# SEISMIC ISOLATION FOR MULTISTORIED BUILDINGS **USING ELASTOMERIC BEARINGS**

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## Abstract

Multistoried building structures designed according to conventional methods result in low earthquake resistances. Seismic isolation bearings are considered an effective solution for the structure located in the earthquake areas. The paper presents a simplified procedure to calculate the isolated building according to the Vietnamese code. The bilinear equivalent model was employed to determine the properties of the isolator. Three-dimensional models of a typical building structure were selected to evaluate effects of the isolator. The modal analyses and time history analyses were performed using Etabs V17, with the input record taken according to the earthquake ground motion in Hanoi. The result shows the high effectiveness of isolator on reducing seismic effects.

**Keywords**: Seismic base isolation; lead rubber isolator; multistoried building; seismic behavior; bilinear model.

## **1. Introduction**

Multistoried buildings are important components of the urban planning and becoming increasingly popular in big cities. However, its structure is vulnerable to the effects of horizontal dynamic loads, especially under strong impacts like earthquakes and may lead to damages. Therefore, essential building structures shall be designed with high vitality to ensure safety during and after major earthquakes.

Many current standards and specifications define the performance-based seismic design, as a structural approach, which allows for certain structural damage rates based on the specified earthquake intensity [1-3]. Accordingly, these accepted damages can lead to the loss of structural operation or the need for major repairs of constructions.

Recently, the use of seismic protection devices is becoming increasingly common for constructions in earthquake areas. This technique produces high energy dissipation capacities and/or high values of the ductility [4-9].

Seismic base isolation (SBI) has been considered an effective technique for seismic structural design by providing a special suspension system that isolates the superstructure of the building from its substructure [6, 10, 11]. These systems have a high vertical

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stiffness to ensure the vertical bearing capability and a sufficient horizontal stiffness under the non-seismic lateral impact to maintain the stability of the construction.

On the other hand, as the building exposed to the earthquake, it introduces flexible supports and high dissipation capacities, allowing the building to be decoupled in the horizontal direction from the ground motion. Figure 1 illustrates the principle of SBIs' effects on the seismic responses of the structure from the spectrum point of view.



Figure 1. Effects of SBI approach on the seismic responses: a) on spectral acceleration (lateral force); b) on lateral displacement.

Figure 2 shows a typical application of the SBI device in the global building structure including superstructure, isolation, foundation and soil, order from the top to bottom, respectively. Practically, SBI is considered as a connection between the superstructure and the substructure, which improves earthquake resistances of the building by making it float on the base such that it is not considerably affected by ground motions.



Figure 2. Effects of SBI on contour deformation of the structure.

There are two major SBI systems such as elastomer-based and friction-based, categorized according to their respective operating principles. The elastomeric rubber bearing is a very common system of SBI used over many decades based on the high vertical bearing capacity, low horizontal stiffness, and high restoring capability. The most common elastomer-based SBI is the high damping rubber bearings (HDRB) and lead-plug rubber bearings (LRB). The HDRB uses an elastomer with a special formulation so it presents a considerable energy dissipation capacity with an interesting equivalent damping ratio varying around 10% to 15%. However, it is significantly sensitive by temperature conditions, aging effects, and the scragging phenomenon [6, 12].

The LRB consists of a laminate rubber bearing with a lead plug down its center as shown in Figure 3. The high lateral flexibility of the elastomer, working in shear, is the basis of the lateral displacement capacity. The lead plug, which presents a perfect plastic deformation behavior, plays a role important to dissipate the generated energy, especially due to the cyclic loadings.



Figure 3. Structure of lead-rubber bearing isolator.

Generally, the LRB system provides high energy dissipation capacities with equivalent damping ratios up to 30% based on its practically perfect elastoplastic behavior in shear [6, 13]. Further, the damping ratio of LRB can be modified easily by the selection of the appropriate size of the lead plug. Therefore, it is considered as the ideal device for SBI approach for buildings.

Although the seismic base isolation design is mentioned generally in chapter 10, TCVN 9386-2012, its application in practice is still limited. This paper presents the effectiveness of LRB on the seismic responses of a typical multistoried building located in Hanoi, Vietnam.

