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Design of Base Isolation System for Buildings & Bridges

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Introduction

Seismic isolation is a modern technique used to seismically isolate structures from the ground at the base level. (It is also called base isolation.) Isolation is achieved by introducing the isolating system at the base or at selected locations in order to reduce the transfer of the ground motion effects to the structure. The significant advantage of seismic isolation is its ability to minimize the damage usually associated with earthquake events. However, the disadvantage of seismic isolation is that it may need to be replaced during the lifetime of the structure.

Over the past several decades, seismic isolation has gained in popularity and frequency of use, especially in bridges. Seismic isolation is considered the only practical solution for historical monuments if the superstructure itself cannot be modified or strengthened for obvious reasons.

Today, isolators for seismic isolation systems come in many different forms and designs. Lead-rubber bearing isolators are the most popular and perhaps the most economical. In addition, because elastomeric bearings are installed in bridges for non-seismic performance, including lead-rubber bearing isolators would only be a minor modification to the original bearings. Therefore, this course will focus on seismic isolation systems that use lead-rubber bearing isolators.

The Seismic Isolation Concept

The basic concept of seismic isolation can be illustrated by a helicopter-pier analogy. If a helicopter lands on a rigid pier as shown in Figure 1 (a), the helicopter experiences the same acceleration of the ground as it is transferred through the supporting rigid pier. However, if the helicopter takes off while connected to the ground by a wire (soft support), the helicopter does not feel any of the ground acceleration as shown in Figure 1 (b). Even though the helicopter does not feel the acceleration in the second case, it will experience the same displacement of the ground relative to its position.

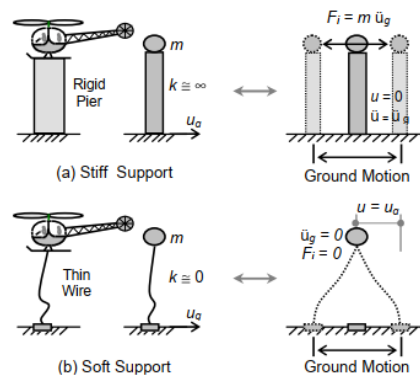


Figure 1. The Concept of Seismic Isolation

The same conclusion is reached when we examine the response spectrum properties. Recall that the response spectrum acceleration approaches zero as the period of the structure approaches infinity (soft support), while the response spectrum acceleration approaches the ground acceleration as the period approaches zero (stiff support). Figure 2 shows these limits for the El Centro earthquake. Note that isolators usually have large energy-dissipating elements that further reduce the forces and displacements of the system (see the effect of increased damping ratios in Figure 2).

In summary, the target of any seismic isolation system is to elongate the period of the structure to limit the transfer of the acceleration from the ground to the structure. This also implies that the structure experiences little force, if any. However, this action is associated with large displacements in the isolators that must be accommodated. Remember that seismic isolation is a tradeoff between large forces and large displacements.

