J-Researchers

JOURNAL OF CIVIL ENGINEERING RESEARCHERS

Seismic performance of concrete buildings with a reinforced moderate moment resisting frame with seismic isolators

Mohammad Nouripoor Azgomi [a,*], Masood Kafi [a]

[a]*Islamic Azad University ,Chaloos, Iran*

Abstract

During an earthquake, there are two main effectual factors causing damage to structural and non-structural members; The two factors are relative lateral displacements of stories (drift) and absolute acceleration of stories. In this study, seismic isolators have been considered as a solution for dealing with damages and their causing factors, because they can both decrease the relative lateral displacements and absolute acceleration of stories significantly. Consideration of a 5 story building which was modeled in ETABS software, showed that using a system of lead rubber bearing base isolator (LRB) can significantly reduce the relative displacements and shear forces of stories (on average, about 50%); so the structural design leads to the optimal degree.

Keywords: Base isolator, concrete moment frame, drift;

1. Introduction

During an earthquake, there are two main effectual factors causing damage to structural and non-structural members; The two factors are relative lateral displacements of stories (drift) and absolute acceleration of stories. So there are two design approaches for reducing the vulnerability of structural and non-structural members. First we should be aware that rigid buildings are favorable because they reduce the lateral displacement between two stories, but they cause many accelerations. In contrast, since flexible buildings have less energy absorption, they have less story accelerations in earthquake; but they have large displacements which are destructive to members that are sensible to lateral displacements. So we should seek an approach which can reduce both relative lateral displacements and absolute acceleration of stories, significantly. seismic isolators are an option to gain this goal. In fact, in the case of isolated structures, instead of changing the seismic capacity, the seismic demand of structure reduces through isolation [1-5].

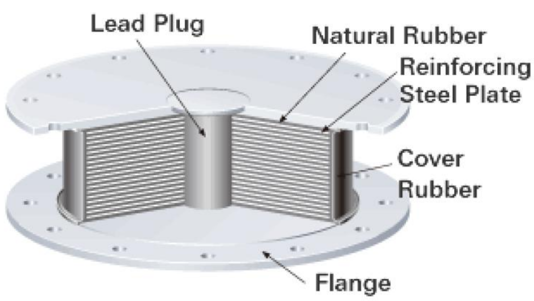
* Corresponding author. e-mail: masood_kafi@yahoo.com

This study examines the impact of the use of lead rubber bearing base isolator (LRB) in the seismic performance of moderate RC frames. A five story building has been modeled in ETABS as a case study.[Then in designed building, under each column a lead rubber bearing base isolator (LRB) is placed, and building analysis and design process runs again. Finally, the relative displacement, spectral acceleration and shear of stories are compared [5-7].

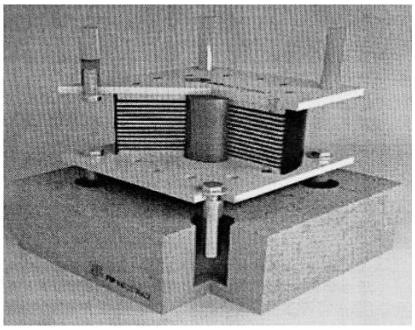
2. Lead rubber bearing base isolator

This type of isolator was invented in 1975 in New Zealand. As shown in Figure 1, it is composed of three main parts: layers of steel plates, rubber layers and lead core.

To enhance the damping effectiveness of elastomeric rubber isolators which are made with low attenuation rubber, one or more lead cores are used at their center. The lead core which is injected in the support hole by force, yields under the shears caused by earthquake in the low tensions about 8 to 10 Mpa and in the normal temperature and deforms physically. In this case, lead acts as an elastoplastic material or rolled crystallized, thus, under successive cycles of hysteresis loops shows two-line behavior and increases the attenuation of rubber from 3% up to 10 %. Lead core with rubber, causes initial rigidity for service loads and dissipates earthquake's energy input. In most cases, the secondary rigidity (plastic) has one-tenth to one-sixth of initial rigidity (elastic). Lead is chosen because the material doesn't encounter fatigue and has a stable performance in energy dissipation.



(a)



(b)

Figure 1. (a) Lead rubber bearing base isolator and (b) the section cut

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, ke, post yield stiffness, kp, 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 2 shows an idealized bilinear model based on test data.

