down further.

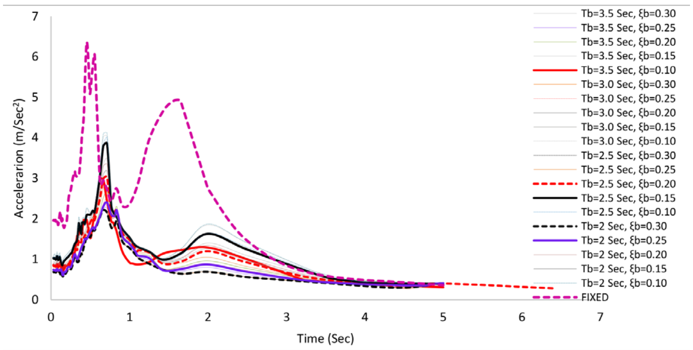


Fig.11-Floor acceleration response spectra at top floor

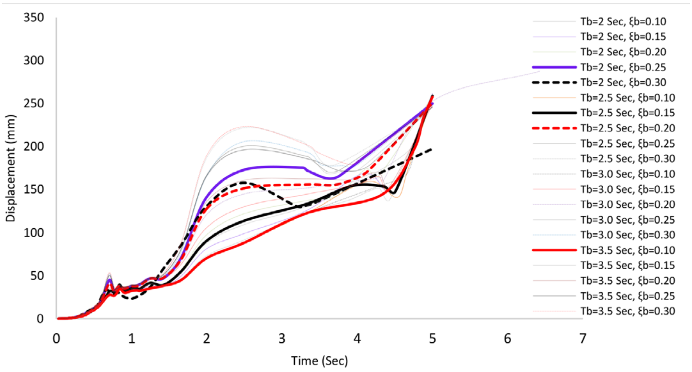


Fig.12-Displacement spectra at ground floor (Top of LRB)

Similarly, Fig.12 shows the floor displacement spectra at ground floor (top of the isolator & column interface). Displacement spectra depict the LRB performance for all studied systems. From all the cases studied system ξ=0.25, Tb= 2.0 S and ξ=0.30, Tb= 2.0 S evaluate the better response than other governing optimum cases of LRB performance.

Floor Time History Plot

In time history analysis of building lead rubber bearings designed are linked at bottom of the respective column at ground level to ensure all the properties of spring. Table 6 shows the performance of all the LRB system considered in this study. The time history for base shear of the BI building (ξ = 0.30, Tb = 2.0 sec.) and fixed building comparisons are illustrated in Fig. 13. The maximum base shear in fixed building occurs 4900 kN at T-4.9 sec. and for base isolated building, the base shear reduces 1140 kN drastically.

Similarly, Fig. 14 dipict floor acceleration time history for fixed and base isolated building at the top level of the building. The maximum top floor acceleration in fixed building occur 2.48 m/sec² and for base isolated building, the base shear reduces 0.68 m/sec².

Displacement and Acceleration Plot

In base isolation technique of building, seismic forces are dissipated by flexible bearing with high damping material. Fig. 15 shows storey forces variation for both fixed and BI building structure. In fixed structure dynamic forces absorbed by the structural itself caused heavy forces and moments induced in structural element. Fig. 15(a) shows the 67 mm base displacement at ground level (Top of LRB interface). Fig. 15(b) shows the maximum storey acceleration comparison for both the systems. Thus, acceleration of BI building successively lowered in each storey of the building in compare to the fixed structure, due to flexibility

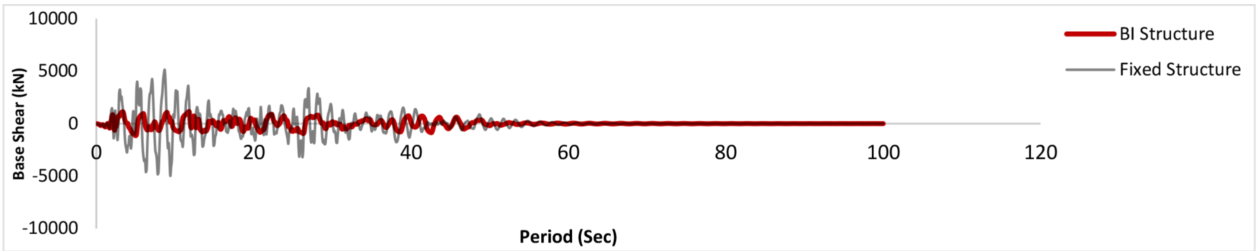


Fig.13-Plots the time history at ground floor (Top of LRB)