The theoretical basis of the SBI for the building structure is first outlined by systems of multi-degree-of-freedom. The bilinear model of SBI and the procedure of iteration are represented, which was considered as the simplified method, to determine 106

the effective parameters of the equivalent linear viscoelastic model. Three-dimensional models of a 15-story building were analyzed to evaluate the effect of SBI on the seismic response of the structure. To do so, time history analysis was conducted with a record according to ground motion in Hanoi by using Etabs V17 software. The effect of SBI was clarified by comparisons of the results between the fixed-base structure and isolated structure.

## 2. Theoretical basis of seismic isolation

## 2.1. Linear theory of two-degree-of-freedom

The linear theory of seismic isolation has been given in detail by Kelly [14]. Figure 4 illustrates the basis of theory by a two-mass structural model. The mass m represents the superstructure of the building and  $m_b$  is the mass of the base floor above the isolation systems. The structural properties are represented by  $k_s$ ,  $c_s$  (stiffness and damping, respectively). Similarly, the isolation is characterized by  $k_b$ ,  $c_b$ . Absolute displacements of the two masses are assumed by  $u_s$  and  $u_b$ . Accordingly, the relative displacements are used as defined below:

$$v_b = u_b - u_g; \quad v_s = u_s - u_b \tag{1}$$

where  $u_g$  is the ground displacement,  $v_b$  is the isolation system displacement and  $v_s$  is the inter-story drift.



Figure 4. Parameters of two degrees-of-freedom isolated system.

The mathematical model of system is expressed as the following:

$$m\ddot{v}_b + m\ddot{v}_s + c_s\dot{v}_s + k_sv_s = -m\ddot{u}_g \tag{2}$$

$$(m+m_{b})\ddot{v}_{b}+m\ddot{v}_{s}+c_{b}\dot{v}_{b}+k_{b}v_{b}=-(m+m_{b})\ddot{u}_{g}$$
(3)

which can be written in matrix form as follows:

$$\begin{bmatrix} M & m \\ m & m \end{bmatrix} \begin{bmatrix} \ddot{v}_b \\ \ddot{v}_s \end{bmatrix} + \begin{bmatrix} c_b & 0 \\ 0 & c_s \end{bmatrix} \begin{bmatrix} \dot{v}_b \\ \dot{v}_s \end{bmatrix} + \begin{bmatrix} k_b & 0 \\ 0 & k_s \end{bmatrix} \begin{bmatrix} v_b \\ v_s \end{bmatrix} = \begin{bmatrix} M & m \\ m & m \end{bmatrix} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \ddot{u}_g$$
(4)

where  $M = m + m_b$ . The form of equation (4) can be reduced as below:

$$\mathbf{M}\ddot{\mathbf{v}} + \mathbf{C}\dot{\mathbf{v}} + \mathbf{K}\mathbf{v} = -\mathbf{M}\mathbf{r}\ddot{u}_{a} \tag{5}$$

The mass ratio  $\gamma$  is defined as follows:

$$\gamma = \frac{m}{m + m_b} = \frac{m}{M} \tag{6}$$

and nominal frequencies  $\omega_b$  and  $\omega_s$  given by

$$\omega_b^2 = \frac{k_b}{m + m_b}; \quad \omega_s^2 = \frac{k_s}{m} \tag{7}$$

The damping factor  $\xi_b$  and  $\xi_s$  are given by

$$2\omega_b\xi_b = \frac{c_b}{m+m_b}; \ 2\omega_s\xi_s = \frac{c_s}{m}$$
(8)

## 2.2. Extension of theory to Multi-degree-of-freedom

The two-degree-of-freedom analysis of the equivalent linear model can be developed suitably for the case of a multistoried building. Generally, the structural system of the building is represented by a mass matrix, **M**, a damping matrix, **C**, and stiffness matrix, **K**. If the structure were conventionally based, the relative displacement, **u**, of each degree of freedom with respect to the ground would be given by