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

$$k_{eff} = k_d + \frac{Q}{D} \tag{1}$$

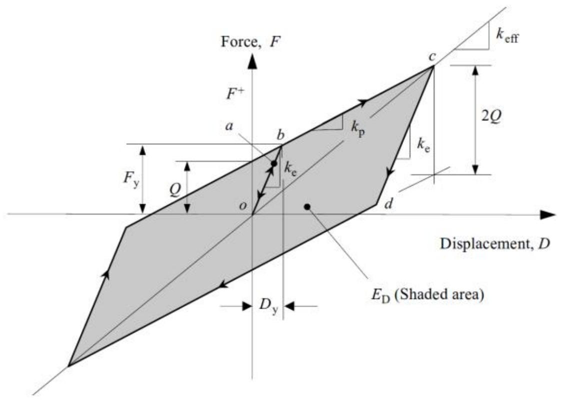


Figure 2. Bilinear model of isolator unit.

The yield displacement, Dy, which is conveniently used in some computer programs to define the bilinear model, is also derived from ke, kd, and Q.

$$D_y = \frac{Q}{k_e - k_d} \qquad (2)$$

The yield force, Fy, at the yield displacement, Dy is determined as

$$F_y = Q + k_d . D_y \qquad (3)$$

The *effective damping*, βeff , is defined as follows:

$$\beta_{eff} = \frac{E_D}{2\pi k_{eff} D^2} \qquad (4)$$

Where ED is the energy dissipated per cycle as shown in Figure 2. 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 = 4$Q(D-D$y*)*, and the effective damping βeff , becomes:

$$\beta_{eff} = \frac{4Q(D - D_y)}{2\pi k_{eff} D^2} = \frac{2Q(D - D_y)}{\pi k_{eff} D^2} \qquad (5)$$

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

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, $f$yl, and the *lead-plug area*, Al.

$$Q = A_1 f_{y1} \qquad (6)$$

The *postyield stiffness*, kd, is shown as follows:

$$k_d = \frac{A_b G f_L}{t} \qquad (7)$$

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:

$$6.5k_d \le k_e \le 10k_d$$

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, $\eta = k_d/k_e$.

Table 1: shows a summary of parameters which are used for isolator modeling in ETABS

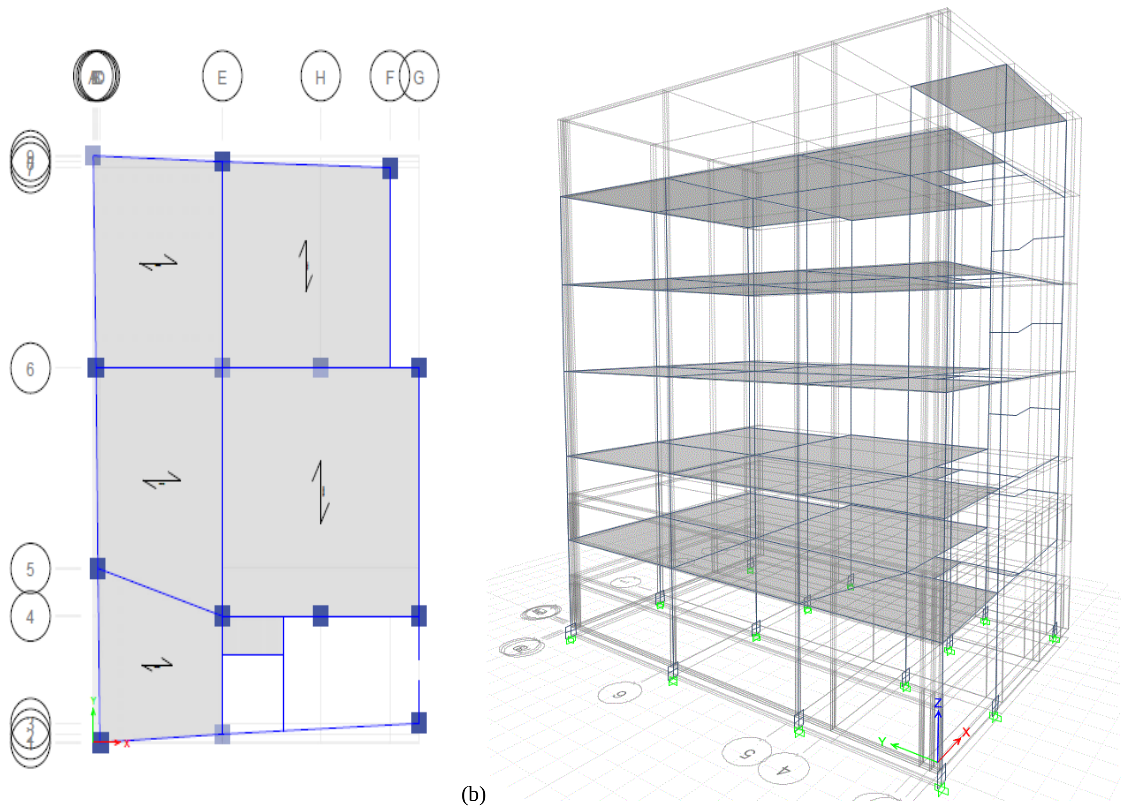
DD(cm)	Diameter of Lead Plug (cm)	Isolator Height (cm)	G (MPa)
11	6	35	0.64
Fy1 (MPa)	Keff (Kg/m)	Dy (m)	Fy (kg)
8.82	62635.6	0.0068	2769.19
Ke (Kg/m)	Ceff (kg.sec/m)	η	
405097.3	84156.13	0.1	