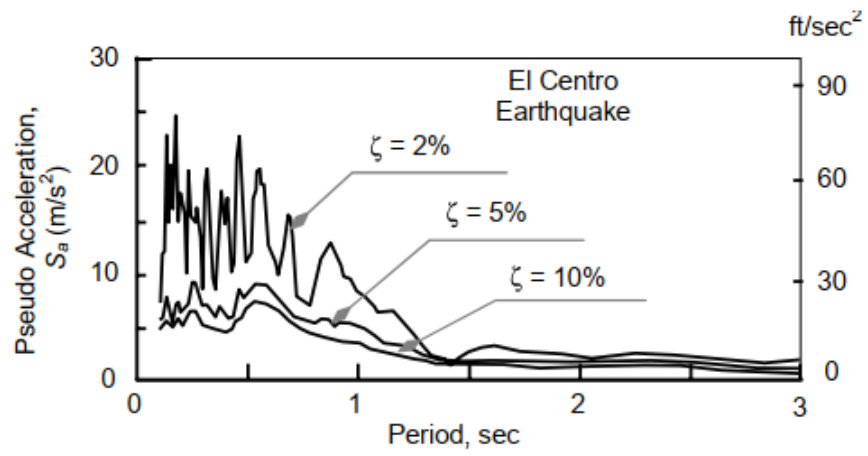


Figure 2. Response Spectrum

Lead-Rubber Bearing Isolator

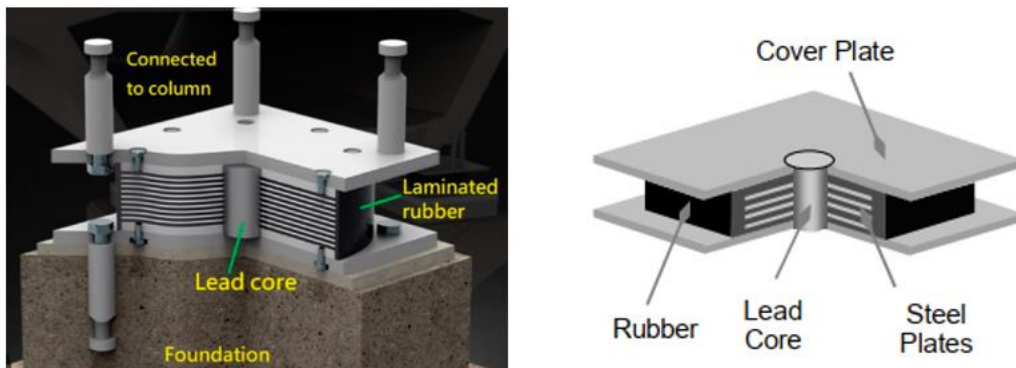


Figure 3. Lead-Rubber Bearing

As mentioned earlier, this course will consider the lead-rubber bearing isolation system as a model isolator to explore the concept and the design requirements for isolators in general. The lead-rubber bearing isolator consists of a rubber pad reinforced with laminated steel sheet as shown in Figure 3. A circular lead core is inserted in the middle of the rubber pad as shown in the same figure. The pad is then attached to two steel plates at both faces as an interface to connect the isolator with the structure.

The rubber used in these isolators consists of the same elastomeric material used in bridges with special specifications to accommodate seismic requirements. The rubber in this case serves as a soft material that provides soft support for isolation purposes. The rubber itself is not a good energy dissipater, as it is a purely elastic material. Furthermore, under regular loads, the structure may experience large uncomfortable displacements that are due to its low stiffness. In addition, the structure may be subjected to low-frequency vibration under normal conditions. Therefore, lead core is inserted in the middle of the rubber pad to handle these shortcomings.

It can be summarized the functions of its components as:

The Function of Laminated Rubber

- 1) The steel plate reinforced rubber will firmly support the structure. (Load supporting and rotational absorption function)

- 2) High rigidity in the vertical direction as compared to the single rubber provides with the stable support of the structure.
- 3) Transform the seismic vibration into a slow movement. (Horizontal Elasticity Function)
- 4) Softness in the horizontal direction will calm down the severe seismic vibration and make it a long-period vibration of the structure.
- 5) Returns the structure to the original position (Restoration function). The restoration force of the rubber will return the structure to the original position after the earthquake terminated.

The Function of Lead Plug

- 1) Damps the severe vibration of structure. (Vibration damping function)
- 2) The Lead Plug will be plastically deformed along with the deformation of laminated rubber to absorb the seismic energy, quickly damps the vibration, and controls the displacement due to the earthquake as well.
- 3) Depresses the vibration other than the earthquake (Trigger function)
- 4) High rigidity of the lead plug will hold the structure until the external force becomes as high as a certain level to prevent the vibration due to the traffic vibration or the strong wind.

As a material, lead has moderate stiffness and a large capacity of energy dissipation. As a result, it is considered ideal for this system to achieve three important goals:

1. Limit large displacements that are due to lateral forces under normal conditions because of its elastic stiffness.
2. Yield under seismic excitations at low force levels to activate the function of the rubber as an isolator.
3. Serve as a damper on account of its large energy dissipation capacity

The elastomer as a material is considered to be linear elastic. The properties of the elastomer depend on its hardness, which is usually specified by the manufacturer. In the absence of manufacturer data, the AASHTO code provides the shear modulus of elasticity and creep properties for elastomer at different hardness values. This information is also provided in Table 1 in Appendix 1 at the end of this course. In contrast, lead as a material exhibits ideal elasto-plastic behavior in shear. The lead properties in shear are also given in Table 2 in Appendix 1.

