



## Cost Viability of a Base Isolation System for the Seismic Protection of mid-rise reinforced concrete moment frames

Kamyar Bagherinejad <sup>a\*</sup>, Shahin Charkhtab <sup>a</sup>, Seyedhamed Hosseini <sup>b</sup>

<sup>a</sup> Islamic Azad University, Chaloos, Iran

<sup>b</sup> Universiti Teknologi Malaysia, Johor, Malaysia

---

### Abstract

Seismic isolation is effective in reducing seismic demand for buildings and decreasing seismic damage costs. This study investigates the effect of lead-plug rubber bearing isolator on the casting cost of mid-rise reinforced concrete moment frames. A five story concrete frame building case study is modeled by ETABS software. Then in the designed structure a series of lead-plug rubber Isolators are applied and the building is re-designed. Next the casting costs in these two different cases are compared. Based on the results of this case study, using of base isolator would decrease the weight of steel rebar and the volume of concrete about 20 percent in comparison of ordinary building.

© 2017 Journals-Researchers. All rights reserved

*Keywords:* Base isolator, concrete moment frame, cost viability;

---

### 1. Introduction

Strong earthquakes cause tangible and intangible losses and disrupt normal operation of structures. Such destructive seismic effects can be reduced by installing energy dissipation devices and seismic

isolation systems. It is worth to mention that cost-benefit assessments of seismic risk seismic isolation systems provide important information to decision building makers [1-5]. The results are also valuable in performance-based and consequence-based earthquake engineering [6].

Seismic isolation has been successfully applied in practice to decrease seismic risk [7] in building

---

\* Corresponding author. Tel.: +989111481964; Fax: +981333511729; e-mail: k.bagherinejad@iauc.ac.ir

structures. The success of this system is based on that an isolated structure, which includes a superstructure and isolator, has a much longer vibration period as compared with a fixed structure (i.e., structure without base isolation), and that strong ground motion contains less energy in the long vibration period range. Consequently, seismic isolation systems are very effective. One exception could be when isolated structures are excited by near fault motions containing strong velocity pulses. The performance of isolated systems subjected to near-fault motions have been investigated [8,9].

The earthquake resistant structures can be categorized into rigid structures and flexible structures. In rigid structures, the control methods that are applied to withstand extreme loads are basically reducing the inter-story displacement. In flexible structures, such as base-isolated buildings, the key control approach is to reduce the excitation input with the use of dampers and isolators. Figure 1 shows a Comparison of base-isolated and fixed-based building.

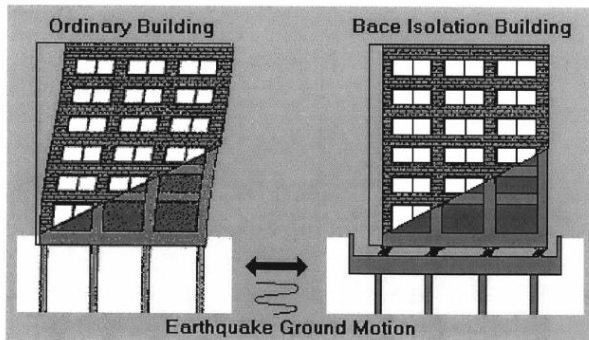


Figure 1. comparison of base-isolated and fixed-based building

This study investigates the effect of lead-plug rubber bearing system on the cost viability in mid-rise reinforced concrete moment frames. A five stories concrete frame building case study has been simulated using ETABS [10] software. Then in the designed structure a series of lead-plug rubber isolators are applied and the building is re-designed. Finally the total rebar weight and concrete volume for these structures (before and after of using isolator) are compared.

In this study, just the casting amount of rebar and concrete are investigated and the cost of isolator

should be added. Also the seismic damages and repair costs are not considered.