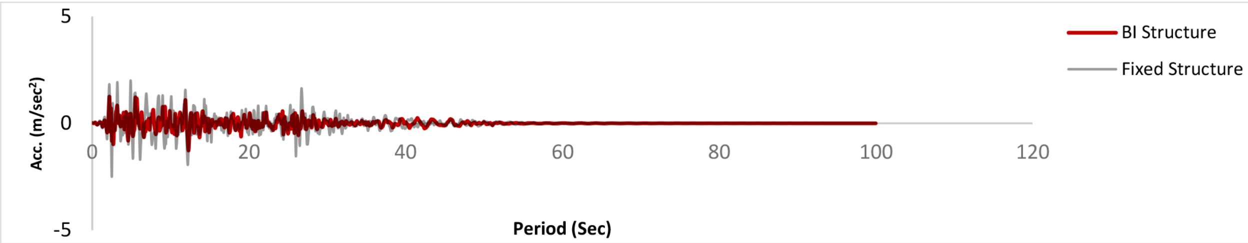
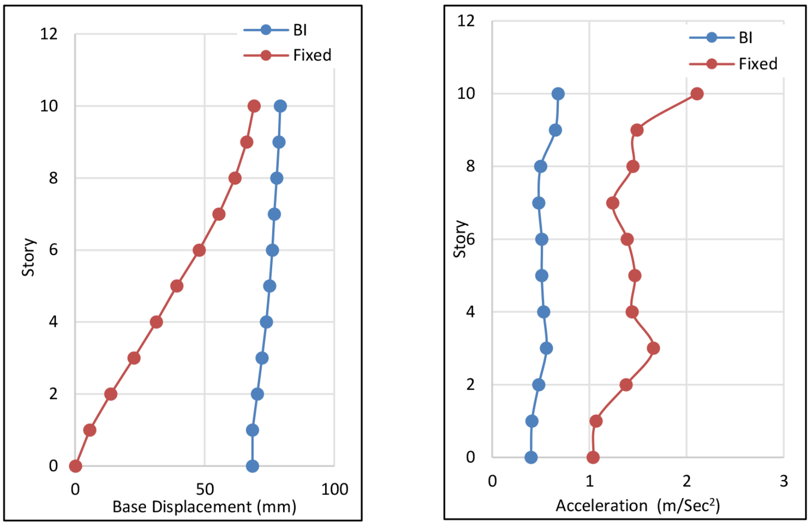


Fig.14- Plots the time history at top floor



(a) (b)

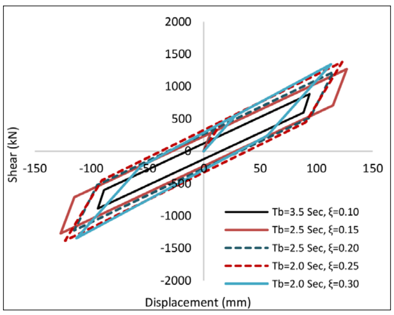
Fig.15- Story plot for Fixed and BI base (a) Displacement & (b) Acceleration

dissipation of earthquake forces at the base of the building.

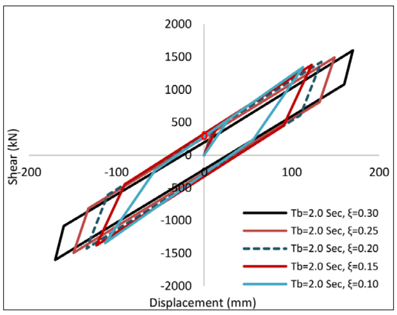
Force-deformation of LRB

Lead rubber bearings constructed of high damping rubber, have a nonlinear force deflection relationship. This relationship, termed the hysteresis loop, defines the effective stiffness (average stiffness at specified displacements) and the hysteretic damping provided by the system. [12] Fig. 16(a) depicts the bi-linear hysteresis curve for each optimum case shown in Table 6. Each case shows different shear resisted by the bearing with corresponding to the bearing displacement. Maximum force resisted by the case 1. Tb = 2.0 Sec, ξ = 0.25 and lower force dissipated by the case 2. Tb = 3.5 Sec, ξ = 0.10.

