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Design and analysis of Base Isolated Structure

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Abstract− *Base isolation is a method used to decouple the super structure from the ground by installing a flexible link between them to make the structure safe from the damaging effects of ground motion. There are various methods to make the structure flexible. Using High Damping Rubber Bearing (HDR) is one of the ways to increase flexibility of the structure and increase its time period. HDR is made up of alternate layers of high damping rubber laminated with steel shims. This paper presents a design procedure to proportion the diameter and thickness of layers of rubber and steel shims. Fixed base and base isolated structures were modelled in ETABS. After seismic analysis of both structures, a comparative study was conducted between the response of the two structures. Inter storey drifts and shear forces were seen to be greatly reduced in base isolated structure. Displacement of the base isolated structure, however, was increased. Most of the deformation occurred in the flexible HDR installed at the base. Moreover, time period of the base isolated structure greatly increased (upto 2.5sec) which decreased the probability of resonance of the structure with common time period of the earthquake on hard soil i.e in the range 0.03-0.33 sec.*

Keywords *– Base Isolation, Seismic Performance, Time Period, HDR, Inter-storey Drifts*

I. INTRODUCTION

The need to study earthquake engineering and its seismic resistant structures is increasing because of the damage caused by the earthquakes resulting in human and economic loss. Various Earthquakes have occurred in the past that have caused catastrophic damages and has affected millions of people.

An earthquake of magnitude 7.6 hit Northern Region of Pakistan and Kashmir on 8th Oct 2005 leaving thousands of people injured and around 80,000 people dead. Millions of people lost their homes in the devastating Earthquake that occurred.

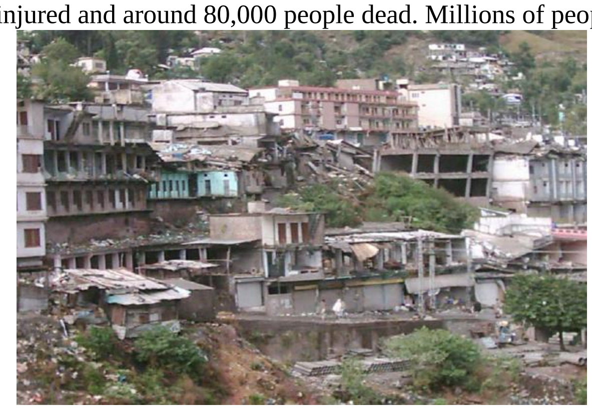

Figure 2 Earthquake Damages, 2005 Kashmir Earthquake

Figure 1 Strcutural Damages, Kashmir 2005 Earthquake

An earthquake of magnitude 8.3 hit Chile on 16th Sep 2015 leaving 9000 people homeless, 13 dead and 6 missing. 90,000 people were without electricity for several days. 500 buildings were destroyed.

Figure 3 Destruction caused by Chile Earthquake, September 17, 2015.

Figure 4 A woman walks over rubble next to a cemetery after an earthquake in Illapel

Figure 5 Damaged structure in Chile after it was hit by 8.8 magnitude earthquake.

An earthquake of magnitude 7 hit Kumamoto, Japan on 16th April 2016, killing 35 people and injuring more than 2000

Figure 7 A damaged house in Kumamoto after getting hit by earthquake

Figure 6 Earthquake damages in the town of Mashiki

An earthquake of magnitude 6.6 hit Tajikistan-Afghanistan on 10th April 2016.

Figure 8 A villager remove debris from their house destroyed by an earthquake at a settlement in Kumsangin region of Tajikistan.

Seismic isolation introduced flexibility at the base of the structure. The natural time period of the base isolated structure is greater than the fixed based structure, isolation shifts the time period of the structure away from the dominant time period of common earthquakes. During the earthquake, due to high flexibility of the isolator, the deformation is concentrated to the isolation joint and the superstructure behaves like a rigid body.

It can be achieved by the introduction of isolator between foundation and structure. The most common example is an elastomeric rubber bearing and the other way is by allowing free sliding between structure and foundation. There are various types of bearing available as shown in figures.