## 2. Lead rubber bearing base isolator

Lead-plug rubber bearings were invented in New Zealand in 1975. The mechanism of lead-plug rubber bearings is very similar to that of low-damping natural rubber bearings. As shown in Figure 2, there are three main pieces of equipment, layers of steel plates, rubber layers and lead core, respectively. Same as the steel shims in natural rubber bearings, the layers of steel provide vertical stiffness and the layers of rubber supply the device with high lateral flexibility. Lead core is the device that will supply extra stiffness to the isolators and appropriate damping to the system.

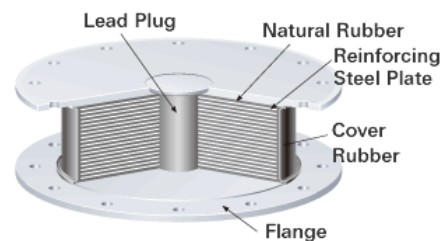


Figure 2. Lead rubber bearing base isolator

The performance of the lead-plug bearing depends on the imposed lateral force. If the lateral force is small, the movement of the steel shims is restrained by the lead core, and the bearing displays higher lateral stiffness. As the lateral force becomes larger, the steel shims force the lead core to deform or yield, and the hysteretic damping is developed with energy absorbed by the lead core. Consequently, the lateral stiffness of the bearing is reduced. The equivalent damping of the lead-plug bearing varies from 15% to 35%.

### 3. Bilinear Model and Model Parameters of Lead-Plug Bearing System

The bilinear model, used to express the relation between the shear force and the lateral displacement, can be defined by three parameters: elastic stiffness,  $k_e$ , postyield stiffness,  $k_p$ , and characteristic strength,  $Q$ . The characteristic strength,  $Q$ , is usually utilized to estimate the stability of hysteretic behavior when the bearing experiences many loading cycles. Figure 3 shows an idealized bilinear model based on test data.

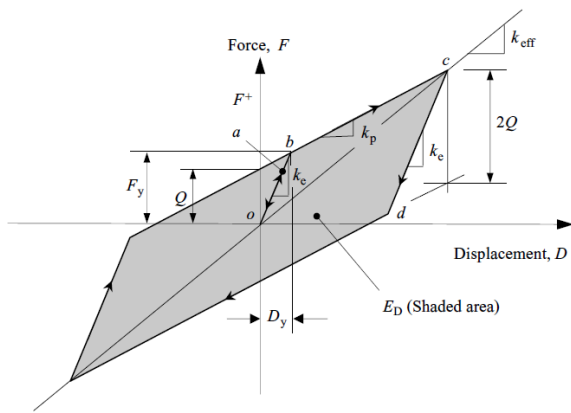


Figure 3. Bilinear model of isolator unit.

Effective stiffness of the bearing,  $k_{eff}$ , at the postyield region can be expressed in terms of the postyield stiffness,  $k_p$ , and the characteristic strength,  $Q$ , with corresponding lateral displacement,  $D$ .

$$k_{eff} = K_p + \frac{Q}{D} \quad (1)$$

Table 1

Values of isolation system damping

Effective damping, $\beta$ (percentage of critical)	$B_{vH}, B_{1D}, B_R, B_{1M}, B_{mD}, B_{mM}$ (where period of the structure $\geq T_0$ )
$\leq 2$	0.8
5	1.0
10	1.2
20	1.5
30	1.8
40	2.1
50	2.4
60	2.7
70	3.0
80	3.3
90	3.6
$\geq 100$	4.0

Equation 2 is an estimate of peak displacement in the isolation system for the design earthquake. In this equation, the spectral acceleration term,  $SDI$ , is the same as that required for design of a conventional, fixed-base structure of period,  $TD$ . A damping term,  $BD$ , is used to decrease (or increase) the computed displacement where the equivalent damping coefficient of the isolation system is greater (or smaller) than 5 percent of critical damping. Values of coefficient  $BD$  (or  $BM$  for the maximum considered earthquake) are given in Table 1 for different values of isolation system damping,  $\beta D$  (or  $\beta M$ ).

$$D_D = \left(\frac{g}{4\pi^2}\right) \left(S_{D1} \cdot \frac{T_d}{B_D}\right) \quad (2)$$

The isolation system for a seismically isolated structure should be configured to minimize eccentricity between the center of mass of the superstructure and the center of rigidity of the isolation system. In this way, the effect of torsion on the displacement of isolation elements will be reduced. As for conventional structures, allowance must be made for accidental eccentricity in both horizontal directions.

