STUDY ON LAMINATED RUBBER BEARING BASE ISOLATORS FOR SEISMIC PROTECTION OF STRUCTURES

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Abstract

Base isolation or seismic base isolation is an effective means for protection of structures, its contents and its occupants during the event of an earthquake. The principle of base isolation is vibration isolation. It decouples the building from damaging action of the earthquake. The isolator partially reflects and partially absorbs input seismic energy before it gets transmitted to the superstructure. Laminated Rubber Bearing Isolators are placed between the superstructure and foundation, which reduces the horizontal stiffness of the system. It thereby increases the time period of the structure and decreases the spectral acceleration of the structure. The superstructure acts like a rigid body, thus inter storey drift is reduced. Such type of isolators are used in practice in India, yet a proper design procedure based on IS code is unavailable. The paper presents design procedure for LRB adopting the procedure of IS 1893:2002 (Part-1) for earthquake resistant design of buildings. Design charts have been developed and presented in this paper which gives isolator diameter and rubber thickness as design outputs. The design procedure requires different input parameters like fundamental period and damping of the fixed base structure, axial load on the column, seismic zone, type of soil and shore hardness of rubber. These design charts enable the designer to easily arrive at the isolator parameters to achieve seismic isolation. Using the charts, case study has been done using SAP2000. Building displacement and acceleration are compared for model with and without base isolator. Comparative study of linear and non-linear base isolators has also been carried out. Linear and non-linear time history analysis has been done using El Centro earthquake.

Keywords: *base isolation, laminated rubber bearing, IS Code, seismic protection, design charts, time history analysis, SAP2000*

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1. INTRODUCTION

Earthquake is one of the major natural disasters which cause damages to the buildings. Due to its damaging power, it is not only important to have strong structures, but also seismically protected structures. Base isolation is a simple and practically feasible method of seismic protection of structures.

1.1 Base Isolation

There are two major types of base isolation, namely, elastomeric and sliding. Both systems are designed to take the weight of the building and let the foundations move sideways during an earthquake. This paper deals with the laminated rubber bearing isolator, which falls under the first category. A layer of rubber with much lower horizontal stiffness is introduced between superstructure and the foundation. After the isolation, the system has a natural period much longer than the fixed base natural period. A typical low damping natural rubber bearing isolator is shown in Figure 1[1].

When the period is increased, pseudo-acceleration is decreased and hence the force in the structure gets reduced (Figure 2[2]). However, the displacement of the system increases drastically. This is due to the deformation of the rubber layer.

LRB isolators have cylindrical rubber bearings, which are reinforced with steel shims. Shims and rubber is placed as alternate layers. Steel plates are also provided at the two ends of the isolator. The steel shims boost the load carrying capacity, thus the structure is stiff under vertical loads and flexible under horizontal loads.

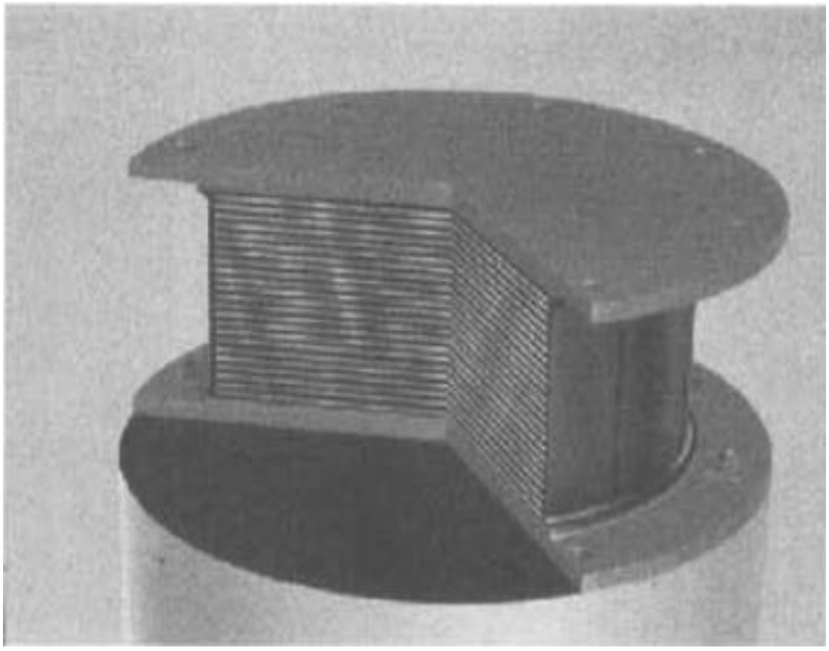

Fig -1: Low damping natural rubber bearing[1]

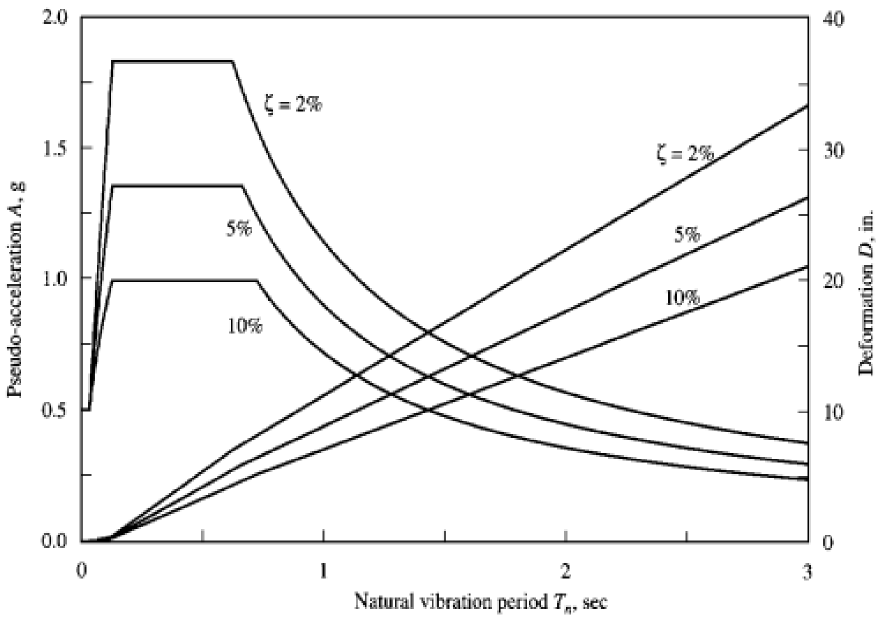

Fig -2: Elastic design spectrum [2]

