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Design Of Base Isolated Rcc - Framed Structure With Lead Elastomeric Bearing

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ABSTRACT

In this paper,the design of lead core elastomeric bearing for a base isolated R.C.C framed structure by Newzeland standard guideline is being explained. A model of school building , (G+3) storied structure is considered for analysis and design having an overall plan dimension 54m X 16m. The analysis of the structure is done by linear dynamic response spectrum method to find the dynamic force distribution in each floor. The aim of this journal is to obtain dynamic characteristics such as natural frequency, modeshape of the structure using theoretical modal analysis and to explain the design procedure for the structure.The codal provision for lead elastomeric bearing is explained in AASHTO and IBC has given the guideline. This journal improves the public understanding in design of Base isolated structures.

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INTRODUCTION

During earthquake, the traditional building structures in which the base is fixed to the ground, respond with a gradual increase from ground level to the top of the building. This may result in heavy damage or total collapse of structures. To avoid these results, while at the same time satisfying in-service functional requirements, flexibility is introduced at the base of the structure, usually by placing elastomeric isolators between the structure and its foundation. The mechanism of the base isolator increases the natural period of the overall structure, and decreases its acceleration response to earthquake / seismic motion.

Typical earthquake accelerations have dominant periods of about 0.1-1.0 Sec. With maximum severity often in the range 0.2-0.6 Sec. Structures whose natural periods of vibration lie within the range 0.1-1.0 Sec therefore particularly vulnerable to seismic attacks because they may resonate. The most important feature of seismic isolation is that its increased flexibility increases the natural period of the structure (>1.5 Sec., usually 2.0-3.0 Sec.).

Because the period is increased beyond that of the earthquake, resonance is avoided and the seismic acceleration response is reduced. The benefits of adding a horizontally compliant system at the foundation level of a building can be seen in Figure 1. Note that the rapid decrease in the acceleration transmitted to the isolated structure as the isolated period increases. This effect is equivalent to a rigid body motion of the building above the isolation level.

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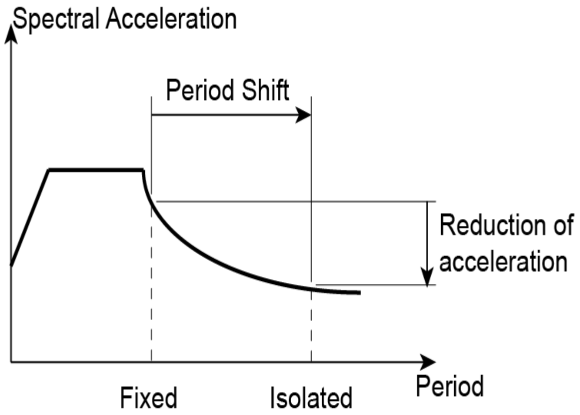

Fig. 1: Acceleration response spectrum ,Anil K. Chopra (2012)

It is seen that most base isolated buildings around the world are important buildings such as hospitals, universities, schools, firehouses, nuclear power plants, municipal and governmental buildings, and some high technology buildings that house sensitive internal equipment or machinery.

The aim of this study is to obtain dynamic characteristics which are natural frequencies and mode shape of the structure using modal analysis and to carry out analytical modal analysis of the structure. Response spectrum analysis is carried out. Design procedures used for base isolated systems are discussed and form the basis for preliminary design procedures.

Description of the Structures: The structures, used for the analyses, are assumed to be serving as school buildings. The detailed descriptions of the buildings are as follows: IS 8827-1978 (2002)

The three-storey building has a regular plan (54m x 16m).

The structural system is selected as concrete Columns size of (360X360) mm.

Beam of dimension (250X400)mm longitudinal direction and (250X300)mm in transverse direction .

Each floor slab has100mm thickness and the story height is 4 meters.

Imposed load considered is 3KN/m^2.