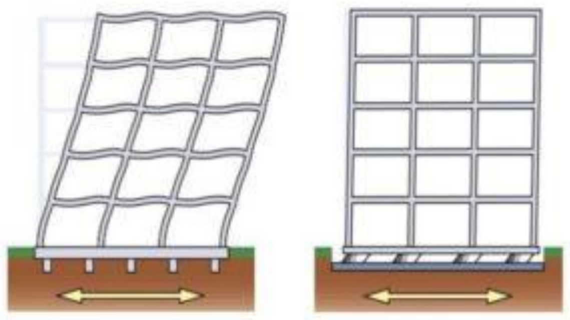

Figure 10 Base Isolation

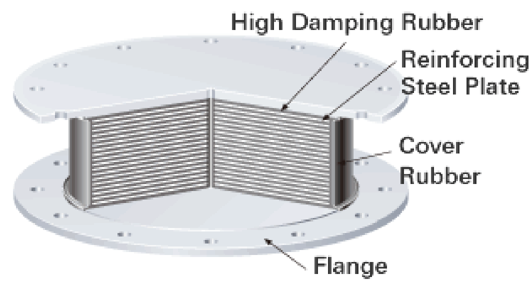

Figure 9 High Damping Rubber Bearing, HDR

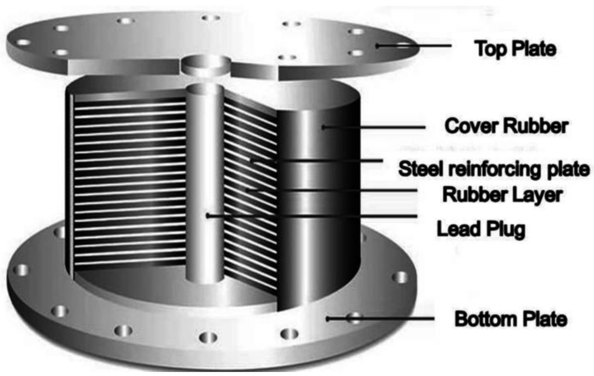

Figure 11 Lead Rubber Bearing

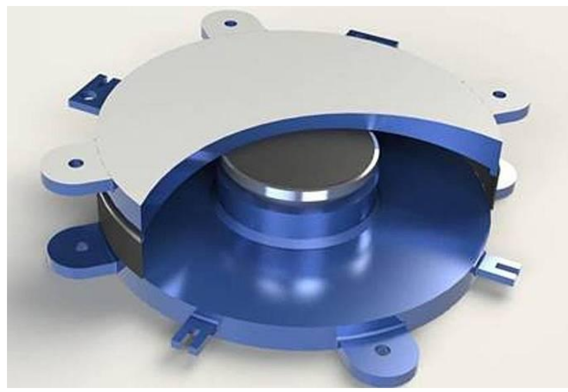

Figure 12 Friction Pendulum Isolator

Figure 14 Seismic Isolator For Buildings

Figure 13 Base Isolator with anchorage plates

II. MODEL DESCRIPTION

A three storey, three bay reinforced concrete moment frame structure was base isolated by using High Damping Rubber Bearing (HDRB). The building consists of three bays in both directions having twenty-five feet width while the height of each story was taken as twelve. The building is considered to be located on site class D i.e stiff soil. Design Based Earthquake was used to design the R.C frame.