1.2 Linear Theory of Base Isolation

This can be explained based on two-mass structural model as shown in Figure 3[1]. The mass *m* represents the superstructure of the building and m_b mass of the base floor above the isolation system. The other parameters are structural stiffness (K_s) and damping (C_s) and base isolator stiffness (K_b) and damping (C_b). The absolute displacements of the masses are given by U_s and U_b and the ground displacement is given by U_g. Therefore, the relative displacements are given by

$$V_b = U_b - U_g \qquad V_s = U_s - U_g$$

The basic equations of motion of the two-degree-of-freedom system are

$$(m+m_b)\ddot{v}_b + m\ddot{v}_s + C_b\dot{v}_b + K_b V_s = -(m+m_b)\ddot{u}_g$$
$$m\ddot{v}_b + m\ddot{v}_s + C_s\dot{v}_s + K_s v_b = -m\ddot{u}_g \qquad [1]$$

This can be written in matrix form as

$$\begin{bmatrix} M & m \\ m & m \end{bmatrix}\begin{Bmatrix} \ddot{v}_b \\ \ddot{v}_s \end{Bmatrix} + \begin{bmatrix} C_b & 0 \\ 0 & C_s \end{bmatrix}\begin{Bmatrix} \dot{v}_b \\ \dot{v}_s \end{Bmatrix} + \begin{bmatrix} K_b & 0 \\ 0 & K_s \end{bmatrix}\begin{Bmatrix} v_b \\ v_s \end{Bmatrix} = \begin{bmatrix} M & m \\ m & m \end{bmatrix}\begin{Bmatrix} 1 \\ 0 \end{Bmatrix}\ddot{u}_g \qquad [2]$$

Where $M = m + m_b$

$M\ddot{v}+C\dot{v}+Kv=-Mr\ddot{u}_g$

Mass ratio γ is given by

$$\gamma = \frac{m}{m+m_b} = \frac{m}{M} \qquad [3]$$

The natural frequencies ω_b and ω_s are given by

$$\omega_b^2=\frac{K_b}{m+m_b} \qquad \omega_s^2=\frac{K_s}{m}$$

The damping factors β_b and β_s are given by

$$2\omega_b\beta_b=\frac{C_b}{m+m_b} \qquad 2\omega_b\beta_b=\frac{C_s}{m}$$

In terms of these quantities, the basic equation of motion becomes

$$\gamma\ddot{v}_s+\ddot{v}_b+2\omega_b\beta_b\dot{v}_b+\omega_b^2 v_b=-\ddot{u}_g$$

$$\ddot{v}_s+\ddot{v}_b+2\omega_s\beta_s\dot{v}_s+\omega_s^2 v_s= -\ddot{u}_g \qquad [4]$$

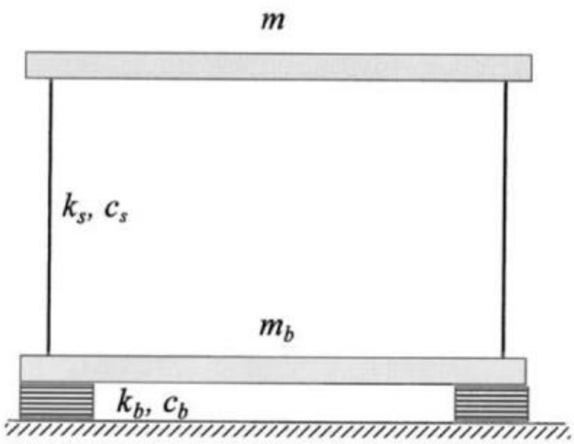

Fig -3: Parameters of two degree of freedom isolation system [1]

2. DEVELOPMENT OF EQUATIONS

2.1 To Find the Thickness of Isolator

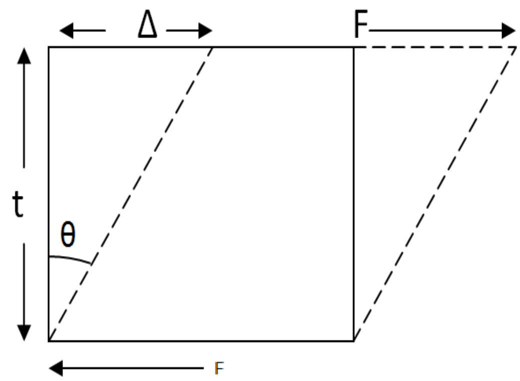

Fig -4: Behaviour of isolator under shear

Shear strain of the isolator, γ is given by (Figure 4),

$$\gamma=\frac{\Delta}{t}$$

Where Δ = Length of deformation
t=thickness of the isolator

γ is assumed to be 100% in this analysis.