Theoritical Analysis of the structure:

In this section, response spectrum method of analysis is discussed. It is a Linear dynamic method Pankaj Awarwal (2008). This method of analysis is based on dynamic response of the building idealized as having lumped mass and stiffness. Modal analysis gives us idea to avoid resonant vibrations. It locates critical points and we can safeguard our structure before the damage through this analysis . Modal analysis gives us an idea about the response of structures due to dynamic loading. First mode shape is most critical because its time period is largest among all time periods of vibrations.

Assumption:

- The total mass acting on the structure is concentrated at each floor.
- The totlal column stiffness is added and assumed as a single bay in each floor.

The response of a N-DOF can be computed in which the system can be considered as if made of N single DOF whose response is superimposed.

Calculation of lumped mass:

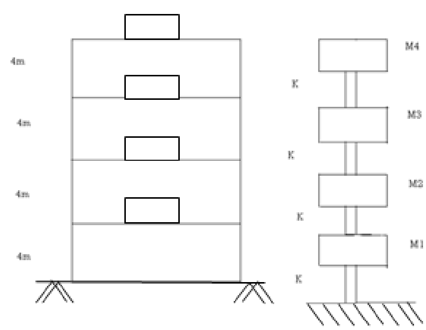

Fig. 2: Shear frame model

Australian Journal of Basic and Applied Sciences, 9(20) June 2015, Pages: 250-256

$M_1 = M_2 = M_3 = 547.2T$
$M_4 = 288T$
$K = 12EI/L^3 = 5868.15KN/m$
$= 28 \times 5868.15 = 164.3X10^3$ KN/m

$$M = \begin{bmatrix} 547.2 & 0 & 0 & 0 \\ 0 & 547.2 & 0 & 0 \\ 0 & 0 & 547.2 & 0 \\ 0 & 0 & 0 & 288 \end{bmatrix}$$

$$\Phi = \begin{bmatrix} 0.011 & 0.027 & 0.027 & 0.0091 \\ 0.021 & 0.020 & -0.022 & -0.018 \\ 0.026 & -0.011 & -0.009 & 0.026 \\ 0.028 & -0.028 & -0.029 & -0.035 \end{bmatrix}$$

$T = 2\pi/\omega$

Modal participation factor :

$$P_k = \sum_{i=1}^{n} Wi\varphi ik \,/\, \sum_{i=1}^{n} Wi(\varphi ik)^2 \quad (1)$$

Modal mass:

$$M = (\sum_{i=1}^{n} Wi\varphi ik)^2 / g(\sum_{i=1}^{n} Wi(\varphi ik)^2) \quad (2)$$

Table 1: frequency and time period

Mode	Frequency, ω (rad/sec)	Time period, T(sec)
1	6.7	0.93
2	19.36	0.32
3	29	0.21
4	34.6	0.18

Table 2: Pk, M and modal mass contribution

Mode	P_k	M	Modal mass contribution
1	44	1754	86.82%
2	12.79	148.79	7.30%
3	-11.09	116.9	5.78%
4	-0.76	0.55	0.027%

Lateral force at each floor in each mode IS 1893 part-1 (2002):

$$Q = A_h \varphi P \omega \quad (3)$$

$A_{h1} = Z/2 * I/R * Sa/g$

$$Q_1 = \begin{bmatrix} 77.94 \\ 148 \\ 184 \\ 104 \end{bmatrix}$$

$$Q_2 = \begin{bmatrix} 111.2 \\ 82.3 \\ -45.3 \\ -60.7 \end{bmatrix}$$

$$Q_3 = \begin{bmatrix} -96.4 \\ 78.5 \\ 32.14 \\ 54.5 \end{bmatrix}$$

$$Q_4 = \begin{bmatrix} -2.22 \\ 4.4 \\ 6.3 \\ 4.5 \end{bmatrix}$$

Storey Shear Force In Each Mode:

$$V_{ik} = \sum_{i=1}^{n} Qik \quad (4)$$

$$V_1 = \begin{bmatrix} 513.9 \\ 436 \\ 288 \\ 104 \end{bmatrix}$$

$$V_2 = \begin{bmatrix} 87.5 \\ -23.7 \\ -106 \\ -60.7 \end{bmatrix}$$

$$V_3 = \begin{bmatrix} 68.74 \\ 165.14 \\ 86.64 \\ 54.5 \end{bmatrix}$$

$$V_4 = \begin{bmatrix} 12.98 \\ 15.2 \\ 10.8 \\ 4.5 \end{bmatrix}$$

Table 3: Storey shear (V),Lateral force (F)

