SEISMIC PERFORMANCE AND ECONOMIC FEASIBILITY OF STRUCTURES BY OPTIMAL POSITIONING OF COMBINED BASE ISOLATION SYSTEMS

Susan Paul [1], Dr. T. Sundararajan [2], Prof. Basil Sabu [3]

[1]M.Tech in Structural Engineering, Mar Athanasius College of Engineering, Kothamangalam
[2] Head, SMSD, Vikram Sarabhai Space Centre, Indian Space Research Organisation, Thiruvananthapuram
[3]Professor, Department of Civil Engineering, Mar Athanasius College of Engineering, Kothamangalam

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Abstract - *Seismic base isolation is an earthquake resistant design method that is based on decreasing the seismic demand instead of increasing the seismic capacity. Earthquake ground motions can cause significant or severe structural damages. Recorded accelerograms for bi-directional ground motions compatible with the reference elastic response spectrum have been used for the evaluation of the seismic response of the structure. Modeling and analysis is done using the finite element software SAP2000 version 18 for El-Centro earthquake ground motion records. Maximum vertical reaction is obtained from analysis in SAP2000 software and this vertical reaction and the total mass of structure are used for designing the lead rubber bearings and friction pendulum systems manually. The seismic responses of 14 storied reinforced concrete structure base isolated with different types of isolators such as Lead Rubber bearing and Friction Pendulum System are determined by performing dynamic nonlinear analysis. Time-history analysis is carried out in order to evaluate floor response, accelerations and displacements during a ground motion. This paper intends to demonstrate how an isolation system can be efficient, evaluating its effectiveness for the building in terms of, base shear, storey drift and storey displacement and storey acceleration reductions. Combinations of base isolation systems are placed optimally at the base of the structure to achieve the most efficient and economically feasible earthquake resistant structure.*

Key Words: *Base isolation, lead-rubber bearing, friction pendulum system, non- linear time-history analysis, storey acceleration, floor displacement, storey drift, base shear.*

1. INTRODUCTION

Base isolation is most effective methods to reduce vibrations transmitted from ground to the structure and one of the most widely accepted seismic protection systems in earthquake prone areas. It mitigates the effect of an earthquake by essentially isolating the structure from potentially dangerous ground motions, especially in frequency range where building is mostly affected. When the seismic isolation system is located under the structure, it is referred as "base isolation". The role of the base isolator under seismic loading is to isolate the structure from the horizontal components of the earthquake ground movement, whereas the vertical components are transmitted to the structure relatively unchanged. Base isolators deflect and absorb the seismic input energy horizontally transmitted to the structures. The principle of seismic isolation is to introduce flexibility in the basic structure in the horizontal plane, while at the same time adding damping elements to restrict the resulting motion and the basic concept of base isolation is to increase the natural period of the building to take it away from resonance with the forcing motions of earthquake and thereby reducing the design base shear. The successful seismic isolation of a particular structure is strongly dependant on the appropriate choice of the isolator devices, or systems, used to provide adequate horizontal flexibility with minimal centering forces and appropriate damping. It is also necessary to provide an adequate seismic gap which can accommodate all intended isolator displacements. A reasonable design displacement should be of the order of 50 to 400 mm, and possibly up to twice this amount if 'extreme' earthquake motions are considered. The primary function of an isolation system is to support a structure while providing a high degree of horizontal flexibility. This gives the overall structure a long effective period and hence low maxima for its earthquake generated accelerations and inertia forces. The expected life of an isolated structure will typically range from 30 to 80 years and its maintenance problems should preferably be no greater than those of the associated structure.

1.1 Review of Literature

Pradeep Kumar T. V et al. [1] have shown force-deformation behavior of isolation bearings. The isolation system is determined to increase the natural period of the structure away from the high-energy periods of the earthquake and a damper to absorb energy in order to reduce the seismic force. The most common isolation bearing used was the lead rubber bearing. It has been observed that lead rubber bearings have little strain-rate dependence for a wide frequency range which contains typical earthquake frequencies. The isolation bearings are modeled by a bilinear model based on the three parameters: initial stiffness, lower stiffness, and characteristic strength. It provides relationship to find out the yield displacement and yield force for an equivalent bilinear isolation bearing system. Compared to the conventional method the newly derived equations give accurate results and are less time consuming. The graphical representation of the new relationship shown in the paper is useful for bearing design.