The effective (fundamental) period of an isolated structure is based on amplitude-dependent, nonlinear (pushover) stiffness properties of the isolation system. The effective periods,  $T_D$  and  $T_M$ , correspond to design earthquake displacement and maximum considered earthquake displacement, respectively, in the direction under consideration. Values of effective (fundamental) periods,  $T_D$  and  $T_M$ , are typically in the range of 2 to 4 seconds, and the value of the effective period,  $T_D$ , typically is 15 to 25 percent less than the corresponding value of effective period,  $T_M$ .

The yield displacement,  $D_y$ , which is conveniently used in some computer programs to define the bilinear model, is also derived from  $k_e$ ,  $k_p$ , and  $Q$ .

$$D_y = \frac{Q}{k_e - k_p} \quad (3)$$

The characteristic strength,  $Q$ , of the *lead-plug bearing* is dominantly controlled by the shear strength of the lead core. Shear yield occurs at the lead core under a low level of shear stress. Equation 4 exhibits the relation between the *characteristic strength*,  $Q$ , and the product of lead yield stress,  $f_y$ , and the *lead-plug area*,  $A_l$ .

$$Q = A_l f_{y1} \quad (4)$$

The *postyield stiffness*,  $k_p$ , is shown as follows:

$$k_p = \frac{A_b G f_L}{t} \quad (5)$$

Where  $A_b$  is the bonded area of rubber;  $t$  is the total rubber thickness; and the coefficient,  $f_L$ , is typically 1.5.  $G$  represents the *tangent shear modulus* of rubber, which is determined from dynamic shear tests.

The *elastic stiffness*,  $k_e$ , is not easily determined, but it can be approximately estimated as shown below:

$$6.5 k_p \leq k_e \leq 10 k_p$$

The yield force,  $F_y$ , at the yield displacement,  $D_y$  is determined as

$$F_y = Q + k_p D_y \quad (6)$$

The *effective damping*,  $\beta_{eff}$ , is defined as follows:

$$\beta_{eff} = \frac{ED}{2\pi k_{eff} D^2} \quad (7)$$

Where  $ED$  is the energy dissipated per cycle as shown in Figure 3. For the bilinear model,  $ED$  is considered as the area of the hysteresis loop bounded by the lateral displacement  $-D$  and  $+D$  at each cycle. Thus,  $ED = 4Q(D - D_y)$ , and the effective damping  $\beta_{eff}$ , becomes:

$$\beta_{eff} = \frac{4Q(D - D_y)}{2\pi k_{eff} D^2} = \frac{2Q(D - D_y)}{\pi k_{eff} D^2} \quad (8)$$

In design practice, the effective stiffness and the effective damping are determined at the design displacement,  $DD$ , and the maximum displacement,  $DM$ .

For nonlinear response history analysis, the following parameter of the bearing in both principal directions of the superstructure is required: The ratio of postyield stiffness to elastic stiffness,  $\eta = k_p/k_e$ .