Therefore, $\Delta= t$

S_d is the spectral displacement of the structure as per IS 1893-2002 Part I. We assume that the isolator gets deformed keeping the structure intact. Hence the maximum displacement of isolator is S_d

i.e,

$$S_d = t \qquad [5]$$

But, $$S_d=\frac{Sa}{\omega^2} \qquad [6]$$

Therefore $$t=\frac{S_a}{\omega^2} \qquad [7]$$

Where,
S_a= Spectral acceleration of the isolator
ω = frequency of the structure

By considering the zone factor (Z), importance factor (I) and response reduction factor (R), the above equation can be written as

$$t=\frac{A_h}{\omega^2} \qquad [8]$$

Where, the horizontal acceleration coefficient,

for DBE, $$A_h=\frac{Z}{2}\frac{I}{R}\frac{S_a}{g}$$

for MCE $$A_h=Z\frac{I}{R}\frac{S_a}{g}$$

2.2 To Find Diameter of Isolator:

The linear frequency of the isolator is given by,

$$f=\frac{1}{2\pi}\sqrt{\frac{k}{m}} \qquad [9]$$

Where k= Stiffness of the isolator
m= Mass of the isolator

$$2\pi f=\sqrt{\frac{k}{m}}$$

$$\omega^2=\frac{k}{m} \qquad [10]$$

ω= Natural frequency of the isolator

Horizontal stiffness of the isolator,

$$K_H = \frac{\text{Load}}{\text{Deflection}} \quad [11]$$

Load = Shear stress X Cross sectional area

From eq (11),

$$K_H = \frac{GA}{t} \quad [12]$$

Substituting the value of stiffness in Eq.(10), we get

$$\omega^2 = \frac{GA}{tm}$$

$$\frac{GA}{\omega^2 t} = \frac{W}{g} \quad [13]$$

Using Eq(5) the above equation can be modified as,

$$\frac{Gg}{\omega^2 S_d} = \frac{W}{A} \quad [14]$$

Also

$$S_d = \frac{S_a}{\omega^2} \quad [15]$$

Substituting Eq(15) in Eq(14),

$$\frac{G}{(\frac{Sa}{g})} = \frac{W}{A}$$

Therefore,

$$A = \frac{W\,(\frac{Sa}{g})}{G} \quad [16]$$

$$D = \sqrt{\frac{4W(\frac{Sa}{g})}{\pi G}} \quad [17]$$

Incorporating the Importance factor, Response reduction factor and Zone factor, the above equation can be modified as

$$D = \sqrt{\frac{4Wf\alpha_1\alpha_2\alpha_3}{\pi G}} \quad [18]$$

Where

$$\alpha_1 = \frac{I}{R}$$

$$\alpha_2 = \begin{cases} \frac{z}{2} & \text{for DBE} \\ Z & \text{for MCE} \end{cases}$$

$$\alpha_3 = \begin{cases} 1.0 & \text{for hard soil} \\ 1.36 & \text{for medium soil} \\ 1.67 & \text{for soft soil} \end{cases}$$

2.3 Layering of Isolator

To keep the ratio of the horizontal and vertical stiffness equal for the different isolator sets, a parameter called Shape factor, S is introduced, which is a dimensionless measure of the aspect ratio of the single layer of the elastomer. For a single pad in the form of a complete circle, the compression modulus E_C is given by

$$E_C \approx 6GS^2 \quad [19]$$

Also,

$$K_v = \frac{E_c A}{t} \quad [20]$$

Considering Eq (12) and Eq(20), the following relation can be obtained.

$$\frac{E_c}{G} = \frac{K_v}{K_H} \quad [21]$$

From Eq(10),

$$\frac{E_C}{G} = \frac{\omega_v^2}{\omega_H^2} \quad [22]$$

Or, it can be further modified as

$$\frac{E_C}{G} = \frac{f_v^2}{f_H^2} \quad [23]$$

Therefore Eq(19) can be re-written as,

$$6S^2 = \frac{f_v^2}{f_H^2} \quad [24]$$

It is assumed that $f_V = 20\, f_H$

Therefore, $S \approx 10$

$$S = \frac{\text{Loaded area}}{\text{Force free area}}$$

For circular isolator,

$$S = \frac{\text{Cross section area}}{\text{Curved surface area}}$$

$$S = \frac{\pi D^2/4}{\pi D t} \quad [25]$$

$$S = \frac{D}{4t} \quad [26]$$

Therefore,

$$t=\frac{D}{4S} \qquad [27]$$

The above equation shows that by varying the number of sandwich layer, quite a large variation in vertical stiffness of the individual isolator element could be achieved.

3. DESIGN CHARTS

After the equations were developed, a set of charts were prepared for easy designing of circular laminated rubber bearing isolator (LBR). The charts were prepared according to IS 1893 (Part 1): 2002. Charts were prepared for all the four seismic zones, namely, low (zone II), moderate (zone III), severe (zone IV) and very severe (zone V). The three types of soil sites, namely, rocky or hard soil site (Type I), medium soil site (Type II) and soft soil site (Type III) are also considered. Charts for different damping ratios like 0, 2, 5, 7, 10, 15, 20, 25, and 30 are prepared. Importance factor (I) and Response reduction factor (R) is taken as 1 for all the charts to enable the designer to choose their criteria. Diameter for circular rubber isolators having shear modulus value 0.35MPa, 0.7MPa, 1.05MPa, 1.40MPa is developed. Chart 1 is a typical chart to find the thickness of rubber for zone V and three soil conditions for Design basis earthquake for 5% damping. Chart 2 is to find the diameter of isolator for building with desired time period 2 seconds for Design basis earthquake for zone V and for soft soil condition for axial load varying from 50kN to 10000kN.