Minal Ashok Somwanshi and Rina N. Pantawane [2] includes non-structural components which are sensitive to large ground motion which produces floor accelerations, velocities, and displacements. During an earthquake, the building produces this motion, resulting in peak floor accelerations higher than the peak ground acceleration. Thus earthquake ground motion can cause significant or severe structural damages. The use of base isolation is the best method to reduce the inter storey drift and floor accelerations. The modeling and analysis of 13-storey rigid jointed plane frame for fixed base and base isolated cases. Modeling and analysis are done using E-TABS software for Bhuj earthquake ground motion records. Maximum vertical reaction is obtained from analysis in E-TABS software. Time-history analysis is carried out in order to evaluate floor response, accelerations and displacements during a ground motion. The isolation systems are proved to be for the building in terms of maximum shear force, maximum bending moment, base shear, storey drift and storey displacement reductions.

P.A Shirule et al. [3] used an 18-storey symmetrical R.C.C. building as a test model. Lead Rubber Bearing (LRB) and Friction Bearing (FB) are used as isolation system in this study. Nonlinear Time history analysis is used on both of fixed base and base isolated buildings. There are two portions; one is comparative study of performance of fixed base condition and base isolation (LRB and FB) condition and the comparative study of performance by three different time histories Bhuj, Koyana and Lacc T.H. The base shear, displacement and acceleration are compared from 3 times histories analysis between fixed base condition and base isolated condition. It is found that the displacement is increased with period of the isolated building. The base shears in each direction are decreased with LRB by 46 % and with FB by 35% in base-isolated building compared to the fixed base building.

Radmila B. Salic et al. [4] have demonstrated the effect of dynamic response of the seven-story residential building under the earthquake ground motions. Mode shapes, natural frequencies and damping ratios of the existing fixed-base building are obtained by Ambient Response Testing and Modal Identification Software. The non linear dynamic analysis of fixed base model and model base isolated with lead rubber bearing has been performed by finite element software ETABS (Nonlinear version 9.0.4). The Dynamic responses of fixed base and seismic isolated models have been calculated for four types of real earthquake time histories of different frequency characteristics whose value is determined based on the detailed site response analysis. The increase of natural period of structure increases flexibility of the same structure. In seismic isolated model, base shear force is highly reduced. Increased flexibility of the system led to increase of the total displacements due to the elasticity of the existing isolation. Implementation of the isolation system resulted into the reduction of the inter-story drifts. Analysis of seismic isolated model has shown significant reduction of the story accelerations.

1.2 Types of Base Isolation Systems

1.2.1 Lead Rubber Bearing (LRB)

The LRB was invented in New Zealand in1975 and has been used extensively in New Zealand, Japan and United States. Rubber reinforced with steel plates provides stable support for structures. Multilayer construction rather than single layer rubber pads provides better vertical rigidity for supporting a building. The steel plates in the bearing force the lead plug to deform in shear. This bearing provides an elastic restoring force and also, by selection of the appropriate size of lead plug, produces required amount of damping. The force deformation behavior of the bearing is shown in Fig 1. Performance of LRB is maintained during repeated strong earthquakes, with proper durability and reliability.

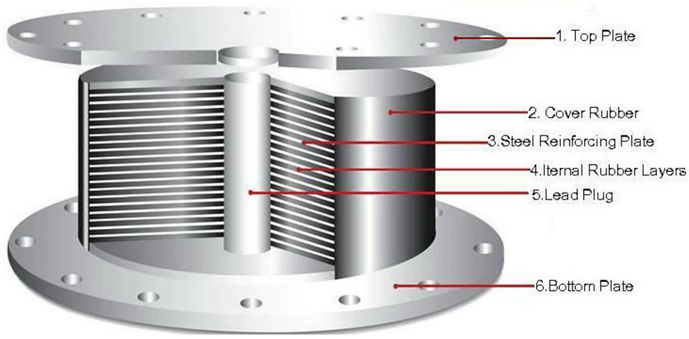


Fig -1: Section of Lead Rubber Bearing

1.2.2 Single Friction Pendulum System (FPS)

Sliding friction pendulum isolation system is one type of flexible isolation system suitable for small to large-scale buildings. The friction pendulum bearing provides strength and stability. Its properties are not affected by aging or temperature. The bearing's low profile, high strength, and high vertical stiffness reduce installation cost. Typically Friction Pendulum bearings measure 90cm in diameter, 20cm high, and weigh 900kg. The shiny surface on the inside of the bearing is the dense chrome which reduces the friction between the articulated slider and the concave surface to allow for lateral displacement when ground shaking occurs. It combines sliding action and a restoring force by geometry as in Fig 2.