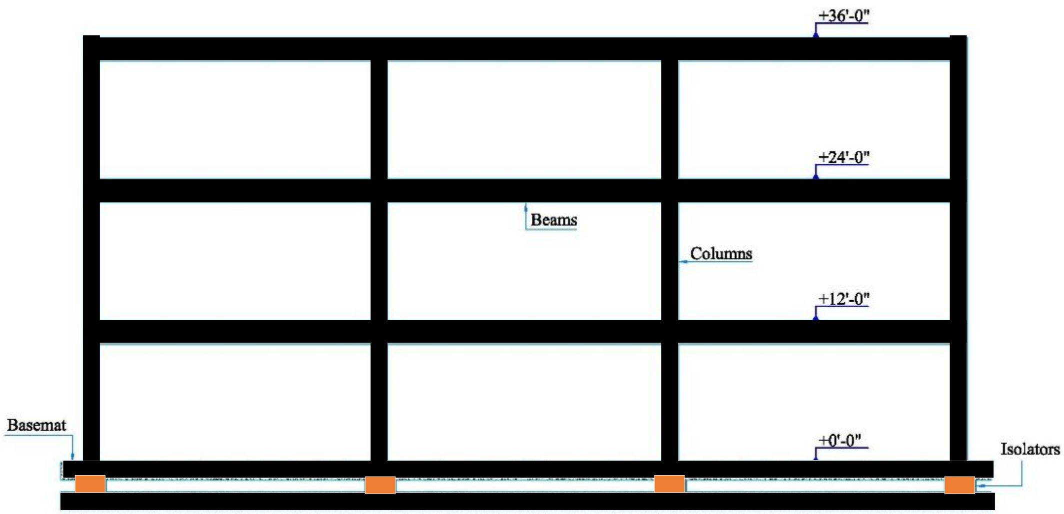

Figure 15 Elevation of the Model Structure

A. MATERIAL PROPERTIES

4000psi was taken as strength for concrete, with 0.3 as poison ratio. 60ksi was used as yield strength of reinforcement.

B. SEISMIC HAZARD:

- **Design Based Earthquake (DBE):** Earthquake with a return period of 475 years and 10% probability occur in 50 years

- **Maximum Capable Earthquake (MCE):** Earthquake with a return period of 1000 years and 10% probability occur in 100 years

The analysis was conducted on a) a fixed based R.C frame structure and b) base isolated R.C frame structure under Design Based Earthquake (DBE) and Maximum Considered Earthquake (MCE).
According to UBC97, a 5% Damped Response Spectrum of DBE was obtained by probabilistic analysis. An example of a typical spectrum is shown in the figure.

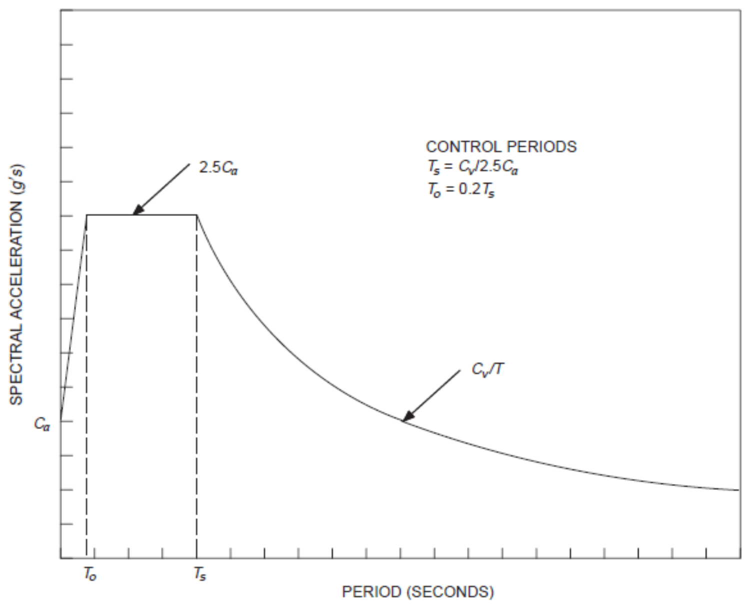

Figure 16 UBC97 Spectrum

As the analysis is to be conducted in a building built in seismic zone 3 and with SD soil type, the typical spectrum from UBC97 is to adjusted accordingly. This was done by selecting the corresponding values of Cv and Ca from the UBC97 for specific site conditions. Site Specific response spectrum is shown in the figure

For computing response spectrum for MCE the DBE spectrum was amplified by 1.3 to study reasonable behavior of the structure under maximum considered earthquake. Generally, the range of amplification factor is 1-1.5.