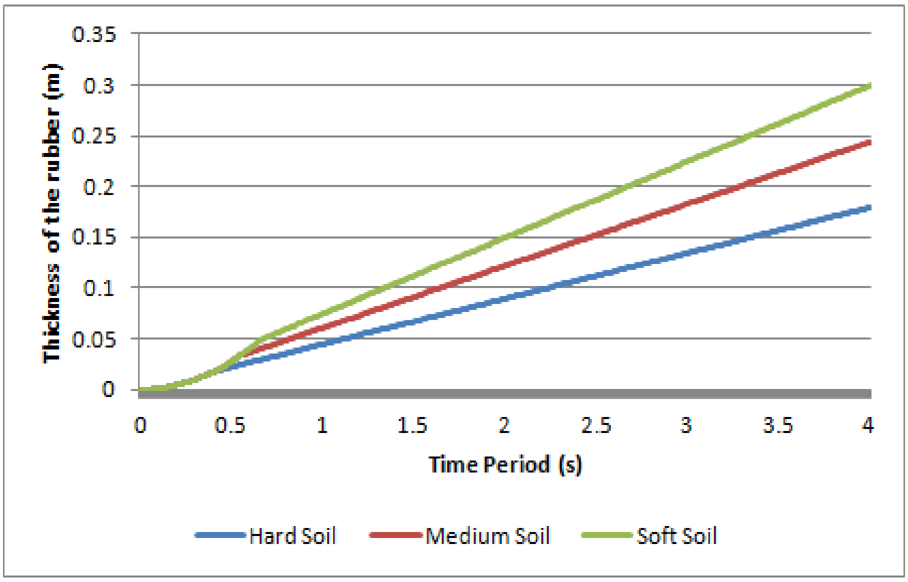

Chart – 1: Chart for DBE for 5% damping in Zone V

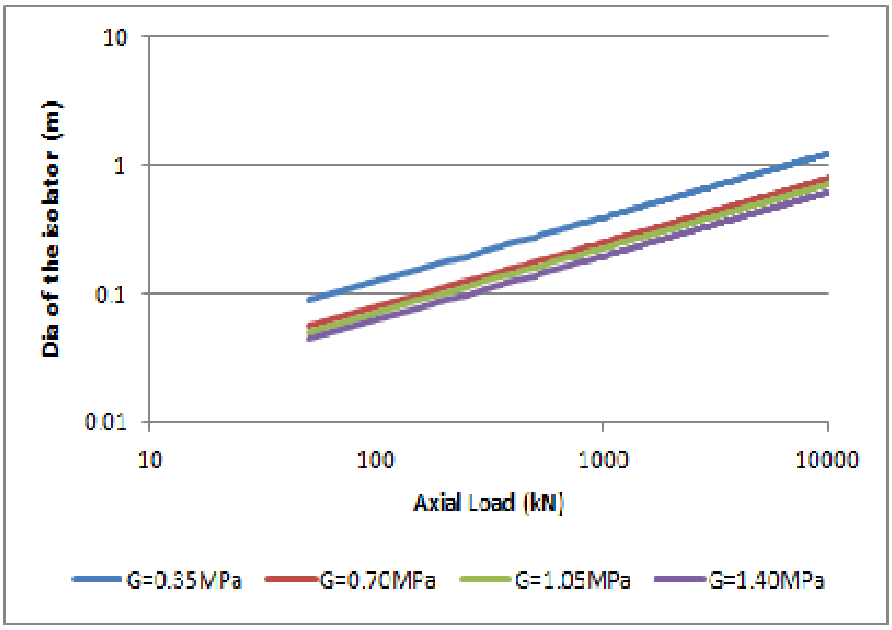

Chart -2:.Chart for DBE for T=2s Soft soil condition(Zone V)

3.1 Interpretation of Charts

3.1.1. To get the Thickness

To get the thickness of the isolator, the desired time period of the structure after isolation should be assumed. Corresponding value of thickness can be obtained from the graph (Chart 1) according to the soil condition, damping and type of the earthquake considered. According to the type of structure and importance of structure, Response reduction factor (R) and Importance factor (I) can be incorporated to get the final thickness of rubber in the isolator. Further calculations can be done for obtaining the layering.

3.1.2. To get the Diameter

The diameter of the isolator can be obtained by knowing the axial load coming on the column and the shear modulus of the rubber used. From the corresponding charts (Chart 2) for particular design time period and soil condition, the value of diameter can be taken. Further calculations considering the Response reduction factor (R) and Importance factor (I) should be done to get the final diameter of the isolator.

4. CASE STUDY

4.1Description of the Structure Analyzed

The structure analysed is a two bay three storied reinforced concrete framed structure consisting of three frames (Frame-1 to Frame-3). The centre to centre distance between the columns is 3000mm and the height of each storey is 3600mm. The column section is of 300mm X 400mm size consisting of two 16mm bars at top and bottom. The beam section is also of 300mm X 400mm size consisting of two 12mm bars on either side.

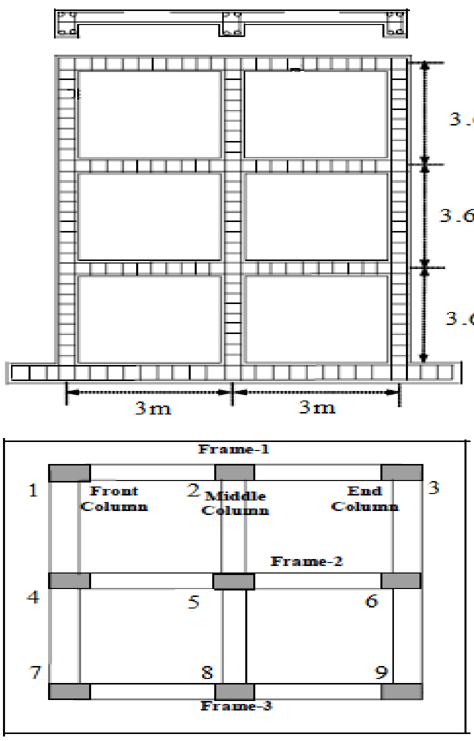

Fig -5: Elevation and plan view of the frame

Column has 8mm diameter ties spaced at 150mm centres and beam has 8mm diameter two legged stirrups at 100mm centres. The slab is 150mm thick with 12mm bars at 200mm centres with reinforcement for support moment provided separately. Figure 5 shows the elevation and typical plan view of the frame tested for verification of time history analysis methodology.