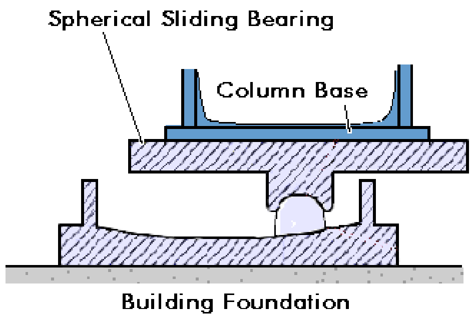


Fig -2: Single Friction Pendulum System

1.3 Costs and Benefits of Seismic Base Isolation

Base isolation allows for a reduction in structural elements of the building with less ductile detailing needed. Crawl spaces or basements can have multiple benefits as in siting services, additional income from a car park and flexibility for future development. Protection of the 'contents' with controlled movement caused by seismic isolators contents are not subject to violent and sudden shakes thereby reducing the impact on the contents. The integrity of the internal structures like stairs, internal walls and partitions are well protected. Building is safer for occupants and contents are protected and continuity of operations is much more likely. Structures can include buildings, bridges, storage containers, tanks, power facilities and most other structures requiring protection from damaging forces of earthquakes, and vibration in general. Base isolation systems offer better seismic performance, lower bearing costs and lower construction costs as compared to conventional seismic isolation technology. Friction pendulum system reduces the size and cost of the bearings and reduces the displacements required for the structure's seismic gaps. The inclusion of all aspects of seismic isolation in a new structure will add no more than 3% to total construction cost and considerably less when assessed against the benefits of isolation.

2. STRUCTURAL MODELING AND ANALYSIS

The modeling and analyses of the structure are done in the finite element analysis software SAP2000 v.18 which predicts the geometric nonlinear behavior of space frames under static or dynamic loadings, taking into account both geometric nonlinearity and material nonlinearity. The software accepts static loads (either forces or displacements) as well as dynamic (accelerations) actions and has the ability to perform eigen values, nonlinear static pushover and nonlinear dynamic analyses.

A fourteen storied (G+13) reinforced concrete structure of area 20 x 12 m^2 having storey height of 3.2 m has been considered for the study. Thickness of slab is 150 mm and has concrete grade of M 25. Thickness of external wall and internal wall are 230 mm and 150 mm respectively and the unit weight of brick masonry is considered as 20kN/m^3. Live load intensity is considered as 4 kN/m^2 [IS 875- Part 2] and the superimposed load intensity is considered as 1.5 kN/m^2 [IS 875- Part 1].

As per Table 8 of IS: 1893 (Part 1) 2002, percentage of imposed load to be considered in seismic weight calculation, since the live load class is above 3 kN/m^3, 50% of the imposed load has been considered. Beams and columns of size 300 x 400 mm and 350 x 700 mm respectively are adopted having M25 and Fe415 grades of concrete and reinforcement bars.