Mode	Storey shear, (V) “KN”	Lateral force, (F) “KN”
1	525.9	58.9
2	467	148
3	319	186.6
4	132.2	132.2

V=Storey shear force due to all mode
F =lateral force at each storey

Design of Isolator:

Range Of Rubber Properties:

Rubber compounds used for isolation are generally in the hardness range of 37 to 60, refered in Himat T Solanki et al. (2008) with properties as listed in Table 4. As compounding is a continuous process intermediate values from those listed are available. As seismic demands have increased over the last 10 years the softer rubbers tend to be used more often. The lowest stiffness rubber has a shear modulus G of about 0.40 MPa although some manufacturers may be able to supply rubber with G as low as 0.30 MPa. There is uncertainty about the appropriate value to use for the bulk modulus, $K\infty$, with quoted values ranging from 1000 to 2000 MPa. The 1999 AASHTO Guide Specifications provide a value of 1500 MPa and this is recommended for design.

Table 4: Natural Rubber Properties

Hardness IRHD±2	Young's Modulus E (MPa)	Shear Modulus G (MPa)	Material Constant k	Elongation at Break Min, %
50	2.2	0.64	0.73	500

The design process starts with preliminary design of a fixed base structure. Following are the preliminary design of the base isolators. The design methodology for bilinear elastomeric isolation systems, those with lead rubber in particular, is presented here. First basic characteristics (like time period, mode shape, base shear) of non-base isolated building are obtained. Then, for the base isolated building a target value of time period or maximum lateral displacement is set. Using these target values, isolator details are worked out and its stiffness and damping are decided. Using this base isolator, building is analyzed and seismic force and lateral displacement are obtained. If the result is within target values, then design of base isolation is right, else another set of properties are considered and analysis is done again. The detailed procedure is explained below:

First, select the material properties for the bearing:

Effective yield stress of lead (fyl), Shear modulus of rubber (Gr), material constant for rubber (k). Determine the maximum loads on isolator (PD+L).

The steps followed are explained below:

Assumed values for trial

B_b = 330mm

B_{pl} = 140mm

t_i = 8mm

T_r = 100mm

Step 1: Vertical Stiffness And Load Capacity:

The dominant parameter influencing the vertical stiffness, and the vertical load capacity, of an elastomeric bearing is the shape factor. The shape factor of an internal layer, Si, is defined as the loaded surface area divided by the total free to bulge area

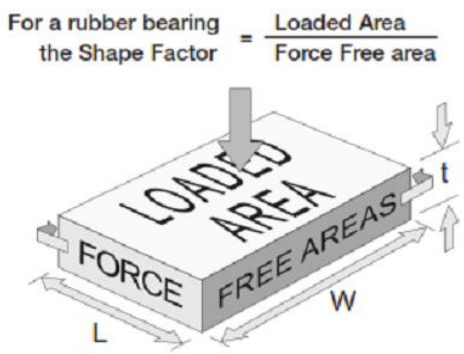

Fig. 3: shape factor

Shape Factor, $S = (A_b - A_{pl}) / (\pi B_b t_i)$

$=[(3.14x165^2)-(3.14x70^2)]/(3.14x330x8)$

=8.45

Vertical stiffness, $K_{vi} = (E_c A_r)/ t_i$

$E_c = E(1+2kS^2) = 2.2(1+2x0.73x8.45^2)$

=231.5 N/mm

$\in = \sqrt{(Bb^2 - \Delta^2)}$

= 330

Reduced rubber area, A_r

$= 0.5\{B^2 \sin^{-1} [\in / B_b] - \Delta \in \}$

$= 0.5 \{(330^2 \sin^{-1} 1) - (1x330)\}$

$= 85,364.85\ mm^2$

Therefore the vertical stiffness, K_{vi}

= (231.5 x 85,364.8)/8

= 2470245.6 N/mm

Step -2 Compressive Load Capacity:

The vertical load capacity is calculated by summing the total shear strain in the elastomer from all sources. The total strain is then limited to the ultimate elongation at break of the elastomer divided by the factor of safety appropriate to the load condition.