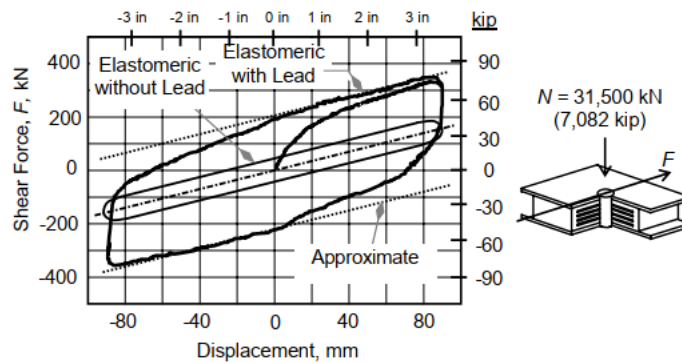


Figure 4. Lead-Rubber Bearing Hysteretic Behavior

When combined, elastomer and lead form an ideal system that exhibits ideal bilinear hysteretic behavior as shown in Figure 4. Extensive experimental testing was conducted on lead-rubber bearings under constant vertical load, N , and subjected to varying cyclic shearing force. Some test results are shown in Figure 4, which illustrates the contribution of both rubber and lead material to stiffness and to energy dissipation. The large elastic stiffness and large hysteretic loop are due to lead contribution. Upon yielding of lead, the overall effective stiffness of the bearing will only be the stiffness of the elastomer.

Analysis of Seismically Isolated Structures

Because of the relatively high stiffness ratio between the structure and the isolator, the structure is considered to behave as a rigid body with all deformations concentrated in the isolator as shown in Figure 5. With this assumption, the system may be treated as an equivalent single degree of freedom system with its mass concentrated in the building; the stiffness and displacements of the system are concentrated in the isolator.

Because the isolator properties are known through their hysteretic behavior, inelastic dynamic analysis can be used to analyze the system under any excitation. Indirect analysis using force reductions and ductility demand/capacity will also be valid.

In general, the system must be designed to meet the required specifications and the conditions of serviceability. Such requirements include, for example, the design of the bearing to carry the vertical gravity loads and to meet the strain limitations, a minimum yield force to resist wind during normal conditions, and a minimum displacement capacity (ductility capacity) to meet the expected large inelastic displacements during earthquake excitations.

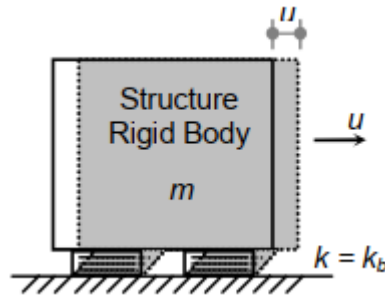


Figure 5. Seismic Isolation Model

Design of Seismically Isolated Structures

Design requirements of this section will be given according to AASHTO specifications for design of elastomeric bearings. According to AASHTO, elastomeric bearings with reinforcement steel sheets may be designed using the allowable stress design method. As indicated earlier, the bearing consists of a stack of elastomer layers and steel sheet layers bonded together.

The bearing components are typically arranged as shown in Figure 6, which are usually optimized by the manufacturer. To get a sense of the bearing details, view the following dimensions as general dimensions:

- The elastomer layer thickness (around 12 mm) between steel sheets is designated as h_{ri} .
- The total thickness of rubber layers is $h_{rt} = \sum h_{ri}$.
- The total thickness of bearing, including steel sheets and end plates, is designated as h_b .
- The thickness of steel sheets is typically taken as 3 millimeters.
- The end steel plates are typically taken as around 20 millimeters.
- The cover of elastomer around steel sheets is taken as around 12 millimeters.

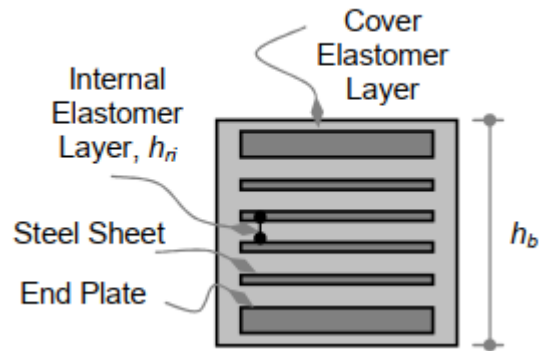


Figure 6. Typical Elastomeric Bearing Without Lead Core

The area of steel sheets is designated as the bonded area, which is considered the effective area in resisting bearing deformations. The overall dimensions of the bearing in plan are given as follows:

L = Dimension along the axis of the bridge.

W = Dimension perpendicular to the axis of the bridge.

A shape factor, S, is defined as follows:

$$S = \frac{\text{plan area}}{\text{free to bulge area}} = \frac{L W}{(L + W)(2)(h_{ri})}$$

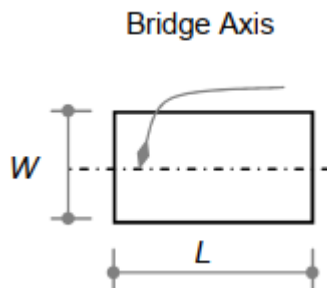


Figure 7. Bearing Dimensions in Plan

Allowable compressive stress

Allowable compressive stress of elastomer is given as a function of its shape factor defined earlier. The allowable compressive stress for steel reinforced bearings under dead and live loads, $\sigma_{c,all}$, is given as follows:

$$\begin{aligned}\sigma_{c,all} &= G.S/\beta \\ \sigma_{c,all} &\leq 7 \text{ MPa (1,000 psi)}\end{aligned}$$

where:

β = Factor taken as 1.0 for internal layers and as 1.4 for cover layer as defined in Figure 6.