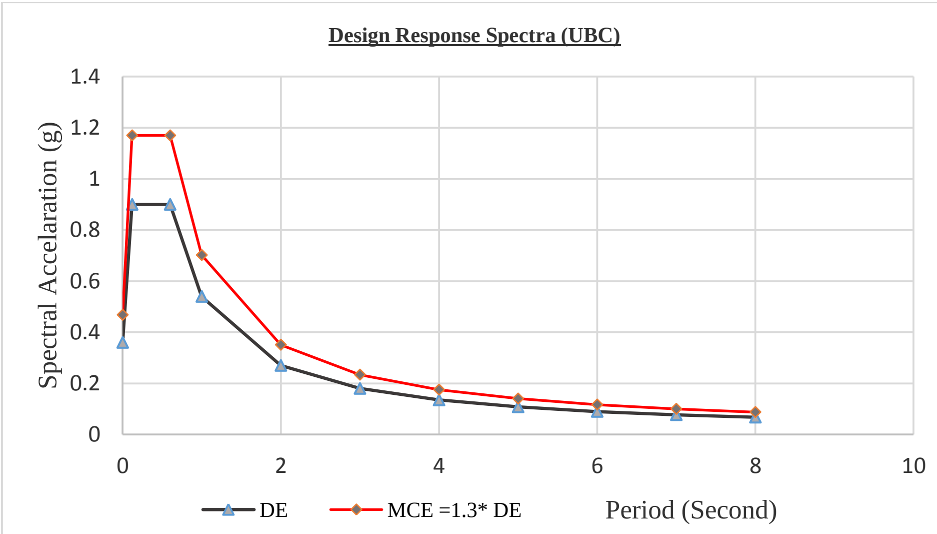

Figure 17 Design Response Spectra

III. DESIGN OF ISOLATOR

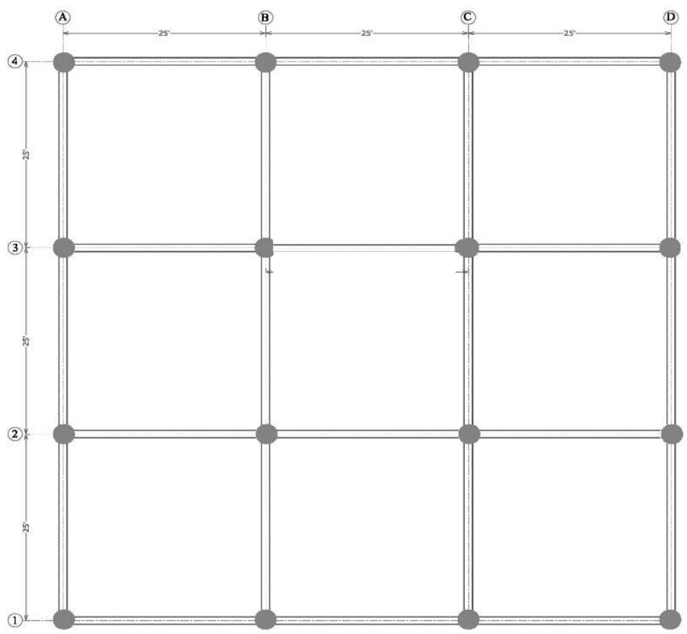

Figure 18 Plan of the Structure

A. TYPES OF ISOLATORS

Two types of isolators were designed:

Isolator Type	No. of Isolators	Load on one (kips)	Total load (kips)	Load on one (tonne)
1	Twelve	783	9396	355
2	Four	1554	6216	705
Total Load			15612	

Table 1 Types of Isolators

B. DESIGN OF ISOLATORS

Next step is to select shear modulus for two type of bearings. To save the cost of mold, it's better to design same size of isolators but us different damping values of rubber used.

Type	Shear Modulus, MPA		Damping Percent	
1	G_1	0.85	β_1	0.11%
2	G_2	1.59	β_2	0.19%

Table 2 Properties of Isolators

Computation of stiffness of the isolator:
Initially the target time period for isolator is selected as 2.5 sec
KH1 = Mass * (2π/T)2 = 355*1000* (2π/2.5)2 = 2.24 MN/m = 12.8 Kip/in
KH2 = Mass * (2π/T)2 = 705*1000* (2π/2.5)2 = 4.45 MN/m = 25.4 Kip/in
Design Displacement Estimation:

Type of the Soil	S_D		
Seismic Zone	3	Code Used	
C_{VD}	0.51	16R	UBC97
B_D	1.36	A16C, for 15% effective damping	UBC97
γ	1.5		
T_r	8 in	Total Height of Rubber	Assume

Table 3 Design Displacement Estimation

$$D_D = \frac{g}{4\pi^2}\frac{C_{VD}T_D}{B_D}$$

D_D = 0.23 meter

$$Area = \frac{Stiffness * Rubber\ Thickness}{Shear\ Modulus}$$

$A_1 = 0.53\ m^2$; φ_1 = Diameter of Isolator 1 = 0.824 m = 32"
$A_2 = 0.56\ m^2$; φ_2 = Diameter of Isolator 2 = 0.846 m = 33"
As P = Load/Area $P^1 = 6.32$ MPa $P^2 = 12.59$ MPa

Actual Stiffness of Bearings:

$$Stiffness = \frac{Area * Shear\ Modulus}{Rubber\ Thickness}$$

$K_H^1 = 0.85 * 0.53/0.2 = 2.25$ MN/m
$K_H^2 = 1.59 * 0.56/0.2 = 4.452$ MN/m

Composite Stiffness

$K_H = \sum$ (No. of Bearing * Stiffness of Bearing)
$K_H = 12*2.25 + 4*4.45 = 44.8$ MN/m

$$Angular\ Frequency = \sqrt{\frac{k}{m}}$$

$$Angular\ Frequency = \sqrt{\frac{44.8\ x\ 10^6\ N/m}{7081480\ Kg}}$$

$w_n = 2.51$ rad/sec
$T = 2\pi/w_n = 2.5$ sec

Calculating the composite damping:

$$\beta = \frac{K_H^1\beta_1 + K_H^2\beta_2}{K_H}$$

β = 0.147
Damping Factor, $\beta_{15.3} = 1.359$ by interpolating Table A16C UBC 97
Use the calculated value of damping factor and Time Period, Calculate Design Displacement.
Second Estimation for Design Displacement

$$D_D = \frac{g}{4\pi}\frac{C_{VD}T_D}{\beta_D}$$

D_D = 0.233 m = 23.3 cm

Base Shear (code based elastic)

$$Base\ Shear = \frac{Stiffness * Displacement}{Rw1}$$

Base Shear = 5.22 MN

$$Cs = \frac{Base\ Shear}{Weight}$$

Cs = 7.52%

C. DETAIL OF ISOLATORS

Vertical frequency, f_v = 10Hz; then

$6S^2 = \frac{f_v^2}{f_H^2}$ = 10.20

G_A^1 = 1.75 * 0.85 = 1.487 MPa
G_A^1 = 1.75 * 1.59 = 2.78 MPa
1.75 increase is because of r = 20%
Th Stiffness of both isolators = 2000 MPa

$$E_c = \frac{6GS^2K}{6GS^2+K}$$

E_C^1 = 1612.27 MN/m^2
E_C^2 = 1793.32 MN/m^2
For S = 10.27

$$S = \frac{\phi}{4t}$$

So, t = 20.6 mm,
no. of layers * thickness of single layer = 200mm
no. of layers = 10
S = 824/4*20.6 = 10

$$f_v = \frac{21.16}{421}(22.01) = 22.17Hz$$

Take top and bottom plates' thickness = 1 inch
Thickness of steel shims is taken as 2 mm
H = 2 * 25 + 200 + 9 * 2 = 268 mm