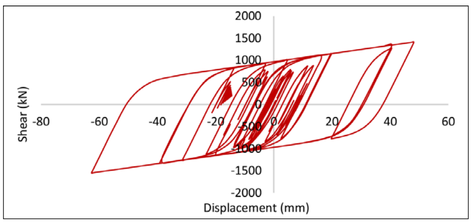
Fig. 16(b) depicts the cases for Tb = 2.0 Sec. with ξ = 0.10, 0.15, 0.20, 0.25, 0.30. As the damping of the bearing increases, the displacement of the bearing gets increased and vice versa. Fig. 16(c) depicts the actual hysteresis of optimum isolator.



a)



b)



c)

Fig.16- Hysteresis curve
(a) Optimum cases as per Table VI,
(b) Optimum design case ξ=0.30 & Tb=2.0 sec.
(c) Time history analysis - case ξ=0.30 & Tb=2.0 sec.

CONCLUSION

The analysis of fixed base and LRB base isolated 3D ten storey RCC building have been performed in this paper. An exhaustive study has been performed on the performance of base isolated structures.

The behavior of building structure resting on LRB isolator is compared with fixed base structure under maximum capable earthquake. A complete list of performance of isolator is presented in Table 6. Seismic base isolation can reduce the seismic effects and therefore floor accelerations, inter-storey drifts, and base shear by lengthening the natural period of vibration of a structure via use of rubber isolation pads between the columns and the foundation. However, in case the deformation capacity of the isolators exceeded, isolators may rupture or buckle.

Therefore, it is vitally important to accurately estimate the peak base displacements in case of major earthquakes, particularly if the base isolated building is likely to be struck by near-fault earthquakes. Near-fault earthquakes may contain long-period velocity pulses which may coincide with the period of the base isolated structures. In such a case, the isolators may deform excessively.

The analysis comparison revels that base isolated structure reduces response performance considerably in compare to the fixed structure which impart a vital role in reducing the sizing of structural members and amount of designed steel requirement as well. Top floor acceleration and displacement floor spectra have been developed to study the exact earthquake response and finding out the optimum design parametric properties of LRB and corresponding cost comparison in case of Indian site area in highly seismic zone IV. According to analysis study, conclusions are as follows:

1. Increase of time period of building – As result of the increased flexibility of the system, natural period of the structure increased from T = 0.6 sec. to T = 4.2 sec, distancing natural period of the system from the predominant periods of the expected earthquake actions.
2. Reduction of base-shear – Reduction of the base-shear force is evident in the model with implemented seismic isolation. For the optimum case of LRB isolator, the base-shear force under the El-Centro earthquake excitation has been reduced 3.2 times in compare to fixed base structure.
3. Increase of displacements – Increased flexibility of the system led to increase of the total displacements due to the elasticity of the existing isolation. Displacements of the system are concentrated at the isolation top plan level. Total displacement at isolation top level is 68 mm under the El-Centro earthquake excitation.
4. Optimum LRB system – After analyzing all cases of different Tb and ξ values of the isolator system optimum design cases found as a) ξ = 10, Tb = 3.5 S, b) ξ = 15, Tb = 2.5 S, c) ξ = 20, Tb = 2.5 S, d) ξ = 25, Tb = 2 S, e) ξ = 30, Tb = 2.0 S.
5. Reduction of storey acceleration – Due to increased flexibility and damping of isolator, it predominantly dissipates most of the earthquake energy. Analysis has been shown significant reduction of floor acceleration. For fixed structure top floor acceleration under earthquake excitation has found 2.48 m/sec^2, where as in base isolated structure for same floor it is found 0.68 m/sec^2.

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