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = -\mathbf{M}\mathbf{r}\ddot{u}_{g} \tag{9}$$

where **r** is a vector that couples each degree of freedom to the ground motion. When this structural model is superimposed on a base isolation system with base mass  $m_b$ , stiffness  $k_b$ , and damping  $c_b$ , Eq. (9) is becomes

$$\mathbf{M}\ddot{\mathbf{v}} + \mathbf{C}\dot{\mathbf{v}} + \mathbf{K}\mathbf{v} = -\mathbf{M}\mathbf{r}\left(\ddot{u}_{g} + \ddot{v}_{b}\right) \tag{10}$$

where **v** is the displacement relative to the base slab and  $v_b$  is the relative displacement of the base slab to the ground. The overall equation of motion for the combined building and base slab is

$$\mathbf{r}^{T}\mathbf{M}\ddot{\mathbf{v}} + (m+m_{b})\ddot{v}_{b} + c_{b}\dot{v}_{b} + k_{b}v_{b} = -(m+m_{b})\ddot{u}_{g}$$
(11)

Equation (11) identifies  $\mathbf{r}^{T}\mathbf{M}\mathbf{r}$  as the total mass *m*, of the building, so that  $m + m_b$  is the total mass carried on the isolation system. The matrix form of these equations is given

$$\mathbf{M}^* \ddot{\mathbf{v}}^* + \mathbf{C}^* \dot{\mathbf{v}}^* + \mathbf{K}^* \mathbf{v}^* = -\mathbf{M}^* \mathbf{r}^* \ddot{u}_{\varrho}$$
(12)

where

$$\mathbf{M}^* = \begin{bmatrix} \boldsymbol{m} + \boldsymbol{m}_b & \mathbf{r}^T \mathbf{M} \\ \mathbf{M} \mathbf{r} & \mathbf{M} \end{bmatrix}; \quad \mathbf{C}^* = \begin{bmatrix} \boldsymbol{c}_b & 0 \\ \mathbf{0} & \mathbf{C} \end{bmatrix}$$

and

$$\mathbf{K}^* = \begin{bmatrix} k_b & 0 \\ \mathbf{0} & \mathbf{K} \end{bmatrix}; \quad \mathbf{r}^* = \begin{bmatrix} 1 \\ \mathbf{0} \end{bmatrix}$$

with

$$\mathbf{v}^* = \begin{bmatrix} v_b \\ \mathbf{v} \end{bmatrix}$$

Equation (12) can be solved directly or through modal decomposition, numerical evaluation [11].

# 3. Estimating properties of isolator by equivalent bilinear model

Practicely, the isolation bearing can be modeled by a bilinear model based on four main parameters such as: (i) the characteristic strength, Q; (ii) the post-yielding stiffness,  $K_2$ ; (iii) yield displacement,  $D_y$ ; and (iv) maximum displacement,  $D_{max}$ , as shown in Figure 5 [6].

The initial stiffness,  $K_1$ , and the effective stiffness,  $K_{eff}$ , are determined as a function of the four parameters as follows:

$$K_1 = \frac{Q}{D_y} + K_2 \tag{13}$$

$$K_{eff} = \frac{Q}{D_{\text{max}}} + K_2 \tag{14}$$

where the maximum displacement,  $D_{max}$ , can be determined as [2]

$$D_{\max} = \frac{MS_a \left(T_{eff}, \xi_{eff}\right)}{K_{eff}} \tag{15}$$

where  $S_a(T)$  is the elastic response spectrum [2], [3],  $\xi_{eff}$  is the effective equivalent viscous damping ratio, expressed as a percentage,  $T_{eff}$  is the effective period of the isolation system [2]:

$$T_{eff} = 2\pi \sqrt{\frac{M}{K_{eff}}} \tag{16}$$

 $K_{eff}$ , is the effective stiffness defined below:

$$K_{eff} = M \left(\frac{2\pi}{T_{eff}}\right)^2 \tag{17}$$

The energy dissipated per cycle (EDC) is determined by the area under hysteresis loop and considered by an equivalent linear viscoelastic system:

$$W_D = EDC = 4Q(D_{\max} - D_y) = 2\pi\xi_{eff}K_{eff}D_{\max}^2$$
(18)

The effective equivalent damping ratio is calculated as follows:

$$\xi_{eff} = \frac{4Q(D_{\max} - D_y)}{2\pi K_{eff} D_{\max}^2}$$
(19)

Figure 5 illustrates a bilinear force-displacement relationship for a typical seismic isolation system that includes the characteristic parameters.