4.2 Design of Base Isolator

Models were created in SAP 2000 without base isolator (Figure 6), with linear base isolator and with non-linear base isolator. Dead load analysis was done for the self weight of the system and axial load acting on each column was obtained (Table 1). The structure was assumed to be in Zone V, built on soft soil. The rubber used for the isolator is assumed to have a shear modulus of 0.35MPa.

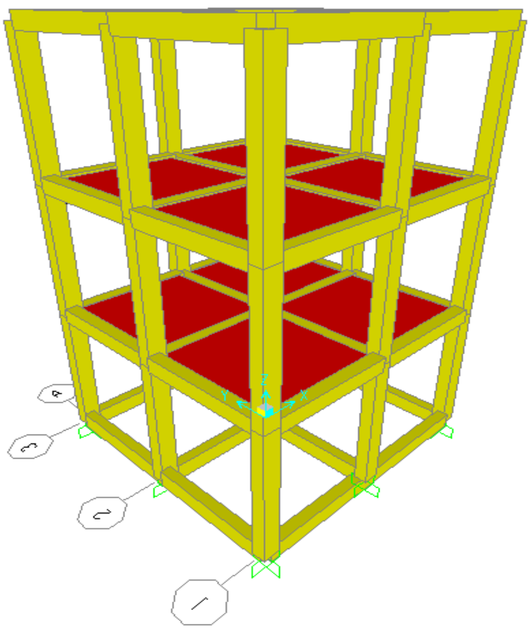

Fig -6: SAP 2000 model of the frame

Table1. Axial load on column and dimensions of base isolator

Column Number	Axial Load (kN)	Thickness of Rubber (mm)	Diameter of Isolator (mm)	Thickness of Layer (mm)
1	81.45	150	220	5.5
2	122.8	150	280	7
3	81.45	150	220	5.5
4	127.1	150	280	7
5	195.1	150	420	11
6	127.1	150	280	7
7	81.45	150	220	5.5
8	122.8	150	280	7
9	81.45	150	220	5.5

Columns 1, 3, 7 and 9 have same axial load. Also, columns 2, 4, 6 and 8 have similar loads. Therefore, 3 isolators were designed for the whole structure.

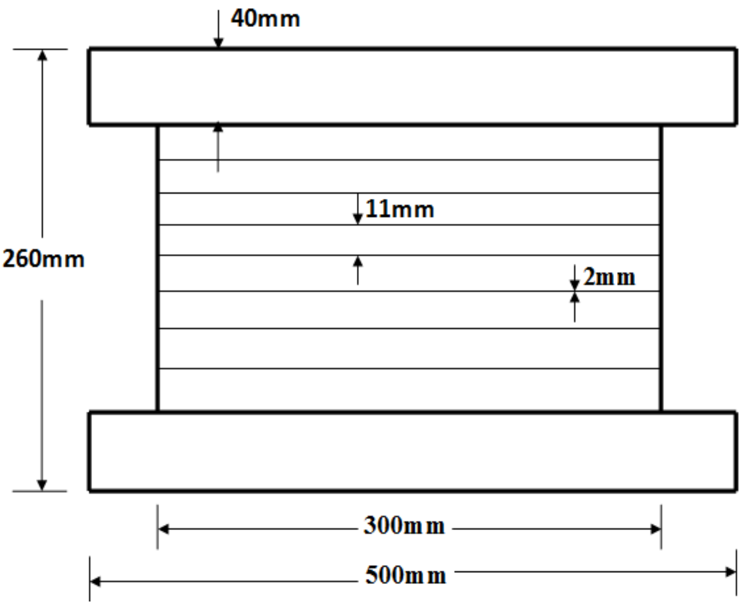

Fig -7: Detail design of isolator for central column

The detail design of isolator below the central column is given in Figure 7.

4.3 Linear Time History Analysis

Initially a gravity load analysis and modal analysis is carried out the system. Linear time history analysis of the frame is carried out using SAP-2000 software. El Centro earthquake (Figure 8) is used in the time history analysis. Figure 9 shows the SAP-2000 model of the frame with base isolator.