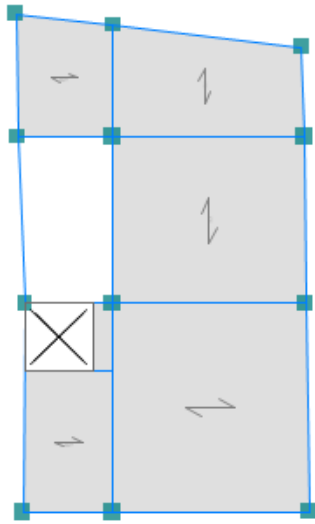
Table 2  
Base isolator parameters

$D_0$ (cm)	Diameter of Lead Plug (cm)	Isolator Height (cm)	G (MPa)
15	10	50	0.64
$F_{y1}$ (MPa)	$K_{eff}$ (Kg/m)	$D_y$ (cm)	$F_y$ (kg)
8.82	18855	2.5	7692.4
$K_p$ (Kg/m)	$\beta_{eff}$ (kg.sec/m)	$\eta$	
30144	32392	0.1	

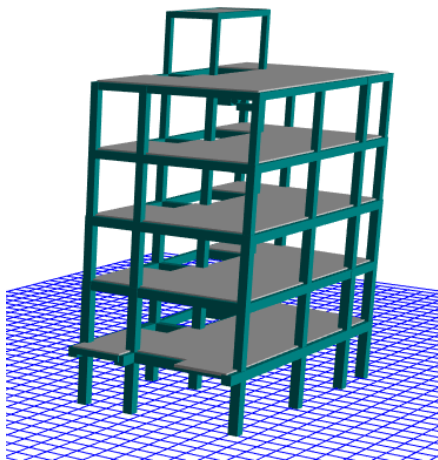
Table 2 shows a summary of parameters which are used for isolator modeling in ETABS.

#### 4. modeling of concrete frame

The intermediate concrete frame was modeled and designed by Etabs software. For seismic parameters Iranian 2800 (4<sup>th</sup> edition) code was employed. Also the response spectra used for analyzing and designing of structure. Figures 4(a) and 4(b) show typical story plane and 3D view of the modeled building.



(a)



(b)

Figure 4. (a) Typical plan of the building model, (b) 3D view of ETABS model

#### 5. Modeling of isolated structure

In this case study, there were 12 columns. So, 12 Lead-Plug Bearing are used under each column. The Isolator was modeled as a Rubber Isolator Link in Etabs. Model parameters of isolated structures were assigned according to table 2. The structure with isolator could be design by FEMA P-750-NEHRP Recommended Seismic Provisions [11]. Because the subjective of this study was the effect of Isolator, seismic parameters for isolated model and concrete frame model was identical. Figure 5 shows the isolators in the model.

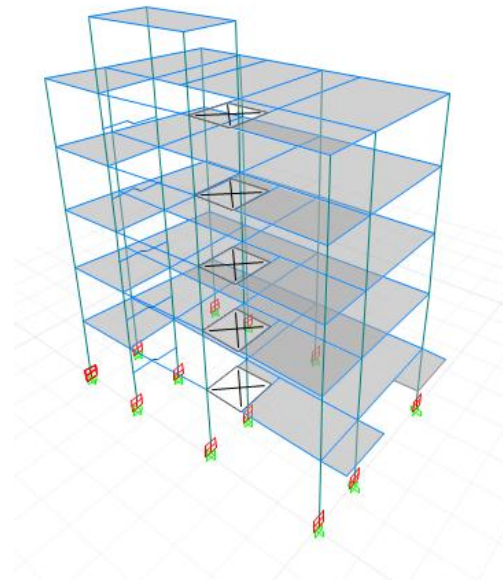
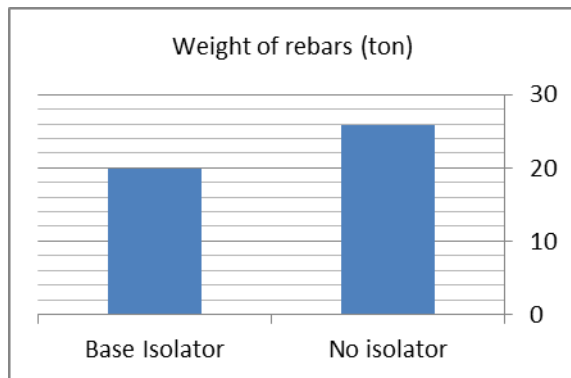