Figure 5. Parameters of bilinear model.

In terms of these parameters, the initial stiffness,  $K_1$ , and the maximum displacement,  $D_{max}$ , three important parameters are derived:

$$Q = \frac{W_D}{4\left(D_{\max} - D_y\right)} \tag{20}$$

$$K_2 = K_{eff} - \frac{Q}{D_{\text{max}}}$$
(21)

$$D_{y} = \frac{Q}{K_{1} - K_{2}} = \frac{Q}{K_{2} \left( 1/\alpha - 1 \right)}$$
(22)

where  $\alpha = K_2 / K_1$ .

Because these equations are coupled with each other, it is necessary to use an iterative procedure to calculate the design parameters, which is clearly illustrated in Figure 6.

On focus to in the application of LRB, it should be noted that the contribution of rubber to the characteristic strength (Q) and yield force ( $F_y$ ) is relatively negligible when compared with the lead plug. Therefore, Q and  $F_y$  are determined by the lead core alone as follows:

$$F_{y} = \frac{1}{\psi} f_{yL} \frac{\pi d_{l}^{2}}{4}$$
(23)

$$Q = F_{v}(1-\alpha) \tag{24}$$

where  $f_{yL}$  is the shear yield stress of the lead,  $d_l$  is diameter of the lead plug, and  $\psi$  is load factor accounting for creep in lead ( $\psi = 1$  for seismic loads).

Furthermore, according to the classification of Naeim and Kelly [6], certain SBI corresponds to a range of the post-elastic ratio, then lead-plug rubber bearing corresponding to  $\alpha = [1/30 \div 1/15]$ .



Figure 6. Iterative design procedure for determination of SBI properties.

## 4. Building model and design

Application on an office building with the properties of the model is detailed as below:

- Architecture: the building has 15 floors, including 1 basement and 14 stories. The floor height is 3,6 m for the stories and 3,3m for the basement. The plan dimensions of the building are 24 m x 30 m, including four bays in the X direction and three bays in the Y direction as shown in Figure 7.

- Structure: the beam dimensions are 30 cm x 60 cm for the main beam systems, sub-beam are 25 cm x 45 cm; the cross-section dimensions of columns: from  $1^{st}$  to  $5^{th}$ 

story 80 cm x 80 cm; from  $6^{th}$  to  $10^{th}$  story 70 cm x 70 cm; from  $11^{th}$  to the roof 60 cm x 60 cm; The concrete wall thickness is 25 cm; and the floor thickness is 15 cm.

- Material: Concrete grade #B25, reinforcement grade CB400-V.

- Loading: The floor loading: dead load 120 daN/m<sup>2</sup>, live load 240 daN/m<sup>2</sup> (on the floor) and 90 daN/m<sup>2</sup> (on the roof); the building is located in Hanoi, based on soil type C and subjected to acceleration with  $a_g = 0,1032$  g and the behaviour factor, q = 3,9 [3].

Figure 7 shows the 3D model of the building by using Etabs [15].



Figure 7. Specific floor plan and 3D model of the building.



horizontal design spectrum used for study.

The total mass of building is M = 11474000 kg used to estimate the parameters of the isolator. Assume that the damping ratio of isolator  $\xi_{eff} = 20\%$  (according to lead plug rubber bearing, [6]); the effective period of the fundamental mode of isolated 112

building,  $T_{eff} = 3(s)$  [2, 12];  $\alpha = 0.05$  ( $\alpha = 1/30 \div 1/15$  for LRB). Based on the block diagram in Figure 6, the properties of a single equivalent isolator are obtained as: yield force, Q = 2487 kN; pre-yield stiffness,  $K_2 = 34113$  kN/m; effective stiffness,  $K_{eff} = 50331$  kN/m,  $D_{max} = 0.153$  m; dy = 0.0038 m.