G = Shear modulus of elasticity of the elastomer as given in Table 1.

S = Shape factor as defined earlier.

Bearings (as rubber material) are excluded from the impact effect of live loads.

Allowable shear deformation (shear strain)

The maximum shear strain in the bearing measured over pure rubber material is given as 0.5. This limitation implies that the total rubber thickness, h_{rt} , excluding steel sheets and end plates, must be at least

$$h_{rt} \geq 2\Delta_s$$

where:

Δ_s = Maximum top displacement of the bearing in the lateral direction (see Figure 9).

h_{rt} = Total rubber height of the bearing ($h_{rt} = \sum h_{ri}$).

Allowable rotation

The maximum rotation of the bearing plan surface, under the dead and live loads is limited to the following:

$$\begin{aligned}\theta &\leq 2 \Delta_d/L \\ \theta &\leq 2 \Delta_d/W\end{aligned}$$

where:

Δ_c = Instantaneous vertical compressive deflection of the bearing.

L, W = Bearing dimensions as given in Figure 7.

Θ = Rotation of the bearing, which is due to the rotation of the supported beam end.

The instantaneous vertical compressive deflection of the bearing is a function of the vertical stress. Unfortunately, the axial stress-strain relationship of rubber is nonlinear. Thus, the deflection is given in AASHTO by means of relation charts. Appendix 1 presents two charts of vertical stress versus vertical strain relationships for elastomer of two hardness grades of 50 and 60.

Stability requirements

The total thickness of the bearing is limited to a maximum to prevent the toppling and rolling of the bearing under large deformations. These limits are given for reinforced bearings as follows:

Rectangular bearings:	$h_b \leq L/3, W/3$
Circular bearings:	$h_b \leq D/4$

where:

D = Bearing diameter in case of circular bearings.

h_b = Total height of the bearing including steel sheets and end plates.

L, W = Bearing dimensions as given in Figure 7.

The requirements above may be waived if the manufacturer provides the bearing with positive mechanical connections to the structure that prevent the instability of the bearing. For example, an interface plate bolted to the superstructure may be considered as a waiver from this stability requirement as long as the manufacturer proves that his or her product is stable under loads.

Lead core dimensions

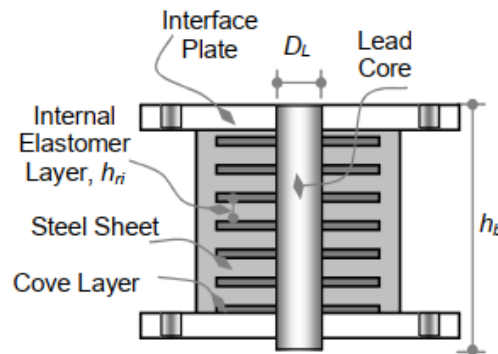


Figure 8. Typical Elastomeric Bearing with Lead Core

The lead core diameter, D_L , is recommended to be limited to the least bearing dimensions as follows:

$$D_L \leq B/3$$
$$D_L \geq B/6$$

where B is the least dimension of the bearing (a minimum of L , W or D).

This is not an AASHTO requirement. Instead, it is a recommendation given by lead-rubber bearing manufacturers. Figure 8 shows a typical arrangement of bearings with a lead core.

Shear stiffness

The bearing stiffness is given as a function of the shear stiffness because its response is basically in the shear mode as shown in Figure 9. For a given force, F_s , with displacement, Δ_s , the stiffness is evaluated as follows:

$$F_s = \tau A_r$$
$$= (G_r \gamma) A_r$$
$$= G_r A_r (\Delta_s / h_r)$$
$$= (G_r A_r / h_b) \Delta_s$$

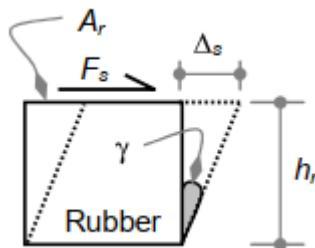


Figure 9. Bearing Stiffness

Consequently, the shear stiffness of the bearing is given as

$$k_r = G_r A_r / h_r$$

Similarly, the shear stiffness of the lead is given as

$$k_L = G_L A_L / h_b$$

where:

G= Shear modulus of elasticity.