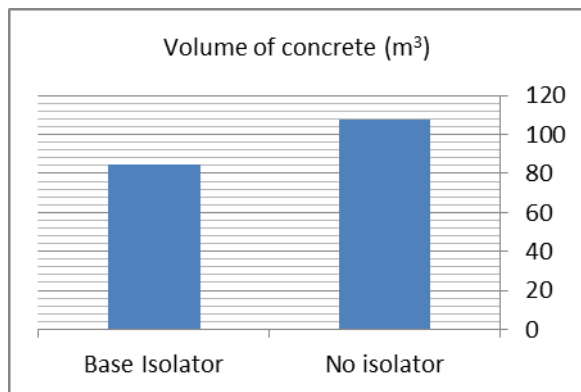
Figure 5. 3D view of Etabs model with isolator

## 6. Results and discussion

After designing the new model, due to the base isolator dimension of beams and columns decreases. The volume of concrete for building by isolator decreased about 21 percent for beams and columns in comparison of the none isolated building. Furthermore, the weight of rebar decreased about 23 percent. Figures 6 (a) and 6 (b) exhibit the differences of casting materials, including steel weight and volume of concrete respectively.



(a)



(b)

Figure 6. comparison of (a) weight of rebar and (b) volume of concrete for building with base-isolator and without base-isolator

Table 3

Period of building	Period of building			
	1st mode	2nd mode	3rd mode	4th mode
With base isolator	2.395	2.323	1.425	0.525
Without a base isolator	0.776	0.729	0.598	0.287

Table 3 demonstrates a comparison of period for two different case study models. The results show that the building without base isolator has a very small period in comparison of ordinary building without base isolator. The reason is the elastic properties of the base isolator.

## 7. Conclusions

In this study the effect of the base isolator investigated in casting cost of a five story residential building. The results show that using base isolator could decrease the weight of rebar and volume of concrete up to 20 percent in a concrete moment frame. However, the cost of isolators are not considered, but using the isolator would decrease the casting costs and furthermore will enhance the behavior of structure after ground motions which will lead to decrease the repair and maintenance cost of isolated building during the time.

## References

- [1] Wen YK, Shinozuka M. Cost-effectiveness in active structural control. *Eng Struct* 1998;20:216–21.
- [2] Kang YJ, Wen YK. Minimum lifecycle cost structural design against natural hazards. Urbana-Champaign: University of Illinois at Urbana-Champaign; 2000.
- [3] Hanai T, Fukuwa N, Mori Y, Minagawa T. Base-isolated houses with restricted displacement according to seismic

- grade and its life-cycle-cost. *J Struct Construct Eng* 2003;572:89–96.
- [4] Takahashi Y, Masaki N, Anahara K, Isoda H. Seismic risk management of a building in seismically active region. *J Struct Construct Eng* 2005;591:25–33.
- [5] Goda K, Hong HP. Optimal seismic design considering risk attitude, societal tolerable risk level, and life quality criterion. *J Struct Eng* 2006;132:2027–35.
- [6] Ellingwood BR, Wen YK. Risk-benefit-based design decisions for lowprobability/ high consequence earthquake events in Mid-America. *Prog Struct Eng Mater* 2005;7:56–70.
- [7] Naeim F, Kelly JM. Design of seismic isolated structures: from theory to practice. New York: John Wiley and Sons Inc.;1999.
- [8] Jangid RS, Kelly JM. Base isolation for near-fault motions. *Earthquake Eng Struct Dyn* 2001;30:691–707.
- [9] Jangid RS. Optimum lead-rubber isolation bearings for near-fault motions. *Eng Struct* 2007;29:2503–13.
- [10] CSI Analysis. Reference Manual for SAP2000, ETABS, and SAFE – Computers and Structures. Inc. Berkeley, California, USA, October 2005.
- [11] NEHRP, Recommended Provisions for the development of Seismic Regulations for New Buildings, Building Seismic Safety Council, Washington, D. C., 1994.