The shear strain from vertical loads, $\varepsilon_{sc} = 6S\varepsilon_c$

Where $\varepsilon_c = P/ K_{vi}\, t_i$

= (572.4x10^3)/(2470245.6x8)

= 0.028

ε_{sc}

= 6x8.45x0.028

= 1.46

The shear strain due to lateral loads is, ε_{sh}

= Δ/ T_r

= 1/100 = 0.01

For service loads such as dead and live load the limiting strain criteria are based on AASHTO

$f\varepsilon_u > \varepsilon_{sc}$ where f=1/3 (factor of safety 3)

1/3 x (500/100) > 1.46

1.67 > 1.46

Therefore strains are within the limit

And for ultimate loads which include earthquake displacements

$f\varepsilon_u > \varepsilon_{sc} + \varepsilon_{sh}$ where f = 0.75 (factor of safety 1.33)

0.75 x (500/100) > 1.46 + 0.01

3.75 > 1.47

Therefore the strains are within the limit

Combining these equations, the maximum vertical load, $P\gamma$ at displacement Δ can be calculated from

$P\gamma$

= { $K_{vi}\, t_i\, (f\varepsilon_u - \varepsilon_{sh})$}/6 S

=1945013.89 N

=19.45 x 10^2 KN

STEP – 3 Buckling Load Capacity:

For bearings with a high rubber thickness relative to the plan dimension the elastic buckling load may become critical. The buckling load is calculated using the Haringx formula as follows:

The moment of inertia ,I calculated as

$I = \pi B_b^4/64$ for circular bearings

$I=3.14 \times 330^4/64$

$=5.81 \times 10^8\ mm^4$

The height of the bearing free to buckle, that is the distance between mounting plates is

$H_r = (n\, t_i) + (n-1)t_{sh}$

An effective buckling modulus of elasticity is defined as a function of the elastic modulus and the shape factor of the inner layers.

$E_b = E\,(1+0.742S^2)$

= 2.2(1+0.742 x 8.45^2)

=118.75 N/mm

Constants T,R and Q are calculated as

$T = E_b\, I\, (H_r/ T_r)$

=118.75 x 5.81x10^8 x (118/100)

=8.14x10^10

$R=K_r\, H_r$

$K_r = G\gamma\, A_r/ T_r$

= (0.64 x 85364.85)/100

= 546.33 N/mm

R= 546.33 x 118

= 64467.5

$Q = \pi/ H_r$

= 3.14/118 = 0.0266

From which the buckling load at zero displacement is

$P_{cr}^0 = R/2\, [\sqrt{1 + ((4TQ^2)/R)} - 1]$

=

64467.5/2[

$\sqrt{1 + ((4\,x\,8.14x10^{10}x\,0.02166^2)/64467.5)}$ -1]

=1894958.36 N

= 1894.95 KN

For an applied shear displacement the critical buckling load at zero displacement is reduced according to the effective footprint of the bearing in a similar fashion to the strain limited load:

$P_{cr}\gamma = P_{cr}^0 \times (A_r/A_g)$

= 1505239.644 N

= 1505.23 KN

Step 4 – Lateral Stiffness And Lead Rubber Bearing Hysteresis:

Hysteresis Parameters For Bearing:

Lead rubber bearings, and elastomeric 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 a specified displacement) and the hysteretic damping provided by the system. A typical hysteresis for a lead-rubber bearing is as shown in Figure

Australian Journal of Basic and Applied Sciences, 9(20) June 2015, Pages: 250-256

