The Asian Review of Civil Engineering
ISSN: 2249-6203 (P) Vol.3 No.2, 2014, pp.19-26

DOI: https://doi.org/10.51983/tarce-2014.3.2.2207

Design of Base Isolated School Building with Elastomeric Bearing

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***Abstract* - In this paper, a school building which is to be located in Coimbatore region is taken. A four storied (G+3) school building having plan dimension of 16m x 54m is considered. The structure is modeled as single degree of freedom. The analysis of the structure is made by linear dynamic response spectrum method and the dynamic responses are found. From linear response spectrum analysis used in this study, the total base shear forces and storey shear forces in the columns and the absolute and relative storey drifts are found and the column having critical value is found judicially. Elastomeric bearing is designed for that column. 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.**
Keywords: **Base isolation, Elastomeric bearing, Base shear, Displacement, Mode shape**

I. INTRODUCTION

During earthquake attacks, 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. are 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. In Figure 1, note 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.

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.

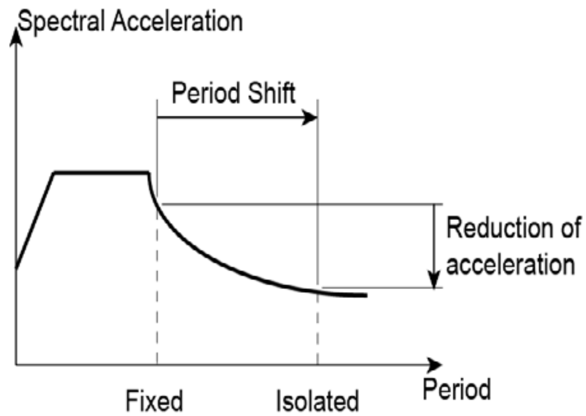

Fig. 1 Acceleration response spectrum

II.DESCRIPTION OF THE STRUCTURES

The structures, used for the analyses, are assumed to be serving as school building. The school building is designed as per IS 8827-1978 'Recommendations for Basic Requirements of School Buildings' .The detailed descriptions of the building is as follows:

The three-storey building has a regular plan (54m x 16m) as shown in Figure 3.1. The structural system is selected as concrete frames with columns size of (360X360) mm in size, and beams of dimension (250X400)mm in 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.

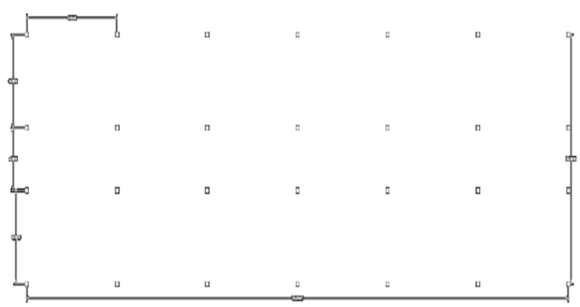

Fig. 2 Column Location of School Building

III. ANALYSIS METHODS

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

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.

Preliminary Data for Analysis

Type of structure - multi-storey RCC framed structure
Seismic zone - III(coimbatore)
Number of stories-four(G+3)
Floor height-4m
Imposed load-3.5 kN/m2
Size of columns-360mm x 360mm

Depth of slab – 100mm thick
Size of beams-250mm x 450mm in longitudinal
Size of beams -250mm x 400mm in transverse direction
Response spectra- as per IS 1893 (Part I):2002

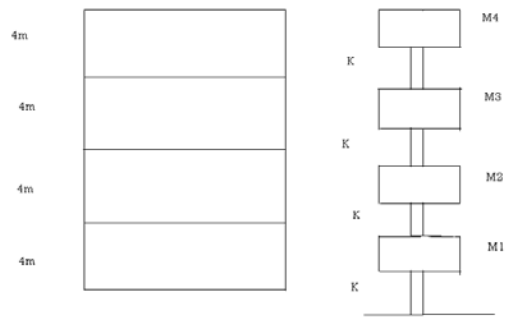

Fig.3 Elevation and lumped mass model

Calculation of lumped mass

$M_1 = M_2 = M_3 = 547.2T$
$M_4 = 288T$
$K = 12EI/L^3 = 5868.15 KN/m$
= 28*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 $P_k = \sum_{i=1}^{n} Wi\varphi ik \,/\, \sum_{i=1}^{n} Wi(\varphi ik)^2$ (1)

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

TABLE I FREQUENCY AND TIME PERIOD

Mode no	Frequency, ω rad/sec	Time period, T secs
1	6.7	0.93
2	19.36	0.32
3	29	0.21
4	34.6	0.18

TABLE II PK, M AND MODAL MASS CONTRIBUTION

Mode no	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

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

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

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

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

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

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

Storey shear force in each mode

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

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

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

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

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

Mode No	V (KN)	F (KN)
1	525.9	58.9KN
2	467	148KN
3	319	186.6KN
4	132.2	132.2KN

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

IV. ISOLATOR PROPERTIES AND MODELLING

The design process starts with preliminary design of a fixed base structure. Following is the preliminary design of the base isolators. A 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).