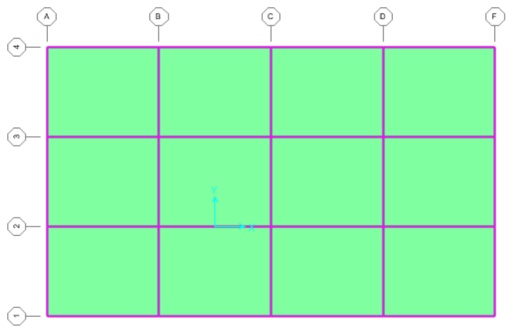


Fig -3: Plan of RC Building (G+5) in SAP2000 v.18

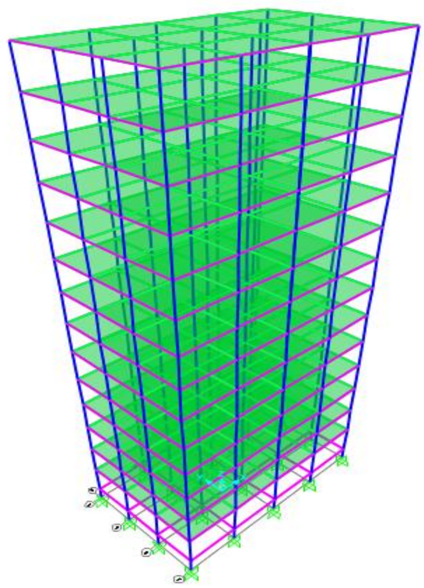


Fig -4: 3D View of RC Building (G+5) in SAP2000 v.18

The reinforced concrete structure is situated in California which belongs to seismic zone 4 with a soil profile type with very dense soil and soft rock with seismic source type A and closest distance to known seismic source is 10 km. Time history analysis has been carried out in the software "SAP2000" using the Imperial Valley Earthquake record of May 18, 1940 also known as the El-Centro earthquake of magnitude 7 having peak ground acceleration of 0.319 g is used for obtaining the various responses.

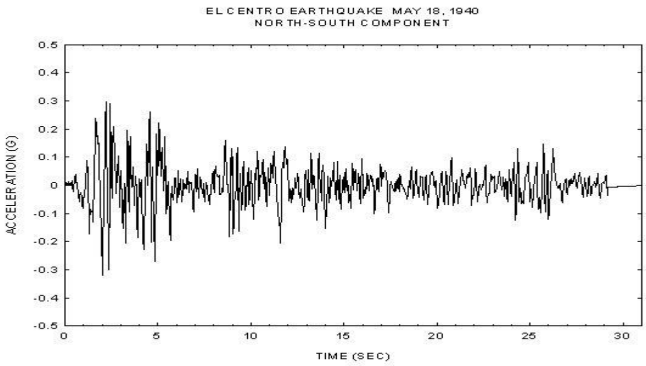


Fig -5: Time History Plot of El-Centro Earthquake

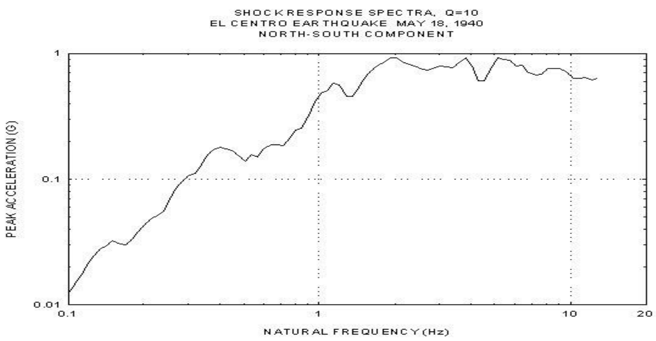


Fig -6: Response Spectra Plot of El-Centro Earthquake

2.1 Design of Base Isolation Systems

2.1.1 Lead Rubber Bearing (LRB)

Set the target values for effective period (T_b) and damping ratio (β). Fix target value of time period, T_b= 3x time period of fixed base building.

The design displacement (D) and required effective Stiffness (K_{eff}) of bearing are determined using relation,

$$K_{eff} = \frac{W_s}{g}\left(\frac{2\pi}{T_b}\right)^2$$

$$D = \left(\frac{g}{4\pi^2}\right)\frac{C_{VM} \times T_b}{B_D}$$

CVM = Seismic coefficient
BD = Damping coefficient
g = acceleration due to gravity

Determination of hysteresis parameters of isolator,

$$\beta_{eff} = \frac{Area(hysteresis-loop)}{2\pi K_{eff} D^2}$$

The characteristic strength of lead core, Q_d is obtained using the relation,

$$Area(loop) = 4Q_d(D - D_y)$$

Yield displacement is given by the equation,

$$D_y = \frac{Q_d}{K_u - K_d}$$

Post yield stiffness can be given as,

$$K_d = K_{eff} - \frac{Q_d}{D}$$

K_V = vertical stiffness of bearing and K_h = horizontal stiffness of bearing

$$\frac{K_V}{K_h} = 500$$

Table -1: Parameters required in SAP2000 for defining LRB for 14 storied RC structure

Parameters in U_1 Direction	
Linear Effective Stiffness	376025.5 kN/m
Effective Damping	0.15
Parameters in U_2 and U_3 Direction	
Linear Effective Stiffness	752.051 kN/m
Effective Damping	0.15
Non Linear Effective Stiffness	5686.6621 kN/m
Yield Strength	156.9144 kN
Post Yield Stiffness Ratio	0.1

2.1.2 Single Friction Pendulum System (FPS)

The basic characteristics like time period of fixed base building, weight of the building, weight on single isolator etc is found out. Then a target time (TD) period is fixed.