L = Lead.

r = Rubber.

The design requirements given above are best illustrated by the following example

Guidelines for isolation system design

In this section a simple guideline for design base isolated structure is presented, the design procedure is summarized in the following steps:

- 1) Selection of the design ground spectrum that depends on the seismic area, the soil type and the structure importance factor
- 2) Selection of the target period of the isolated structure
- 3) Calculation of the isolation system horizontal stiffness to reach the target isolation period
- 4) Selection of the optimal location of the isolators in the structure support points in order to reach, as much as is possible, the coincidence between the center of mass and stiffness
- 5) Calculation of the structure base acceleration at the target isolation period
- 6) Reduction of the base acceleration by considering the damping capacity of the isolation system
- 7) Calculation of the isolator's horizontal displacement
- 8) Design of the isolators according to the reference code
- 9) Once the isolator design has been completed, detailed design of the support (isolators plinth and local reinforcement) must be completed. Note that all around the structure sufficient gap must be provided in order to allow the horizontal movement due to earthquake (normally the gap must be covered by joints that could be simple plates or more complex where required for example in area where there is car transit, etc.)
- 10) For particular application when required a fire protection to the isolator can be provided.

Installation

The installation procedure of isolators generally depends on the structure type. The main steps are:

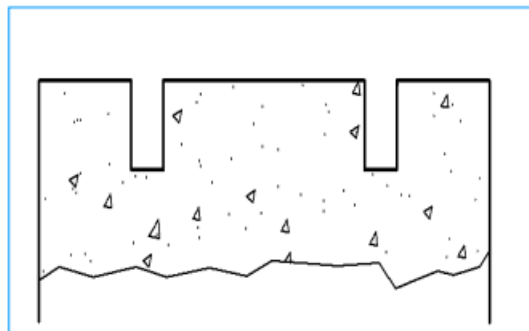
1. Check before installation.

In order to avoid placements mistakes of the bearings, all the technical and description data, printed on the label, shall be checked and compared with the ones showed in the shop drawings.

2. Casting of the substructures.

Substructures shall reach a level about 30 mm lower than the final level.

In order to install the isolators suitable voids spaces must be provided to insert the isolator lower anchor bars. An easy way to leave the voids is to use corrugated steel pipes grouted into the concrete with a diameter at least double compared with the diameter of the anchor bars.



3. Bearing positioning and substructure casting.

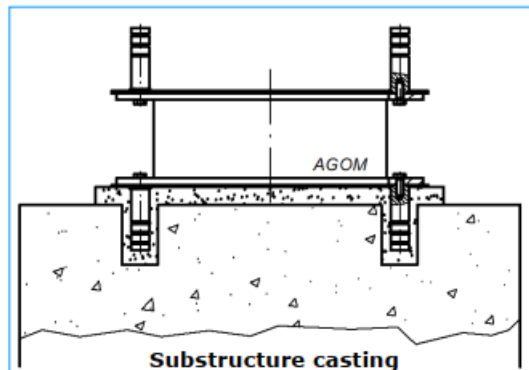
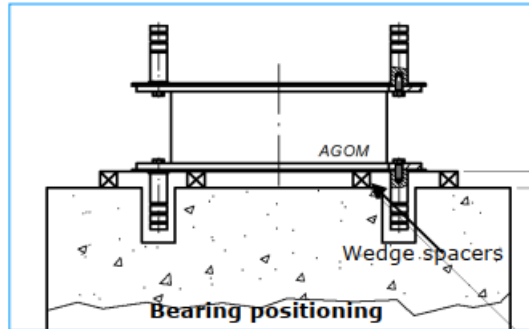
The isolators are placed at the final exact level supporting it by temporary wedge spacers; the maximum deviation from the horizontal plan does not exceed 0.001 radians.

In order to fix the isolators and anchor bars a formwork around the lower base plate must be provided (normally a wood or steel formwork is used).

To grout the isolator a high strength non-shrink, quick setting cement mortar with compression strength > 45 MPa has to be used; if the thickness of the mortar exceeds 40 mm a suitable reinforcement shall be provided.

The temporary wedges used to keep the isolator in right position shall be removed after mortar hardening and remaining voids shall be filled by the same mortar.

The level of the cement mortar shall not exceed bottom level of the isolators steel lower plate to avoid bearings embedding compromising the eventual future isolator replacement.