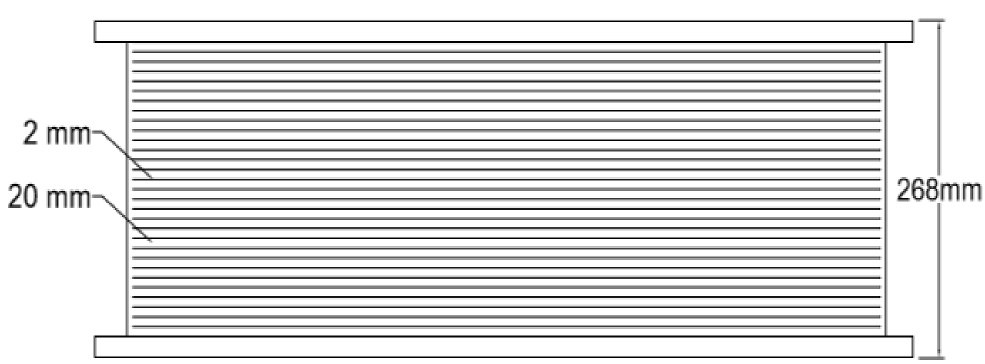

Figure 19 Designed Isolator

IV. MODELLING

Seismic isolator can be modelled in two ways:
Method 1
It can be represented as a nonlinear link element in ETABS. The link is to be added between two nodes, one node (joint I, near joint) is connected to the ground and the other node (joint j, far joint) is connected to the structure. Length, L is the distance that separate the two nodes. Shear, torsion, bending and axial degree of freedom are assigned between the nodes. Link element properties depends on frequency and linearity. A typical link element is shown below.
Method 2:
There is a built-in option available in ETABS to define the isolators. The available templates contain High Damping Rubber Bearing, Lead Rubber Bearing, Low Damping Rubber Bearing and Friction Pendulum system.
Properties needed to define an isolator are directional properties, linear properties (stiffness and damping), shear deformation location, and non-linear properties (stiffness, yield strength, post yield stiffness ratio). Amongst the six degree of freedoms, four (three rotational and one axial) are assigned with linear elastic properties and 2 (shear in x and y direction) are assigned with bi-linear properties.

V. RESULTS

Seismic analysis was conducted on both fixed base and base isolated structure in ETABS under two seismic loads; DBE and MCE. The comparative study was conducted between the response of two structures. The considered parameters are drifts, shear and story displacements

A. STOREY DISPLACEMENTS

It was observed that the storey displacement was comparatively higher in base isolated structure than in fixed base structure because of the flexibility introduced at the base of the structure by isolator. The deformation of isolator was up to 20cm for DBE and it reached up to 27cm for MCE.

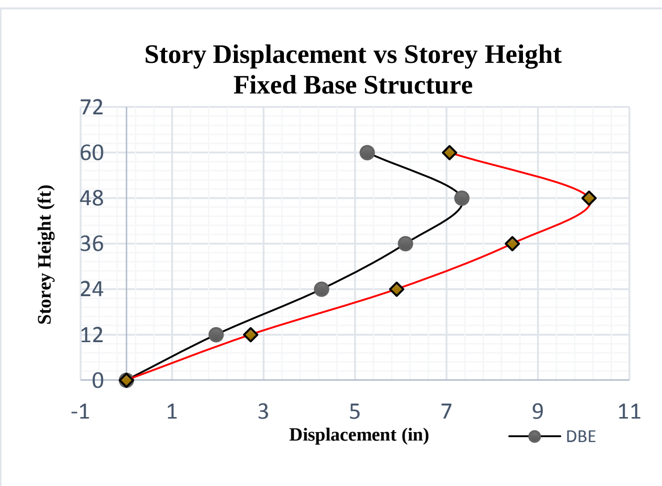

Figure 21 Storey Displacement of Fixed Base Structure

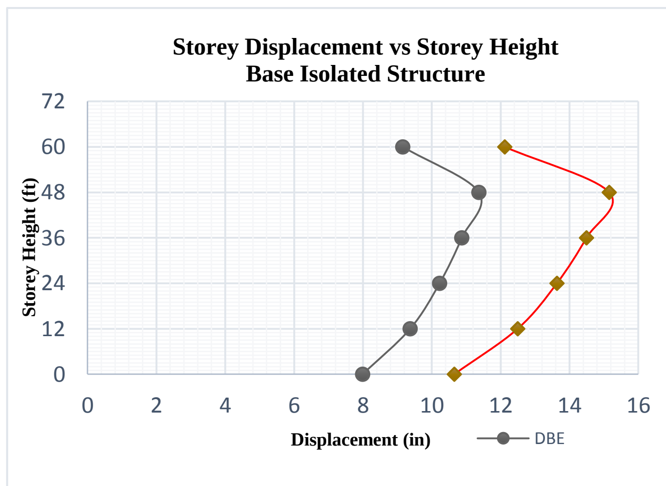

Figure 20 Storey Displacement of Base Isolated Structure

B. STOREY DRIFTS

Quantitative storey drifts can be related to qualitative structural damage as shown in table