4. Modeling of concrete frame

The structure above the isolator is a five story concrete structure with a moderate moment resisting frame system which under each column an isolator is placed. For seismic parameters required for loading and Analysis, the code of practice for seismic resistant design regulations (standard no2800 - 4th edition) was used and all the modeling, analysis and design procedures were done in ETABS software[7]. Spectral analysis and ACI 318-14 were used for the sake of analysis and design phases, respectively. Figures 2 and 3, show the plan and the 3D model of five story building.

5. Modeling of isolated structure

There are two joint elements in ETABS. ISOLATOR1, is used for elastomeric isolators (HDRB, LRB) and ISOLATOR2 is used for friction pendulum isolators (FPS). Linear analysis like damping response spectrum analysis, is supplied by two resources: one of them is assigned damping for isolated superstructure and another is each ISOLATOR1 effective damping, which is assigned automatically in ETABS. For isolator modeling, the Rubber Isolator joint is used. For no-linear modeling of LRB isolator, we should define the incoming table 1 parameters in the software [3-6].



(a) (b)

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

6. Results and discussion

The five story structure with moderate moment resisting frame system, was analyzed and designed by Spectral analysis method and all of the required controls were done. Then by keeping the obtained sections and re-adding seismic isolators under each column, the analysis and design procedure is done again.

6.1. Period of the structure and the relative displacement of stories

As it is obvious from figures 4 and 5, the spectral acceleration has declined in the structure with seismic isolator compared with structures without it.

Table 3 - Period of the structure in two cases, with and without isolator.

	1st mode	2st mode	3st mode	4st mode
With base isolator	1.237	1.142	1.08	0.446
Without a base isolator	0.992	0.864	0.797	0.35

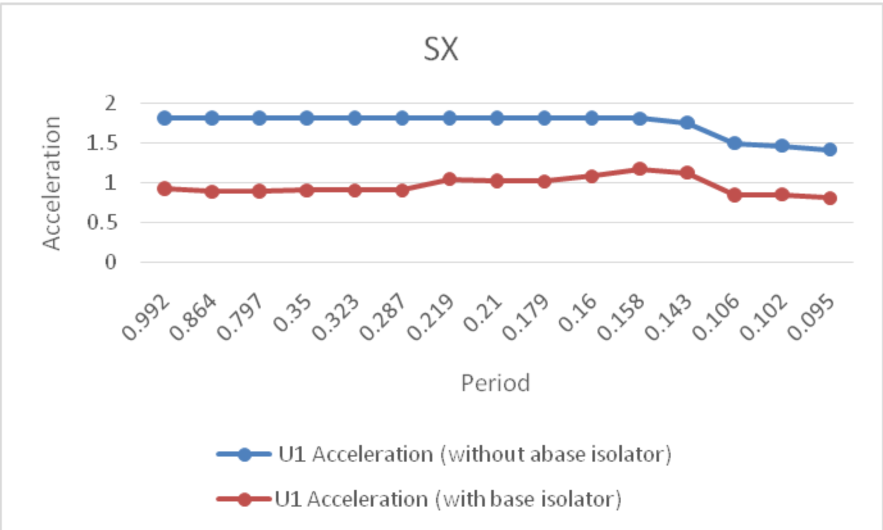


Figure 4 – Values of the spectral acceleration in two cases, with and without isolator, in X direction.