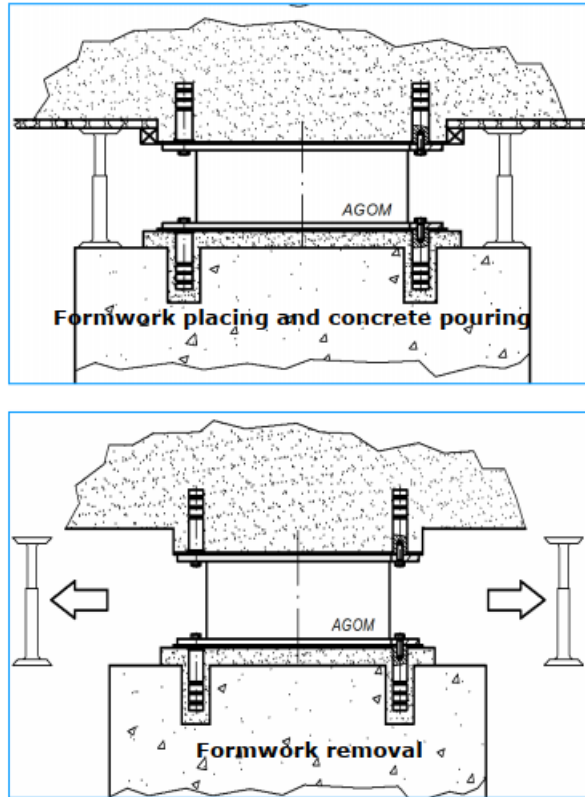


4. Casting of the superstructure – cast-in-situ superstructure

Superstructure formwork must be arranged around the isolator upper steel plate and sealed with adhesive tape or foam to avoid concrete leakage during casting.

The formwork must be arranged in a suitable way to avoid embedding of the isolator upper plate into concrete to avoid bearing embedding compromising the eventual future replacement. The formwork must be supported at the design level during concrete pouring.

When the concrete has reached adequate resistance the supports and formwork have to be removed. At the end of the construction the isolators must be cleaned and the painting of the steel plates repaired if some damages occurred during construction.



5. Casting of the superstructure – prefabricated superstructure

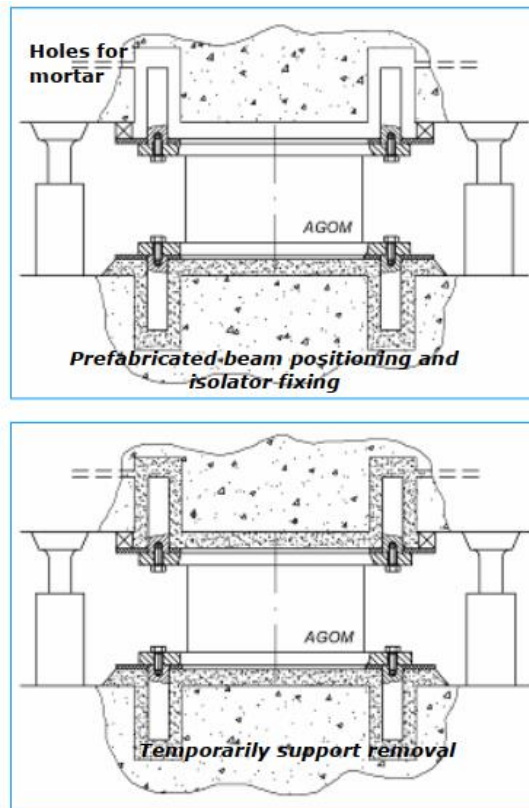
The isolators normally have upper anchorages that must be inserted into the suitable voids of the prefabricated structure.

After the prefabricated beam has been placed in the final position (the beam must be supported on temporary supports), the isolator upper plate must be surrounded by a seal (normally rubber seal with suitable injection and leakage pipes).

The gap and anchorages voids between plate and beam have to be filled by high strength mortar.

When the mortar has achieved sufficient strength to transmit the weight of the bearings, the temporary supports shall then be removed.

At the end of the construction, the isolators must be cleaned and the painting of the steel plates repaired if some damages occurred during construction.



EXAMPLE 1:

A single-span bridge is shown in Example 1, Figure 10. The deck is supported by two longitudinal girders. The bridge lies in a seismic zone with a seismic coefficient of A equal to 0.2. The site is of Soil Type II. The total weight of the bridge is 1,000 kN (224.82 kip). The bridge is subjected to a total live load of 500 kN (112.41 kip).

Also relevant, the short-term forces that are due to wind, braking forces, and others are 50 kN. Shrinkage and temperature displacement is 5 millimeters.