The required area of pads is approximately equal:  $A_r = 11474x9,81x1,4/10^4 = 15,8 \text{ m}^2$ , selecting 32 lead plug rubber bearings with the diameter of 800mm in the bottom of the columns and the concrete walls, so that  $A_r = 16,08 \text{ m}^2$ .

The thickness of elastomer to fit with the total effective stiffness:  $h_r = GA/K_{eff} = 10^3 \times 16,08/50331 = 0,319$  m. Selecting the bearing with 20 layers of 16 mm, so that the total rubber thickness is 0,32 m.

The yield strength of lead is taken as 10 MPa, so that the total area of lead plug needed is:  $A_l = Q/0.95/10^4 = 0.262 \text{ m}^2$ . Choosing the lead plug with the diameter of 110 mm, then the total area of the lead plug is  $A_l = 32x\pi x 0.110^2/4 = 0.304 \text{ m}^2$ ,  $F_y = 3040 \text{ kN}$  and  $Q = F_y(1 - 0.05) = 2888 \text{ kN}$ .

Lead-plug bearings are usually from a low-damping, high-strength rubber with a modulus at 100% shear strain that might vary from 0,4 to 0,7 MPa [6, 12]. The shear modulus value of lead is assumed equal to 0,6 MPa. Then, the post-yield stiffness of plain elastomeric bearings is given by:

$$K_2 = \frac{G(A_b - A_l)}{h} = \frac{0.6 \cdot 10^3 (16,08 - 0.304)}{0.32} = 29580 \text{ kN/m}.$$

The total effective stiffness  $K_{eff}$  is given as

$$K_{eff} = 29580 + \frac{2888}{0,153} = 48455 \,\text{kN/m}.$$

and  $W_D = 4 \cdot 2888(0,153 - 0,0038) = 1723 \text{ kN/m}$ ;

$$\xi_{\text{eff}} = \frac{1723}{(2\pi \cdot 48455 \cdot 0, 153^2)} = 24,18\%.$$

The total effective damping coefficient  $C_{eff}$  is given as:

$$C_{eff} = 2\xi_{eff}\sqrt{K_{eff}M} = 11405 \,\mathrm{kNs/m}$$

The total initial stiffness  $K_1$  is given as:

 $K_1 = K_2 / \alpha = 591600 \, \text{kN/m}$ 

Accordingly, Table 1 shows the properties for one of 32 similar systems used for the building.

| M (kg) | W(kN) | $K_{eff}$ (kN/m) | $C_{eff}$ (kNs/m) | <i>K</i> <sub>1</sub> (kN/m) | Q (kN) | α    |
|--------|-------|------------------|-------------------|------------------------------|--------|------|
| 359000 | 3517  | 1514             | 356               | 18488                        | 90     | 0,05 |

Table 1. Properties of a single SBI.

The link elements are employed to modeling SBI in Etabs software with the link property data as shown in Table 1. Both models of fixed-base building structure and isolated-base building structure are conducted by time history analyses with an artificial ground motion and spectral acceleration, which was built accordingly to TCVN 9386: 2012 by using Etabs, as shown in Figure 8. The seismic performance of SBI is primarily considered overall based on the reduction of bending moment and shear force at the base of the building structure and the drift at the floors. The results are taken into comparing in order to evaluate the effectiveness of SBI as shown in Figures 9-16.

Figure 9 shows the period value of the first five modes of vibration. Accordingly, the SBI application produces a significant effect on the vibration modes, especially on the fundamental mode. For isolated building, the period of the first two modes of vibration is extended significantly when compared to the fixed-base building structure.



Figure 9. Model periods in analysis.

In general, it will be interested in the modes of vibration, which contribute significantly to structural dynamic responses. In this study, the first modes of vibration are used to achieve the SBI efficacy. Correspondingly, Figure 10 shows the first three modes of vibration of the building. The results illustrate that for the isolated building, the deformation occurs mainly in SBI rather than structural components. Moreover, the



effect of bending due to the seismic force is greatly reduced in the isolated building when compared with the fixed-base building.

Figure 10. Modal shapes analysis.

Figure 11 shows the relative drift diagram of the buildings. A significant reduction of drift is gotten by using SBI, especially at the top of the building.