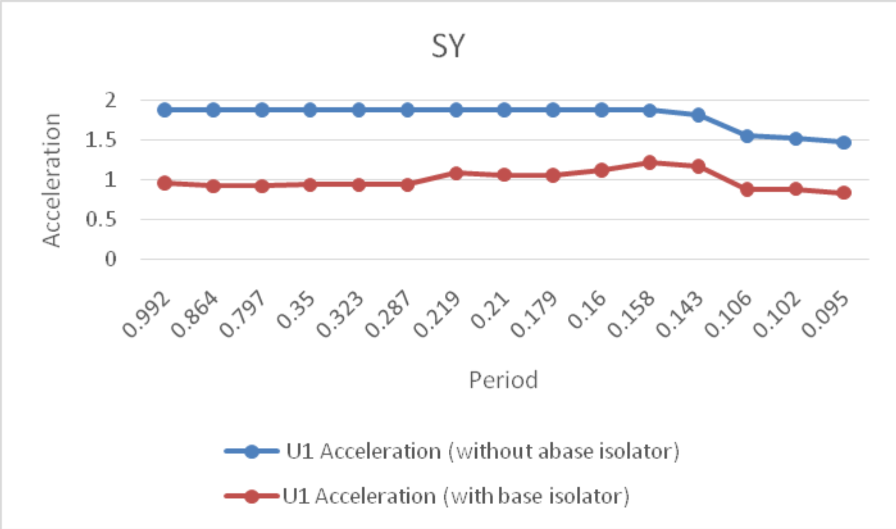


Figure 5 – Values of the spectral acceleration in two cases, with and without isolator, in Y direction.

As it is shown in the figures 6 and 7, in structure with seismic isolator the value of the maximum relative displacement is much less than structure without seismic isolator, due to focuses of displacement in the level of isolators.

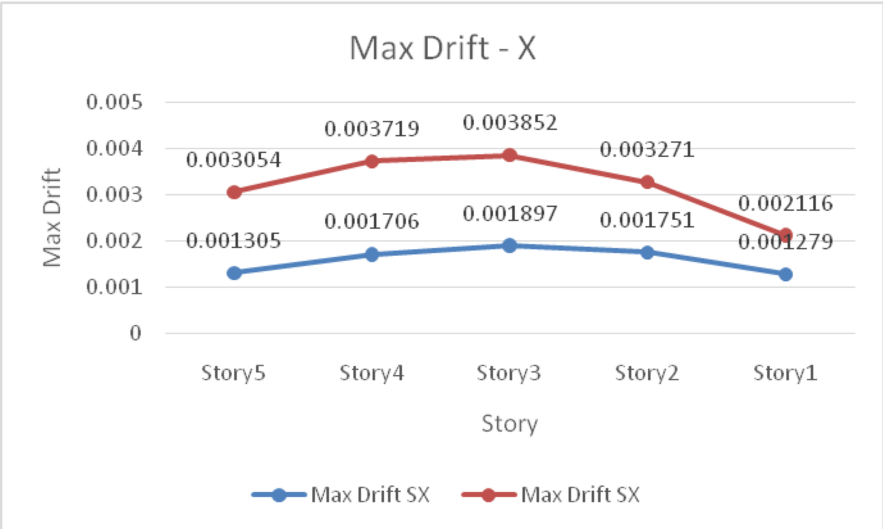


Figure 6 – The value of the maximum relative displacement in two cases, with and without isolateor, in X direction

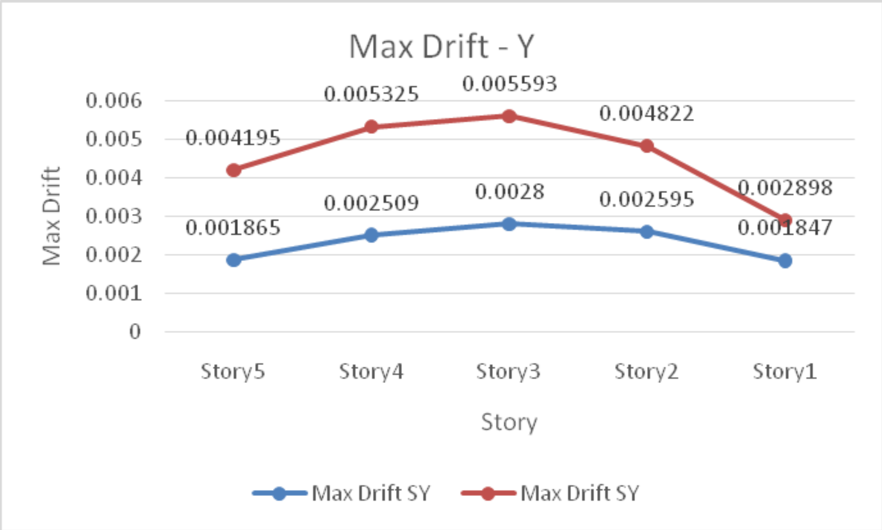


Figure 7 – The value of the maximum relative displacement in two cases, with and without isolator, in Y direction

6.2. Applied shear force to the floors

Because of the nature of isolators that reduce the acceleration and due to Keeping the weight of models constant in two compered ones, it can be easily predicted from the relationship between mass and acceleration forces that the shear force applied to the floors in the case of seismic isolator, decreases; also this issue is shown in the figures 8 and 9 in below.