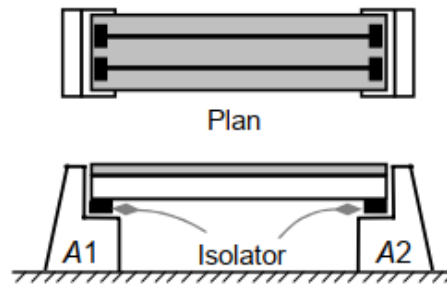


Figure 10. Bridge Layout

The available isolators are lead rubber bearings with a response spectrum provided by the manufacturer. The response spectrum is given in Example 1, Figure 11, for normalized $A = 1$ and for Soil Type I (for rock sites). For any other soil type, the response spectrum must be multiplied by the site amplification factor, S . The isolators also behave according to the equal displacement criterion: elastic and inelastic displacements are equal under earthquake excitation. The elastomer has a shear modulus of elasticity of 1.0 MPa (145 psi) layered at 12 millimeters (0.47 inches).

Use these rubber-lead bearings to isolate the bridge.

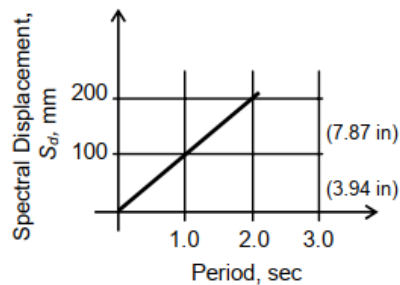


Figure 11. Response Spectrum (Normalized to $A = 1.0$)

SOLUTION:

Because the bridge has two main girders, two isolators are needed for each girder, resulting in a total of four isolators placed as shown in Figure 10. The design must be carried out in two stages. First, the bearings must be designed for dead and live loads and any other loading specified by the code. In this example, and for our objectives, our design will be limited to treatment of dead, live and seismic load effect.

The bearings will be designed of the same height. Therefore, all loads will be equally divided by the number of bearings (by 4).

Part 1: No seismic dimensioning:

(1) Each bearing's share of gravity loads:

$$D = 1,000/4 = 250 \text{ kN (56.21 kip)}$$

$$L = 500/4 = 125 \text{ kN (28.10 kip)}$$

(2) Plan dimensions by trial and error since allowable stresses are a function of the shape factor. Start with $\sigma_{c,all} = 7 \text{ MPa (1,000 psi)}$:

$$A_{req} = (D + L) / \sigma_{c,all} = (250 + 125)(1,000)/7 \\ = 53,571 \text{ mm}^2 (83 \text{ in}^2)$$

Try 231 x 231 millimeters to find the new allowable stress.

$$\text{Shape factor: } S = \frac{L W}{(L + W)(2)(h_{ri})} = \frac{231(231)}{(231 + 231)(2)(12)} = 4.82 \\ \sigma_{c,all} = G.S/\beta = 1.0(4.82)/1 = 4.82 \text{ MPa (699 psi)}$$

$$\text{Therefore, } A_{req} = (250 + 125)(1,000)/4.82 \\ = 77,800 \text{ mm}^2 (120.6 \text{ in}^2)$$

Try 279 x 279 millimeters (11 x 11 inches) to find the new allowable stress.

$$\text{Shape factor: } S = \frac{L W}{(L + W)(2)(h_{ri})} = \frac{279(279)}{(279 + 279)(2)(12)} = 5.81$$

$$\sigma_{c,all} = G.S/\beta = 1.0(5.81)/1 = 5.81 \text{ MPa (842 psi)}$$

Therefore,

$$A_{req} = (250 + 125) (1,000)/5.81 \\ = 64,544 \text{ mm}^2 (100 \text{ in}^2) \\ = 254 \times 254 \text{ mm (10 x 10 in)}$$

Use 280 x 280 millimeters (11 x 11 inches) for overall dimensions. With 20 millimeters (0.787 inch) horizontal cover on each side, the bonded area becomes 240 x 240 millimeters (9.45 x 9.45 inches).

(3) Shear deformations: $h_{rt} \geq 2s = 2(5) = 10 \text{ mm (0.39 in)}$

Use 1-layer, 12 mm each: $h_{rt} = 12 \text{ mm (0.47 in)}$

(4) Rotation should also be checked. This check would be completed in a straightforward fashion as a function of the rotation of the girder ends.