The radius of the sliding surface (R) is given by,

$$T_D = 2\pi\sqrt{\frac{R}{g}}$$

Assuming a friction coefficient = 0.06 and damping = 15%, Design displacement is given by the equation,

$$\beta_{eff} = \frac{2}{\pi}\left[\frac{\mu}{(\mu+D)/R}\right]$$

The effective horizontal stiffness is obtained by,

$$K_{eff} = (\mu + 1)\frac{W}{R}$$

where, W is the total weight of the building

Device horizontal stiffness is obtained from the equation,

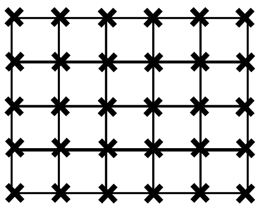
$$K = \frac{w}{R}$$

where, w is the maximum load on the isolator

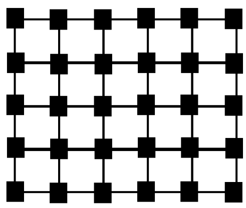
Table -2: Parameters required in SAP2000 for defining FPS for 14 storied RC structure

Parameters in U_1 Direction	
Linear Effective Stiffness	15000000 kN/m
Effective Damping	0.15
Non Linear Effective Stiffness	15000000 kN/m
Damping Coefficient	1.35
Parameters in U_2 and U_3 Direction	
Linear Effective Stiffness	752.051 kN/m
Effective Damping	0.15
Non Linear Effective Stiffness	12076.553 kN/m
Friction Coefficient, Slow	0.03
Friction Coefficient, Fast	0.06
Rate Parameter	40
Radius of Sliding Surface	8.11 m

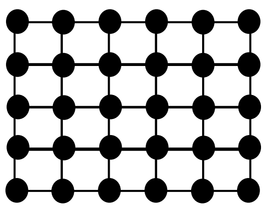
2.2 Models with Different Base Isolators and its Combinations



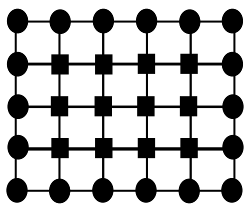
FIXED



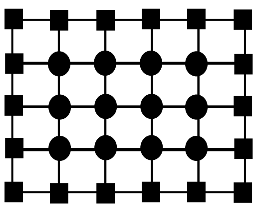
LRB



FPS



MODEL 1A



MODEL 1B

3. RESULTS AND DISCUSSIONS

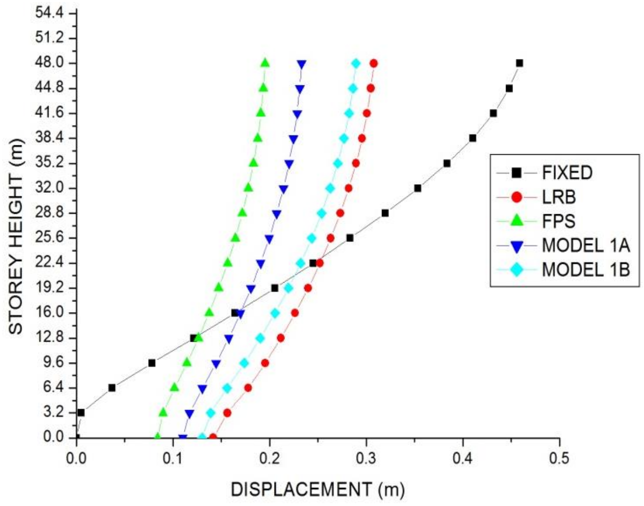


Chart -1: Storey Height v/s Displacement

Table -3: Values and Percentage Reduction in Displacement of 14 Storied Base Isolated Building