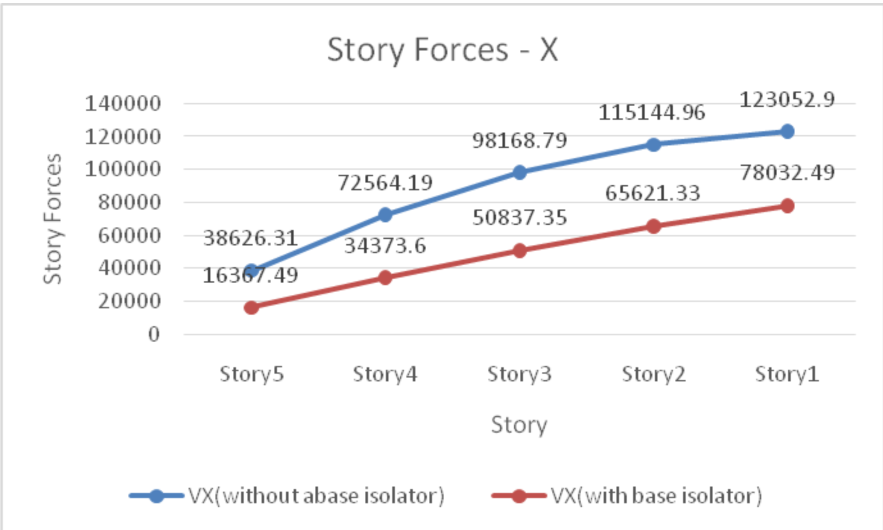


Figure 8 – The value of applied sheer force to the structure's floors in two cases, with and without isolator, in X direction

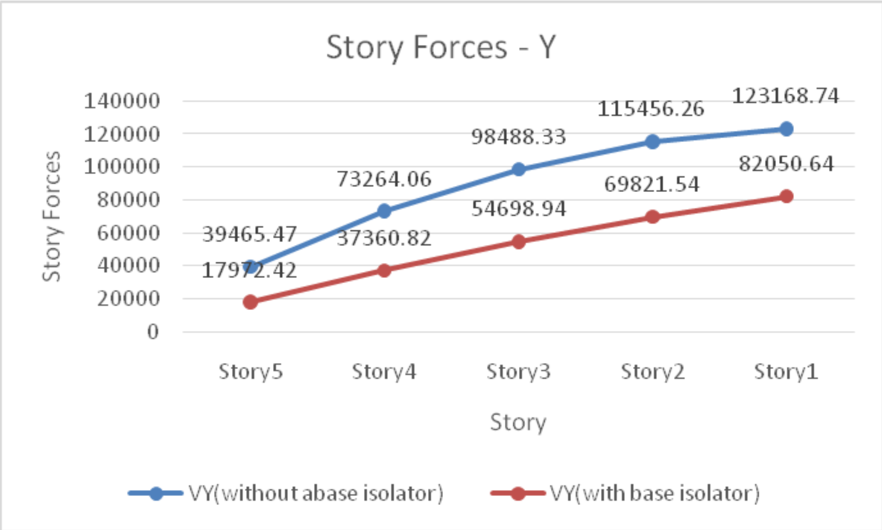


Figure 9 – The value of applied sheer force to the structure's floors in two cases, with and without isolator, in Y direction