TABLE III 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 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

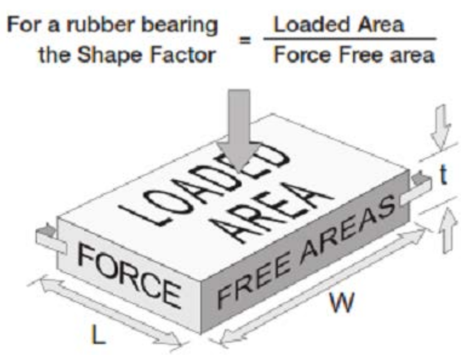

Fig. 4 Shape Factor

Shape Factor, $S = (A_b - A_{pl}) / (\pi B_b t_i)$ =8.45
Vertical stiffness, $K_{vi} = (E_c\ A_r)/\ t_i$ = 2470245.6 N/mm

Step 2 Compressive Rated 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,
$\varepsilon_{sc} = 6S\varepsilon_c = 1.46\ t_{sh}$
The shear strain due to lateral loads is,
$\varepsilon_{sh} = \Delta / T_r$

=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

$$P\gamma = \{ K_{vi}\, t_i\, (f\varepsilon_u - \varepsilon_{sh})\}/6\,S$$
=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, we calculated as
$I = \pi B_b^4/64$ for circular bearings
=5.81 x 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

$$E_b = E\,(1+0.742S^2)$$
=118.75 N/mm
The buckling load at zero displacement is
$$P_{cr}^0 = R/2\,[\sqrt{1 + ((4TQ^2)/R)} - 1]$$
= 1894.95 KN

For an applied shear displacement the critical buckling load at zero displacement

$$P_{cr}\gamma = P_{cr}^0 \times (A_r/A_g)$$
= 1505.23 KN

Step 4 Lateral Stiffness And Lead Rubber Bearing Hysteresis

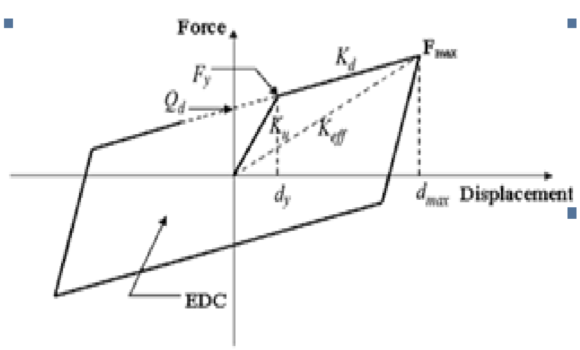

Fig. 5 Bilinear Force deformation behavior

The lead rubber isolation bearing is modeled by a bilinear model based on the three parameters: Ku, Kd, and Qd as shown in Fig. 3.

Isolation bearings will have high initial stiffness, Ku, and after yielding they will have lower stiffness, Kd. The initial stiffness Ku is estimated as a multiple of post yield stiffness Kd for lead–plug bearings.

The hysteretic damping of this bearing is due to the plastic deformation of the lead.

The force intercept at zero displacement is termed Qd, the characteristic strength, where:

$Q_d = \sigma_y A_{pl}$

$= 161.55$ KN

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

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

$= 546.33$ N/mm

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

$F_m = Q_d + K_r\, \Delta$

$= 162.09$ KN

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

$K_{eff} = F_m / \Delta$

$= 162.09$ KN/mm

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

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

$= 4$ secs

Seismic response is a function of period and damping. 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

$\beta = 1/2\,\pi\, (A_h/(\,Keff \times \Delta\hat{}2))$

$= 31$ %

For $\beta = 31\%$ B = 1.7

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

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

$= 70$mm

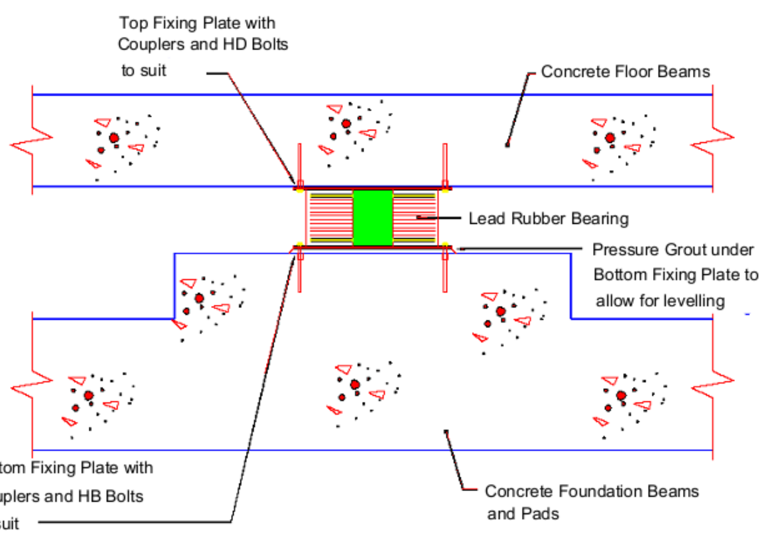

Fig. 6 Connection of Bearing to the Structure

V. SUMMARY OF RESULTS

TALE IV MAXIMUM RESPONSE FOR THE BUILDING

Mode no	Frequency rad /sec	Time period sec	Base shear (KN)	Force at all floors (KN)	Displacement (mm)
1	6.7	0.93	525.9	58.9	0.3
2	19.36	0.32	467	148	0.6
3	29	0.21	319	186.8	0.74
4	34.6	0.18	132.2	132.2	0.8

TABLE V ISOLATOR PROPERTIES

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

The number of rubber layers and lead core sizes are set by a trial-and-error procedure to achieve the required seismic performance. So the solution for seismic performance requires an iterative procedure. On further iteration, the design can be made economical.

VI. CONCLUSION

In order clarify the use of base isolation, a step-by-step procedure is given in this study. Like any structural design, the base isolation design is also iterative in nature. The expected lateral displacement or time period of base isolation system is assumed and the base isolation properties are obtained. At the end it is checked if required time period or displacement is actually obtained. Using the stiffness and damping of base isolation, building is analyzed using response spectrum analysis and seismic response is obtained. Although, this study involves elastomer based lead rubber bearing which have bilinear behaviour, other isolation elastomer based isolation systems will have similar behavior.

Base isolation is known to be quite effective vibration control device However, in this studies, it is shown that base isolation is effective in reducing the response as compared to 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 displacements 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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