VALUES OF DISPLACEMENT (m)				
FIXED	**LRB**	**FPS**	**MODEL 1A**	**MODEL 1B**
0.459	0.308	0.195	0.233	0.289

PERCENTAGE REDUCTION (%) IN DISPLACEMENT				
FIXED	**LRB**	**FPS**	**MODEL 1A**	**MODEL 1B**
0	32.9	57.5	49.2	37.0

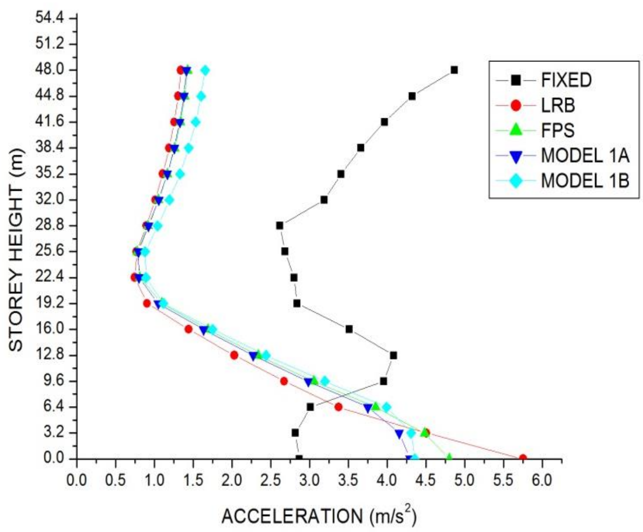


Chart -2: Storey Height v/s Acceleration

Table -4: Values and Percentage Reduction in Acceleration of 14 Storied Base Isolated Building

VALUES OF ACCELERATION (m/s²)				
FIXED	LRB	FPS	MODEL 1A	MODEL 1B
4.867	1.343	1.428	1.414	1.654

PERCENTAGE REDUCTION (%) IN ACCELERATION				
FIXED	LRB	FPS	MODEL 1A	MODEL 1B
0	72.4	70.7	70.9	66.0

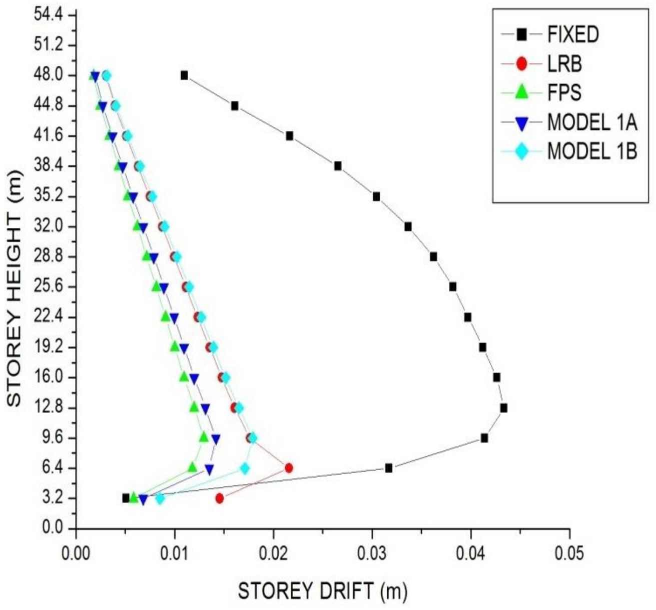


Chart -3: Storey Height v/s Storey Drift

Table -5: Values and Percentage Reduction in Displacement of 14 Storied Base Isolated Building

VALUES OF STOREY DRIFT (m)				
FIXED	LRB	FPS	MODEL 1A	MODEL 1B
0.0110	0.0031	0.0018	0.0020	0.0031

PERCENTAGE REDUCTION (%) IN STOREY DRIFT				
FIXED	LRB	FPS	MODEL 1A	MODEL 1B
0	71.8	83.6	81.8	71.8

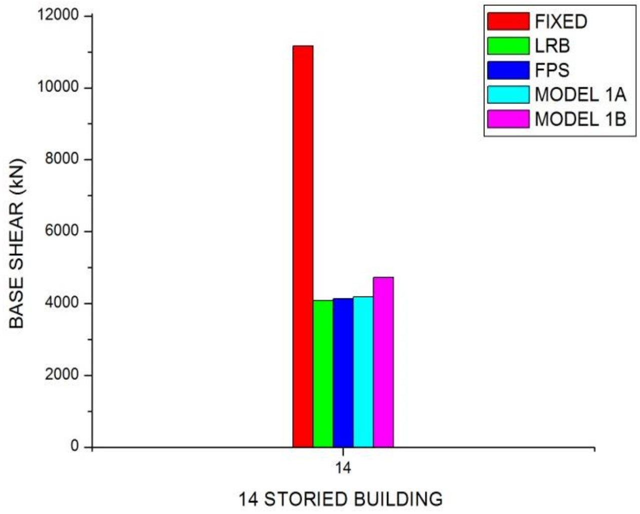


Chart -4: Storey Height v/s Base Shear

Table -6: Values and Percentage Reduction in Displacement of 14 Storied Base Isolated Building