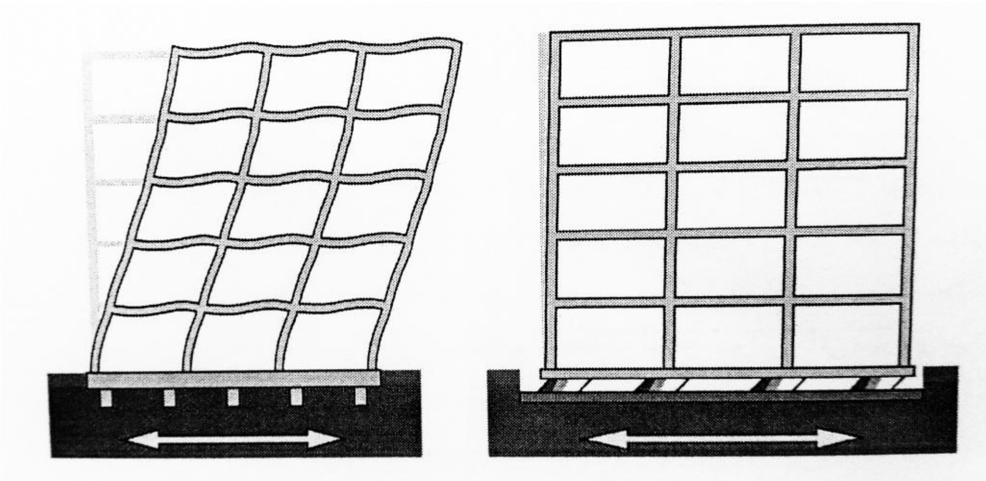


Figure 10 – comparison of base-isolated and fixed-based building

7. Conclusions

In this article a five-floor-building in two cases, with and without isolator, investigated. The results show that seismic isolators have the characteristic that by increasing the period of the system, the spectral acceleration will decrease, but in the other hand, the spectral displacement will increase. However, the interesting point is that this increased displacement, is the displacement of the isolators and originally the displacement of the floors will be reduced significantly. This amount was about 50% (in average) for the investigated building. So, it can be concluded that using seismic isolators result in improvement of seismic behavior of structure which ultimately could lead to some economic advantages in the construction and maintenance of the building.

References

[1] Kelly, Trevor E. " *Base isolation of structures : design guidelines.*" Holmes Consulting Group Ltd, New Zealand (2001).

[2] Yang, Yeong-Bin, Kuo-Chun Chang, and Jong – Dar Yau. "*Base isolation*." Earthquake Engineering Handbook(2003)

[3] Gomez. J.D, and et al , "*Design of Passive Dampers Against Earthquake*." Holmes Consulting Group (2001)

[4] Bagherinejad, K., Hosseini, S., & Charkhtab, S. (2017). Cost Viability of a Base Isolation System for the Seismic Protection of mid-rise reinforced concrete moment frames. Journal Of Civil Engineering Researchers, 1(1), 1-7.

[5] Sepehri, Ahmad, " *Analysis and Design of Dampers and Seismic Isolation*", Elme-omran, Tehran, 2014

[6] American Society of Civil Engineers (ASCE), *Minimum Design Loads for Building and Other Structures, ASCE/SEI 7-10*, 2010.

[7] Computer and Structures, Inc. (CSI), *CSI Analysis Reference Manual for SAP2000, ETABS, and SAFE*, Berkeley, California, 2005.

[8] Naeim, F. and Kelly, J.M., *Design of Seismic Isolated Structures: From Theory to Practice*, JohnWiley & Sons Inc., New York, 1999.

[9] Miyamoto,H . kit, and J.P.Singh. "*Performance of structures with passive energy dissipators.*" Earthquake spectra 18.1(2002):105-119

[10] Cheng,F.Y.,Jiang.H., & Lou,K. (2008). *Smart structures : innovative systems for seismic response control.* CRC Press.

[11] Constantinou , M . C., Soong,T.T., & Dargush, G.F. (1998). *Passive energy dissipation systems for structural design and retrofit.* Buffalo, New York: Multidisciplinary Center for Earthquake Engineering Research.

[12] U.S. Department of homeland security and Federal Emergency Management Agency (FEMA). " *Quantification of Building Seismic performance Factors (FEMA P695)''* Edition June 2009

[13] Kim, Young-Sun CHOUN1 Min-kyu, and S. E. O. Jeong-Moon. "*ANALETICAL AND EXPERIMENTAL STUDIES ON THE SEISMIC RESPONSE OF BASE ISOALTION SYSTEMS FOR ELECTRIC POWER EQUIPMENT." (2004)*

Appendix A. Calculation of seismic isolator

A.1. Characteristics selection for the desired rubber

Table A1 shows the characteristics of some rubber which were published in 1990 by Bridgestone company. In this Project, the rubber IRHD-50 will be used and its characteristics are shown in Table A2.

Table A1- the characteristics of some rubber

Rubber Hardness IRHD ±2	Young's Modulus E (N/cm²)	Shear Modulus G (N/cm²)	Modified Factor k
30	92	30	0.93
35	118	37	0.89
40	150	45	0.85
45	180	54	0.8
50	220	64	0.73
55	325	81	0.64
60	445	106	0.57
65	585	137	0.54
70	735	173	0.53
75	940	222	0.52

Table A2 - the characteristics of IRHD-50

E (N/cm^2)	220
G (N/cm^2)	64
K	0.73

A.2. Calculate the total height of rubber layers

Usually for designing purposes, the shear strain is considered less than 100%, while natural rubber is a viscoelastic substance which has the ability to achieve up to 300% shear strain without breaking its surface. According to recommendations of some reliable sources, in this section, the shear strain is considered 50%.