Storey Drift	Damage State
0.25 – 0.5 %	Non-Structural
0.5 – 1.5 %	Moderate Structural
1.5 – 3 %	Severe Structural
> 3%	Collapse

Table 4 Storey Drifts and Corresponding Damages

Inter storey drifts were seen to be reduced for base isolated structure. Fixed base structure showed a maximum story drift of 1.7% under DBE 2.25% under MCE. This displacement falls in the category of severe structural damages. On the other hand,

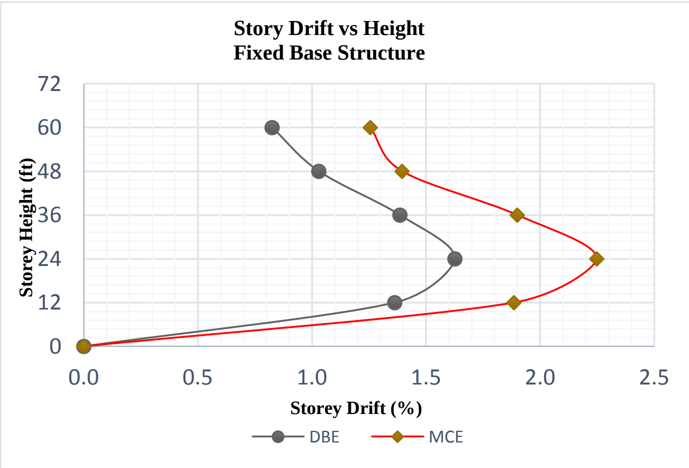

Figure 23 Storey Drifts, fixed base structure

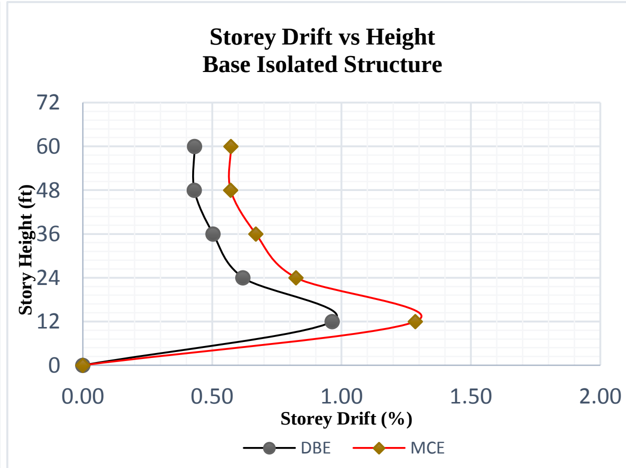

Figure 22 Storey Drifts, base isolated structure

for seismically isolated structure the drifts were reduced from 1.7% to 0.9% and from 2.25% to 1.3% for DBE and MCE respectively. The structural damage was shifted from severe to moderate

C. STOREY SHEAR

Storey shear is directly related to the stiffness of the structure. If the stiffness of the structure is high, it means it offers high resistance to the applied load, thus the storey shear will also be. Similarly, storey shear in flexible structure will be low. Higher flexibility is related to higher flexibility.
Base isolation reduced storey shear up to 16%.