VALUES OF BASE SHEAR (kN)				
FIXED	LRB	FPS	MODEL 1A	MODEL 1B
11170	4083	4125	4188	4727

PERCENTAGE REDUCTION (%) IN BASE SHEAR				
FIXED	LRB	FPS	MODEL 1A	MODEL 1B
0	63.4	63.1	62.5	57.7

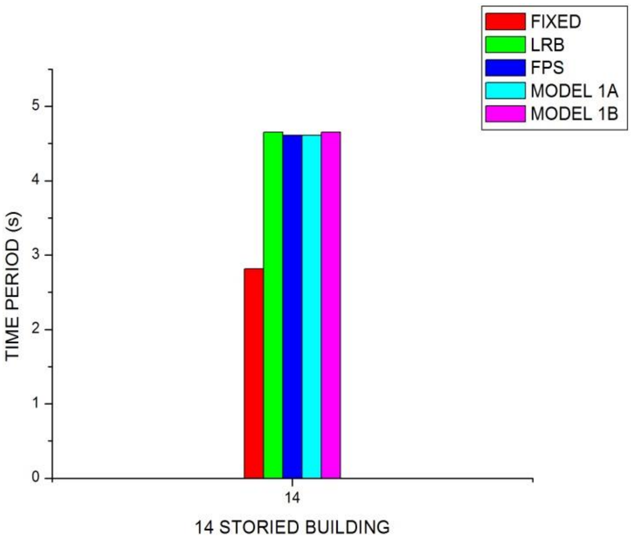


Chart -5: Storey Height v/s Time Period

Table -7: Values and Percentage Reduction in Displacement of 14 Storied Base Isolated Building

VALUES OF TIME PERIOD (s)				
FIXED	**LRB**	**FPS**	**MODEL 1A**	**MODEL 1B**
2.812	4.653	4.608	4.608	4.652

PERCENTAGE REDUCTION (%) IN TIME PERIOD				
FIXED	**LRB**	**FPS**	**MODEL 1A**	**MODEL 1B**
0	39.6	39.0	39.0	39.6

4. CONCLUSIONS

The base isolation systems such as LRB and FPS have been investigated when mounted separately and when mounted in combination. The performance of different base isolation systems on a fourteen storied (G+13) reinforced concrete structure have been interpreted by using non-linear time history analysis. It is concluded that the base isolation systems reduces the seismic response of the RC structure both when mounted separately and in its combinations in comparison to the fixed base structure, thereby reducing the structural damages during strong ground shaking. From the results obtained, it is observed that the displacement, acceleration, storey drift and base shear decreases whereas the time period of the base isolated structure increases when compared to the fixed base structure. It is observed that the fixed base structure have zero displacement at the base whereas, the base isolated structure have sufficient lateral displacements at the base which decreases with the increase in storey height when compared to the fixed base structure. The base isolated structure has an increased storey drift at the base which decreases drastically with the increase in storey height when compared to the fixed base structure.

In case of 14 storied building, FPS and Model 1A (FPS placed at exterior columns and LRB at interior columns) are more efficient in terms of reduction of displacement, acceleration and storey drift of the multi-storied reinforced concrete structure. LRB is comparatively more effective in reduction of base shear than FPS and its combinations. It is observed that the LRB and Model 1B (LRB placed at exterior columns and FPS at interior columns) efficiently increases the time period of the structure when compared to FPS and Model 1A.

Friction Pendulum System is relatively having lower bearing costs and lower construction costs than Lead Rubber Bearing, thus FPS and Model 1A having more number of friction pendulum bearings at the exterior columns can be provided to achieve the most efficient and economically feasible earthquake resistant structure. The economy of base isolation is not viewed in terms of its initial installment but over the design period of the structure during which it is expected to experience earthquake. After an event of earthquake, the repair of structure, and loss of non-structural components may be a more costly affair than installing base isolation. So far, base isolation technology has been adapted in very important structures such as hospitals, laboratories, and data centers etc. Also, base isolation has been found to be extremely useful for retrofitting of the historic structures where the aesthetic, architectural and heritage value is required to be maintained intact.

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