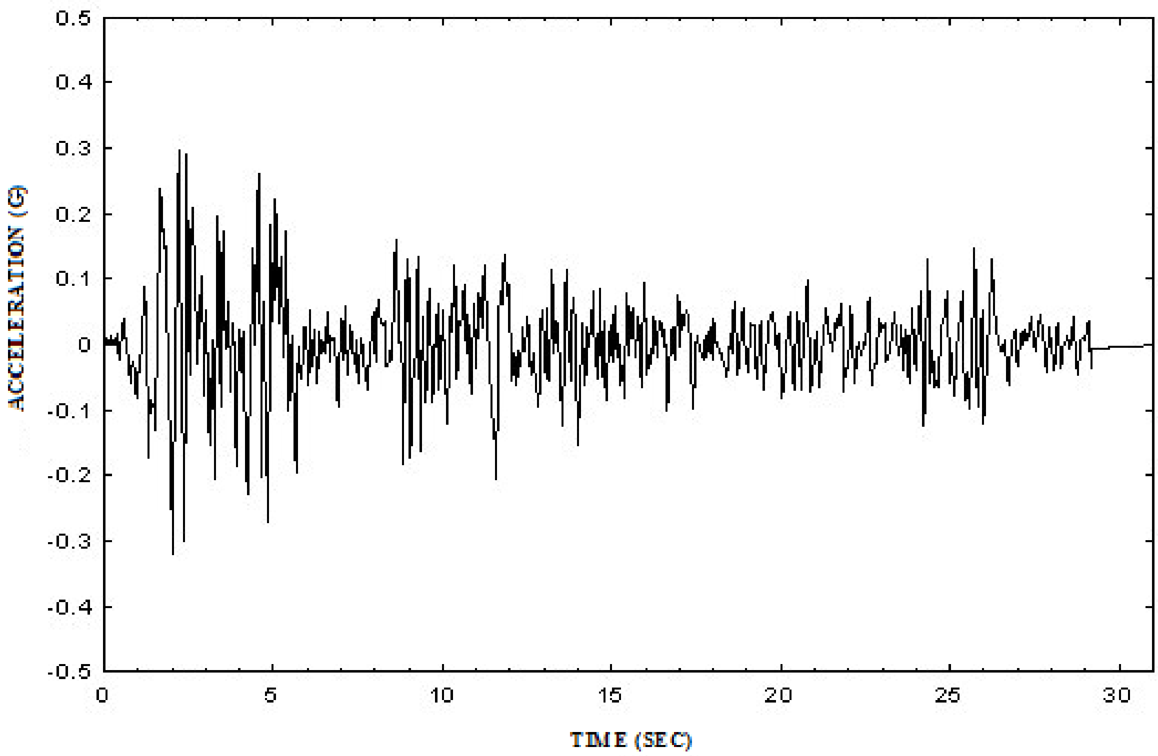

Fig -8: North-South component of El Centro earthquake, May 18, 1940

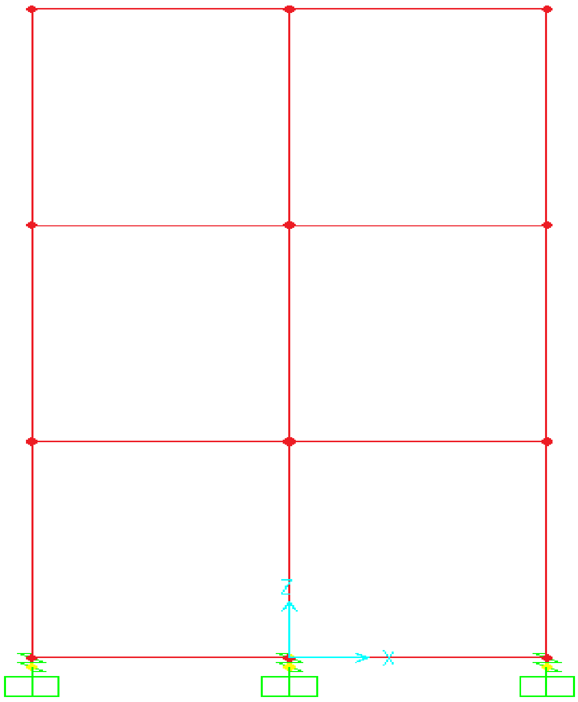

Fig -9: SAP model of the frame with base isolator

Acceleration on the building and displacement of the building, before and after installation of base isolator is compared. Graphs are plotted for the same (Chart 3 and 4).