Figure 11. Story drift diagrams of building subjected to seismic action: a) in X direction; b) in Y direction.

Figure 12-16 show the comparisons of time history responses for two models in terms of the base shear force, the displacement at the top floor and the bending moment of a specific column in the basement. It clearly demonstrates that, by using the SBI, the internal force and displacement of the building due to the effect of the earthquake are significantly reduced. This effectiveness is shown in detail in Table 2. Accordingly, the base shear forces and bending moments reduce from 30% up to 70%, while the displacement at the top of building reduces from 30% to 75% by using the isolator.







116



Figure 14. Dynamic displacement at top story (column 2E) in X direction.



Figure 15. Dynamic displacement at top story (column 4C) in Y direction.



Figure 16. Dynamic moment M33 at node 4 (column 1C, story 1).

|     | Content                               | Max value |        |                      | Min value |        |                      |
|-----|---------------------------------------|-----------|--------|----------------------|-----------|--------|----------------------|
| Ord |                                       | FB (1)    | IB (2) | Ratios<br>(1)/(2), % | FB (3)    | IB (4) | Ratios<br>(3)/(4), % |
| 1   | Base shear force (X),<br>kN           | 1862,2    | 1370,1 | 26,4                 | -2378,1   | -823,0 | 65,4                 |
| 2   | Base shear force (Y),<br>kN           | 2832,3    | 1351,6 | 52,3                 | -2549,8   | -785,2 | 69,2                 |
| 3   | Displacement at top<br>strory (X), mm | 23,7      | 8,5    | 64,1                 | -18,3     | -12,5  | 32,1                 |
| 4   | Displacement at top<br>strory (Y), mm | 19,5      | 4,8    | 75,5                 | -16,7     | -7,1   | 57,3                 |
| 5   | Moment M3-3, kNm                      | 99,3      | 71,4   | 28,1                 | -70,9     | -68,9  | 2,8                  |

Table 2. Comparison between fixed-base and isolated-base structure.

## **5.** Conclusions

In this paper, the effects of SBI on seismic responses of the multistoried building have been performed. The simplified method for estimating the properties of lead-plug rubber bearing was conducted based on the iterative procedure by using the equivalent bilinear model. The seismic performance of LRB was investigated through the numerical analyses of a fifteen-story building. The obtained results show that SBI strongly affects the vibration of the building. It allows to extend the period of the fundamental mode, therefore, reduces the impact of the ground motion on the structure. Further, in the isolated structure, the deformation due to the effect of earthquakes occurs mainly in the SBI instead of structural components as in the fixed-base building structure, resulting in a significant reduction of the internal force and displacement of the main structure's response. Therefore, the seismic resistance of the building is greatly improved. It also confirms the feasibility of the SBI application for multistoried building structures in the earthquake regions such as Vietnam.

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# CÁCH LY ĐỊA CHÂN CHO NHÀ CAO TẦNG SỬ DỤNG GỐI ĐÀN HỒI

Tóm tắt: Kết cấu nhà cao tầng được thiết kế theo phương pháp thông thường có khả năng chống đất thấp. Gối cách chấn được coi là một trong các giải pháp kháng chấn hiệu quả đối với các công trình nằm trong khu vực động đất. Bài báo trình bày nội dung tính toán kết cấu công trình có sử dụng gối cách chấn theo tiêu chuẩn Việt Nam TCVN 9386:2012. Mô hình song tuyến tính tương đương được sử dụng để xác định các thuộc tính của bộ cách chấn. Các mô hình kết cấu không gian của công trình nhà cao tầng điển hình được lựa chọn để đánh giá hiệu quả của bộ cách chấn. Các phân tích dạng dao động và lịch sử thời gian được thực hiện bằng Etabs V17, với số liệu đầu vào được lấy theo chuyển động nền động đất tại Hà Nội. Kết quả cho thấy gối cách chấn có hiệu quả cao trong việc giảm tác động của động đất lên công trình.

**Từ khóa**: Cách ly địa chấn đáy; cách ly cao su chì; nhà cao tầng; ứng xử động đất; mô hình song tuyến tính.

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