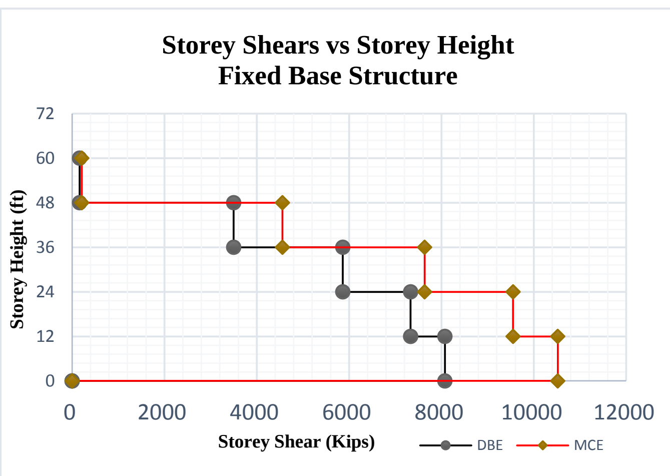

Figure 24 Storey Shear, fixed base structure

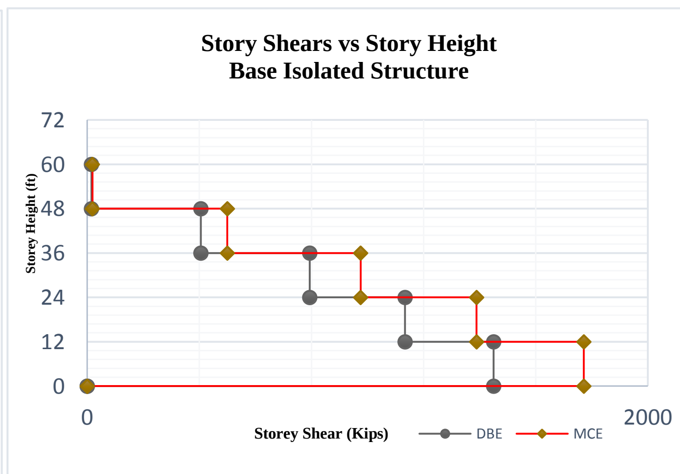

Figure 25 Storey Shear, base isolated structure

D. TIME PERIOD

Base isolation lengthens the time period of the structure. The time period of earthquakes on stiff soil lies between 0.03 and 0.33 seconds. Low and Medium rise buildings also have a time period in the same range, thus making the structure vulnerable to the ground motion. The isolator shifts the time period of the structure from the common time period of earthquake and therefore the probability of resonance is decreased.
The table shows the time period for different mode shapes for Fixed and base isolated structure. The time period of base isolated structure was close to the designed period of the isolator.

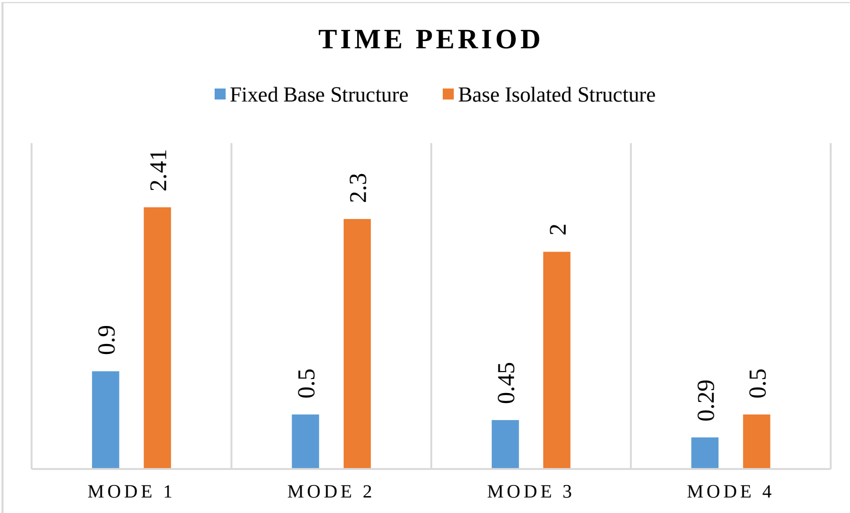

Figure 26 Time period comparison

VI. CONCULSIONS

- Displacement was increase by 30% in seismically isolated structure but inter storey drifts were reduced by 45%
- Maximum deformation in base isolated structure was taken by the isolator
- Also, storey shear was reduced by 80% in base isolated structure.
- Base isolation increased the time period of the structure, thus shifting it from an acceleration to a displacement sensitive

VII. RECOMMENDATIONS

- Shake table test on a base isolated structure to study the experimental result and compare it with the numerical result
- Experimental testing on the isolators to study the properties of the isolators.

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