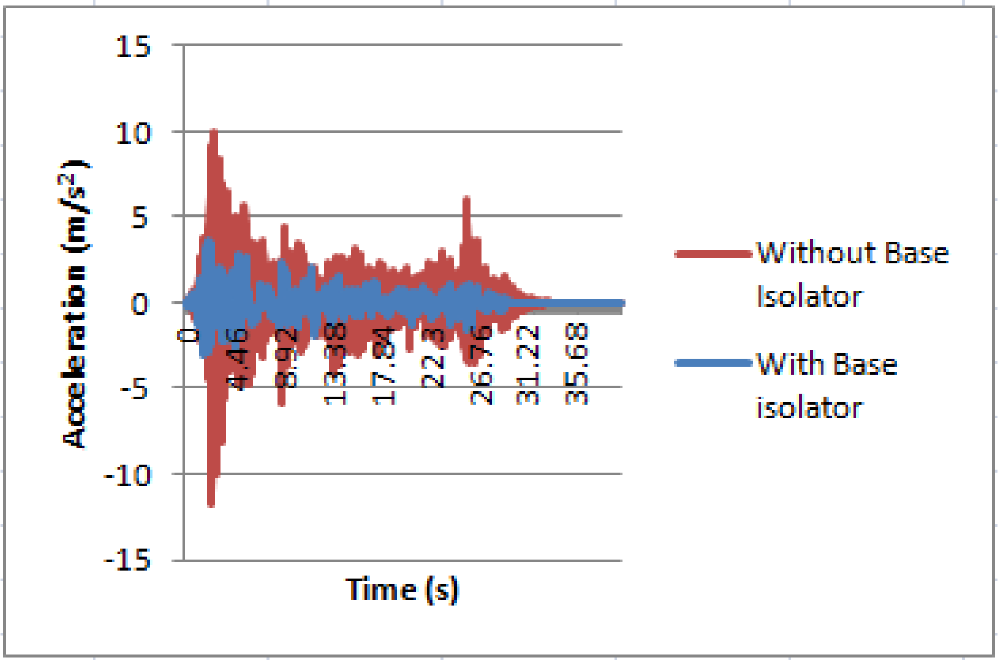

Chart -3: Comparison of acceleration of building with and without base isolator

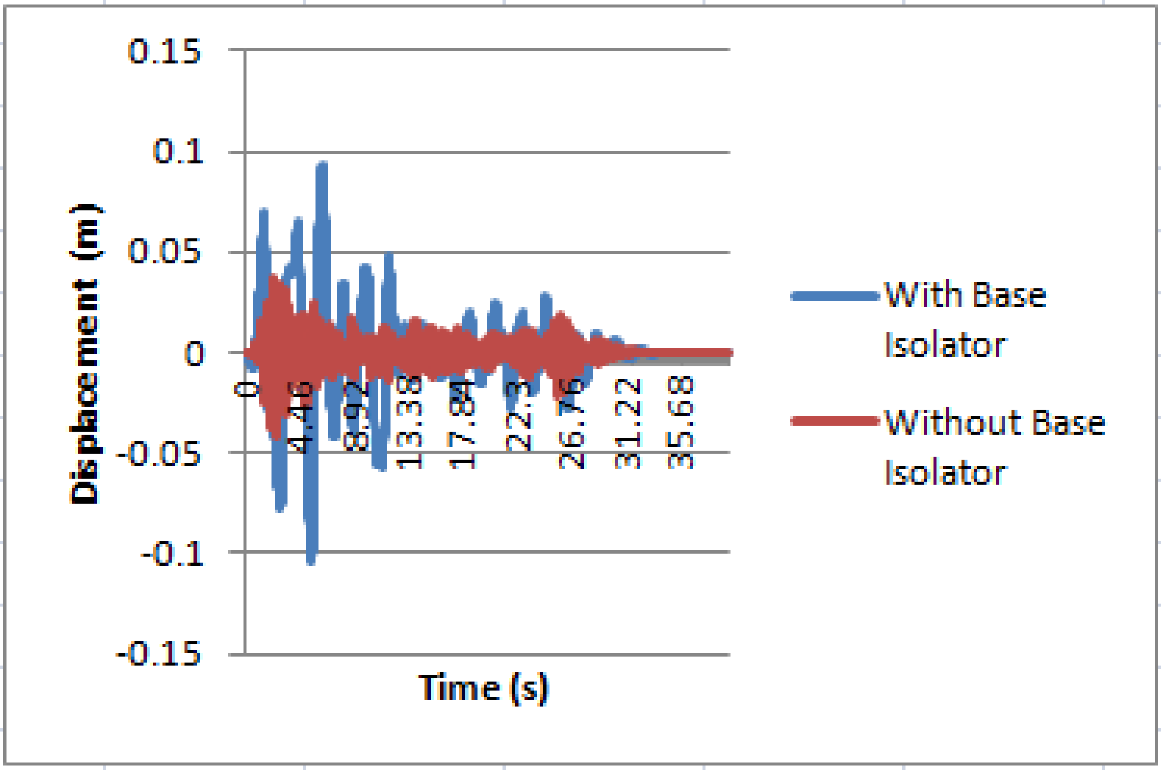

Chart -4: Comparison of displacement of building with and without base isolator.

4.4 Non-Linear Time History Analysis

The non-linear behavior of isolator is simplified as bilinear [3]. The post yielding stiffness ratios (α) are assumed to be 0.05, 0.1 and 0.15 for the isolator. The yield strength of non-linear case (F_1) is taken as one-tenth, one-fifth, one-third, half and three-fourth of yield strength of linear case ($F_{1,\ elastic}$). Fifteen cases are considered in total. Bilinear hysteresis loops were obtained. A typical bilinear hysteresis loop for for α=0.05 and F_1=0.1$F_{1,elastic}$ is shown in Chart 5.

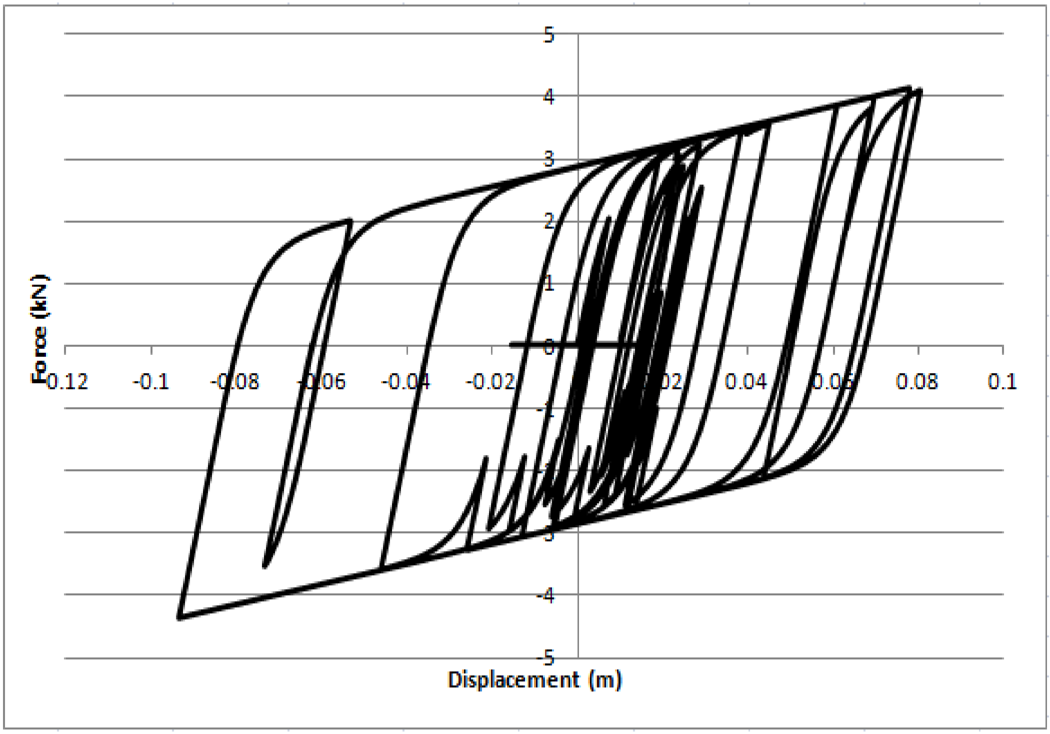

Chart -5: Bilinear hysteresis loop for α=0.05 and F_1=0.1$F_{1,elastic}$

From the hysteresis loop, the additional damping and the effective stiffness values are calculated. The values are given in Table 2.