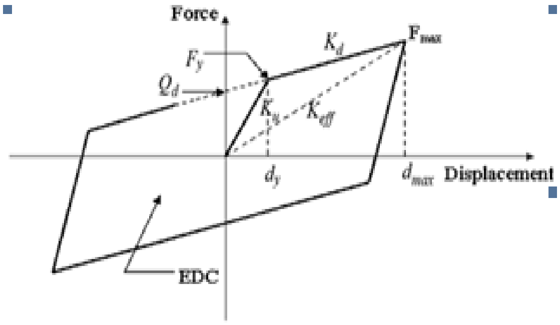

Fig. 4: Hysteretic graph -Lead rubber bearing

For design and analysis this shape is usually represented as a bilinear curve with an elastic (or unloading) stiffness of Ku and a yielded (or post-elastic) stiffness of Kd. The post-elastic stiffness Kd is equal to the stiffness of the elastomeric bearing alone, Kr. The force intercept at zero displacement is termed Qd, the characteristic strength, where:

$Q_d = \sigma_y A_{pl}$
= 10.5 x 3.14 x70^2
= 161553 N
= 161.55 KN

The post-elastic stiffness, Kd, is equal to the shear stiffness of the elastomeric bearing alone:

$K_r = G\gamma A_r / T_r$
= (0.64 x 85364.85)/100
= 546.33 N/mm

The shear force in the bearing at a specified displacement is:

$F_m = Q_d + K_r \Delta$
= 162099.33 N
= 162.09 KN

From which an average, or effective, stiffness can be calculated as

$K_{eff} = F_m / \Delta$
= 162099.33 N/mm
= 162.09 KN/mm

The sum of the effective stiffness of all bearings allows the period of response to be calculated as:

$T_e = 2\pi\sqrt{W/(g\sum \text{Keff})}$
= 4 sec

Seismic response is a function of period and damping. High damping and lead rubber bearings provide hysteretic damping. For high damping rubber bearings, the hysteresis loop area is measured from tests for strain levels, γ, and the equivalent viscous damping β calculated as given below. For lead rubber bearings the hysteresis area is calculated at displacement level Δm as

$A_h = 4\, Q_d\, (\Delta_m - \Delta_y)$
$= 323106\ mm^2$

From which the equivalent viscous damping is calculated as

$\beta = 1/2\,\pi\, (A_h/(\text{Keff} \times \Delta^2))$
= 0.317
= 31 %

For β = 31% B = 1.7

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

$\Delta_m = (S_a T_e^2)/(4\pi^2 B)$
= 70mm

RESULT AND DISCUSSION

- From the analysisthe maximum displacement at the ground floor of the structure is 9.8mm and the isolator is designed for 70mm displavement.

Table 5: Response of building due to seismic load

Mode no	Frequency rad/s	Time period sec	Base shear (KN)	Force at all floors (KN)	Displacement (mm)
1	6.7	0.93	525.9	58.9	9.8
2	19.36	0.32	467	148	50
3	29	0.21	319	186.8	95
4	34.6	0.18	132.2	132.2	90.5

Table 6: Dimension of lead rubber bearing.

DIMENSIONS	
Overall diameter	330mm
Lead core diameter	140mm
Total height	118mm
Total rubber thickness	100mm
Thickness of individual layer	8mm
No of layers	23

Conclusion:

In order to clarify the use of base isolation, a step-by-step design procedure is given in this study. Like any structural design, the base isolation design is also iterative in nature.

Although, this study involves elastomer based lead rubber bearing which have bilinear behavior, other isolation elastomer based isolation systems will have similar behavior.

Base isolation is known to be a quite effective vibration control device However, in this study, it is shown that base isolation is effective in reducing the response as compared to the fixed base system. In the present work, building structure with elastomeric lead rubber bearing having bilinear force deformation behavior is used.

Base isolation helps in reducing the design parameters i.e. base shear and bending moment in the structural members above the isolation interface. The absolute displacement increases, but relative displacements are reduced, thus reducing the damage to the structure when subjected to an earthquake. The shear and bending moments are reduced due to the higher time period of the base isolated structure which results in lower acceleration acting on the structure and also, due to the increased damping in the structure due to the base isolation devices.

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