For buildings with desired isolators, we should consider an effective period and damping. In this design, effective period is three times more than the obtained period from the regulations and the effective damping is intended $\beta_1=0.15$.

$$\beta_1 = 0.15 \rightarrow B_D = 1.35$$

$$D_D = \left(\frac{g}{4\pi^2}\right)\left(S_{D1} \times \frac{T_d}{B_D}\right) = 0.11m$$

$$\gamma_{\max} = 0.50$$

$$t_r = \frac{D_D}{\gamma_{\max}} = \frac{0.11}{0.50} = 0.22m$$

D_D is an estimate of peak displacement in the isolation system for the design earthquake. In this equation, the spectral acceleration term, S_{D1}, is the same as that required for design of a conventional, fixed-base structure of period, T_D. A damping term, B_D, 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 B_D (or B_M for the maximum considered earthquake) are given in Table A3 for different values of isolation system damping, β_D (or β_M).

Table A3 - Values of isolation system damping

Effective damping, β (percentage of critical)	B_{V+I}, B_{1D}, B_R, B_{1M}, B_{mD}, B_{mM} (where period of the structure ≥ T_0
≤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
≥100	4.0

A.3. Lead Plug (core) design

Lead Plug design by taking hardness before and after yield as well as two liner behavior of the force – displacement. The following relationships can be established from compressive strength (Qd) and the amount of energy dissipated (Wd). The energy dissipated per cycle is equal to:

$$K_{eff}=\frac{4\pi^2}{g}\frac{W}{T_D^2}=\frac{4\pi^2}{9.81}\frac{880340.81}{2.01^2}=876898.75\,{}^{kg}\!/_{m}$$

$$k_{eff}=\frac{K_{eff}}{n}=\frac{876898.75}{14}=62635.60\,{}^{kg}\!/_{m}$$

$$W_D=2\pi k_{eff}D^2\beta_{eff}=2\times\pi\times 62635.60\times 0.11^2\times 0.15=714.30kg.m$$

$$Q_d\approx\frac{W_D}{4D}=\frac{714.30}{4\times 0.11}=1623.40kg$$

$$A_P=\frac{Q_d}{f_{py}}=\frac{1623.40}{882000}=0.00184=18.40cm^2$$

f_{py} is shear yield strength for the lead plug, which is considered 8.82MPa. Due to obtained area for the core, its diameter will be selected as 6 centimeters.

$$A_P=28.27cm^2$$

$$Q_d=0.002827\times 882000=2493.72kg$$

A.4. Calculation of shape coefficient

Shape coefficient is an efficient parameter in stiffness and vertical load capacity and its calculation for rubber isolators is considered by dividing ratio of bearing area of the isolator into its surrounding area.

$$\frac{K_v}{K_h} = \frac{\frac{E_c.A}{t_r}}{\frac{G.A}{t_r}} = \frac{E_c}{G} = \frac{E \times \left(1 + 2k.S^2\right)}{G} \geq 400$$

$$\frac{220\left(1 + 2 \times 0.73 \times S^2\right)}{64} \geq 400 \Rightarrow S \geq 8.9 \quad , \quad S > 10$$

$$use \quad S = 15$$

$$E_c = 22\left(1 + 2 \times 0.73 \times 15^2\right) = 7249 \, {}^{kg}\!/\!{}_{cm^2}$$

E_c : Elastic vertical pressure modulus

A.5. Effective cross-sectional area based on the allowable axial stress

The exact amount of the allowable axial stress should be determined by tests or confirmed reports of the Manufacture, but the experimental values are recommended between 6.9 to 8 N/mm. Hence, the area of the isolator can be calculated as follows:

$$\sigma_c = \frac{P_{DL+LL}}{A_0} \leq 80 \, {}^{kg}\!/\!{}_{cm^2}$$

$$A_0 = \frac{130282.20}{80} = 0.163 m^2$$

A.6. Effective cross-sectional area of the shear strain caused by the vertical force

ε_b is the maximum tensile strain for the rubber at rupture point which is considered 500% as recommended by the references.

$$6.S.\frac{P_{DL+LL}}{E_c.A_1} \leq \frac{\varepsilon_b}{3}$$

$$6 \times 15 \times \frac{130282.20}{72490000 \times A_1} \leq \frac{500\%}{3}$$

$$A_1 = 0.095 m^2$$

A.7. Elastic stiffness of isolator

Behavior of Lead Plug Isolators is a two-linear behavior in which K_u is elastic stiffness or stiffness of unloading and K_d is the stiffness after surrender. Since, the lead plug after surrender does not have stiffness, so the stiffness after yield is because of elastic stiffness (K_r).