Table -2: Additional damping and effective stiffness of non-linear isolator

Cases	Additional Damping ζe (%)	Effective Stiffness Ke (kN/m)
α =0.05, F_1=0.10$F_{1,elastic}$	22.12	25.5
α =0.10, F_1=0.10$F_{1,elastic}$	17.53	38.9
α =0.15, F_1=0.10$F_{1,elastic}$	11.86	53.1
α =0.05, F_1=0.20$F_{1,elastic}$	25.04	23.3
α =0.10, F_1=0.20$F_{1,elastic}$	15.85	36.4
α =0.15, F_1=0.20$F_{1,elastic}$	17.19	52.2
α =0.05, F_1=0.33$F_{1,elastic}$	19.48	20.5
α =0.10, F_1=0.33$F_{1,elastic}$	15.91	35.5
α =0.15, F_1=0.33$F_{1,elastic}$	13.97	51.1
α =0.05, F_1=0.50$F_{1,elastic}$	12.98	18.7
α =0.10, F_1=0.50$F_{1,elastic}$	9.83	34.4
α =0.15, F_1=0.50$F_{1,elastic}$	8.01	50.3
α =0.05, F_1=0.75$F_{1,elastic}$	6.60	17.8
α =0.10, F_1=0.75$F_{1,elastic}$	5.67	33.8
α =0.15, F_1=0.75$F_{1,elastic}$	5.82	49.9

4.5 Comparison of Linear and Non-Linear Analysis

Displacement of building with linear and non-linear base isolators is compared. Displacement is seemed to be reduced when isolators are designed as non-linear. The comparison is given in table 3.

Table -3: Displacement reduction in non-linear analysis

Cases	Displacement (m)	Reduction (%)
α =0.05, F_1=0.10$F_{1,elastic}$	0.0789	32.61
α =0.10, F_1=0.10$F_{1,elastic}$	0.0853	27.13
α =0.15, F_1=0.10$F_{1,elastic}$	0.0947	19.10
α =0.05, F_1=0.20$F_{1,elastic}$	0.0885	24.40
α =0.10, F_1=0.20$F_{1,elastic}$	0.0783	33.09
α =0.15, F_1=0.20$F_{1,elastic}$	0.0806	31.12
α =0.05, F_1=0.33$F_{1,elastic}$	0.0915	21.84
α =0.10, F_1=0.33$F_{1,elastic}$	0.0852	27.15
α =0.15, F_1=0.33$F_{1,elastic}$	0.0850	27.33
α =0.05, F_1=0.50$F_{1,elastic}$	0.0927	20.81
α =0.10, F_1=0.50$F_{1,elastic}$	0.0930	20.52
α =0.15, F_1=0.50$F_{1,elastic}$	0.0926	20.86
α =0.05, F_1=0.75$F_{1,elastic}$	0.0963	17.70
α =0.10, F_1=0.75$F_{1,elastic}$	0.0954	18.44
α =0.15, F_1=0.75$F_{1,elastic}$	0.0946	19.11

5. RESULTS

- For the same soil condition and time period, thickness of the isolator decreases with increase in damping percentage.
- Buildings situated on soft soil conditions require thicker isolator than those situated on hard soil conditions, provided the required time period and damping are the same.
- For a particular value of axial load which is to be transferred, the diameter of the isolator increases, as isolator with rubber of lesser value of shear modulus is used.
- The diameter of isolator decreases as the desired value of time period increases, provided the soil condition and the rubber used are the same.
- Buildings situated on soft soils need isolator with bigger diameter than situated on hard rocky soils.
- Both thickness and diameter increases as greater earthquake prone area is chosen.

Linear time history analysis shows that acceleration on the building decreases after the installation of base isolator, whereas the building displacement increases after the installation. The maximum value of acceleration on the building before the introduction of base isolator is 10.96m/s^2 and after the installation is 1.12m/s^2. The value of building displacement is 40.68mm before installing isolator and 117.7mm after the installation.

Results of non-linear analysis shows that a maximum additional damping of 25.04% was obtained for post yielding stiffness ratio of 0.05 and non-linear yield strength taken as one-fifth of linear yield strength.

On comparing linear and non-linear isolators, a maximum displacement reduction of 33.09% in the case of post yielding stiffness ratio of 0.10 and non-linear yield strength taken as one-fifth of linear yield strength was obtained, when the isolators are designed as non-linear.

6. CONCLUSION

The guidelines for designing laminated rubber bearing (LRB) isolators are developed. Design charts for arriving at the details of base isolators are prepared. Different isolator parameters were compared with respect to fundamental period and damping of the fixed base structure, axial load on the column, seismic zone, type of soil and shore hardness of rubber.

Acceleration on building and displacement are altered by the installation of isolator. Acceleration on the building decreases and displacement of the building increases. This increase in displacement can be reduced if the isolator is designed as non-linear. Additional damping is also introduced by the non-linear isolator.

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