$$K_{pd} = \frac{Q_d}{D} = \frac{2493.72}{0.11} = 22125.87 \, {}^{kg}\!/\!{}_{m}$$

hardness of lead plug

$$K_d = K_{eff} - K_{pd} = 62635.60 - 22125.87 = 40509.73 \, {}^{kg}\!/\!{}_{m}$$

$$K_d = K_r\left[1 + \frac{12A_p}{A_0}\right] \Rightarrow 40509.73 = K_r\left[1 + 12\frac{0.002827}{0.163}\right] \Rightarrow K_r = 33531.14 \, {}^{kg}\!/\!{}_{m}$$

A.8. Reduced cross-sectional of the shear strain isolator

$$A_{sf} = \frac{K_r.t_r}{G} = \frac{33531.14 \times 0.22}{64000} = 0.1153 m^2$$

$$\therefore \frac{\pi d^2}{4} = 0.1153 \Rightarrow d = 0.383 m$$

The reduced cross-sectional defined by remaining vertical cross-section after displacement. This reduced cross-sectional can be achieved by considering the shape of isolator as follows.

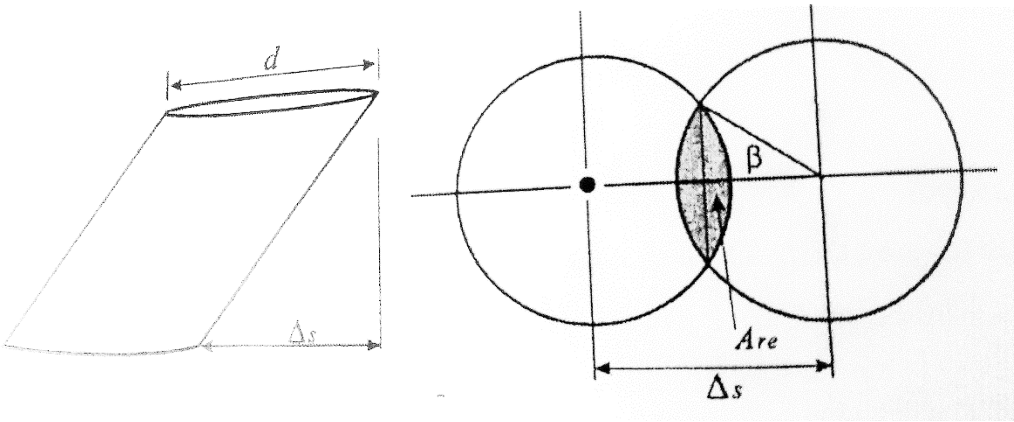


Figure A1- reduced cross-sectional of a circular isolator.

$$\beta = 2\cos^{-1}\left(\frac{\Delta_s}{d}\right)$$

$$\beta = 2\cos^{-1}\left(\frac{0.11}{0.383}\right) = 2.56$$

$$A_{re} = \frac{d^2}{4}(\beta - \sin\beta) = \frac{0.383^2}{4}(2.56 - \sin 2.56) = 0.0737m^2$$

A.9. The final area

$$A = \max(A_0, A_1, A_{re}) = \max(0.163, 0.095, 0.0737) \rightarrow A = 0.163m^2$$

$A_{total} = A_{rubber} + A_{Lead\ Plug} = 0.163 + 0.002827 = 0.1658\ m^2$

Use d= 0.6 m $\rightarrow$ A=0.2827 m^2 $\Rightarrow$

$$\beta = 2\cos^{-1}\left(\frac{0.11}{0.6}\right) = 2.76$$

$$A_{re} = \frac{0.6^2}{4}(2.76 - \sin 2.76) = 0.2155m^2$$

A.10. The number and thickness of the rubber layers

$$S = \frac{\frac{\pi d^2}{4}}{\pi d t} = \frac{d}{4t} \rightarrow t = \frac{d}{4s} = \frac{0.6}{4\times 15} = 0.01m$$

$$N = \frac{t_r}{t} = \frac{0.22}{0.01} = 22$$

A.11. Thick of steel sheets

$$t_s \geq \frac{2(t_i + t_{i+1}).P_{DL+LL}}{A_{re}.F_s} \geq 2mm$$

By using ST37 for sheets, we will have:

$$F_s = 0.6F_y \rightarrow For \quad ST37 \rightarrow F_s = 0.6\times 2400 = 1440\ ^{kg}/_{cm^2}$$

$$t_s \geq \frac{2\times(0.01+0.01)\times 130282.20}{0.2155\times 14400000} = 0.0017$$

$$use \quad t_s = 3mm$$

The overall thickness of each isolator unit is calculated by taking two sheets with 2.50 cm at the top and its bottom:

$$h = 2\times 2.50 + (N-1)t_s + t_r$$

$$h = 2\times 2.50 + (22-1)0.3 + 22 \cong 35cm$$