(5) Stability check:

Because this type of bearings has a positive interface connection, the stability limits may be waived. If desired, the stability check for such bearing may done as follows:

Height limit = $L/3 = 280/3 = 93 \text{ mm (3.66 in)}$

Total bearing height, h_b , is given as follows:

1-layer rubber	12 mm (0.47 in)
0-layer of steel sheets, 3 mm (0.12 in) each:	0 mm (0.0 in)
2-end plates, 12 mm (0.47 in) each:	24 mm (0.94 in)
2-cover layers, 3 mm (0.12 in) each:	6 mm (0.24 in)

Therefore, $h_b = 12 + 0 + 24 + 6 = 42 \text{ mm} < 93 \text{ mm OK}$
(1.65 in < 3.66 in OK)

(6) Lead core diameter:

$DL \leq B/3 = 280/3 = 93 \text{ mm (3.66 in)}$

$DL \geq B/6 = 280/6 = 47 \text{ mm (1.85 in)}$

Use 50 millimeters (1.97 inches) diameter core. As a result, the yield force of the core, F_y , will be

$A_L = \pi D_L^2/4 = \pi (50)^2/4 = 1,963 \text{ mm}^2 (3.04 \text{ in}^2)$

$F_y = \tau_y A_L = 10(1,963) = 19,630 \text{ N (19.63 kN) (4.413 kip)}$

(7) Seismic forces:

Bonded area of rubber: $A_r = A_{\text{bond}} - A_L = (240)^2 - (1,963)$
 $= 55,637 \text{ mm}^2 (86.24 \text{ in}^2)$

Rubber stiffness: $k_r = G_r A_r / h_{rt} = 1.0(55,637) / 12$
 $= 4,636 \text{ N/mm} (26.49 \text{ kip/in})$

Lead stiffness: $k_L = G_L A_L / h_b = 130(1,963) / 42$
 $= 6,076 \text{ N/mm} (34.72 \text{ kip/in})$

Total stiffness:

$$k_b = k_r + k_L = 4,636 + 6,076$$

$$= 10,712 \text{ N/mm} (61.21 \text{ kip/in})$$

Yield displacement of the lead core:

$$\Delta_y = F_y / k_L = 19,630 / 6,076 = 3.2 \text{ mm} (0.13 \text{ in})$$

Period: $T = 2\pi \sqrt{\frac{W}{g K_b}} = 2\pi \sqrt{\frac{250}{9.81(10,712)}} = 0.306 \text{ sec}$

Using the response spectrum from Example 1, Figure 11, the maximum displacement for rock sites and $A = 0.2$ is given as

$$\Delta_{\text{rock}} = S_d = 0.2(100) (0.306) = 6.12 \text{ mm} (0.24 \text{ in})$$

$$\Delta_{\text{EQ}} = S_v \Delta_{\text{rock}} = 1.2(6.12) = 7.34 \text{ mm} (0.29 \text{ in})$$

Because $\Delta_{\text{EQ}} > \Delta_y$, the lead yields under earthquake excitation. The earthquake-induced force may now be calculated as follows:

$$F_r = k_r \Delta_{\text{EQ}} = 4,636 (7.34) = 34,047 \text{ N} (7.65 \text{ kip})$$

$$F_{\text{EQ}} = F_{\text{LC}} + F_r = 19.63 + 34.05 = 54 \text{ kN} (12.14 \text{ kip})$$

If one wants to reduce the earthquake forces, the bearing height may be increased. For example, if four layers of rubber are used, the earthquake force may be calculated by repeating the calculations above as follows:

Total bearing height, h_b , is given as follows:	
4-layer rubber:	48 mm (1.89 in)
3-layer of steel sheets, 3 mm (0.12 in) each:	9 mm (0.35 in)
2-end plates, 12 mm (0.47 in) each:	24 mm (0.94 in)
2-cover layers, 3 mm (0.12 in) each:	6 mm (0.24 in)

Therefore, $h_b = 48 + 9 + 24 + 6 = 87 \text{ mm (3.43 in)}$

Bonded area of rubber: $A_r = A_{\text{bond}} - A_L = (240)^2 - (1,963)$
 $= 55,637 \text{ mm}^2 (86.24 \text{ in}^2)$

Rubber stiffness: $k_r = G_r A_r / h_{rt} = 1.0 (55,637) / 48$
 $= 1,159 \text{ N/mm (6.62 kip/in)}$

Lead stiffness: $k_L = G_L A_L / h_b = 130 (1,963) / 87$
 $= 2,933 \text{ N/mm (16.76 kip/in)}$

Total stiffness: $k_b = k_r + k_L = 1,159 + 2,933$
 $= 4,092 \text{ N/mm (23.38 kip/in)}$

Yield displacement of lead core:

$$\Delta_y = F_y / k_{LC} = 19,630 / 2,933 = 6.7 \text{ mm (0.26 in)}$$

Period: $T = 2\pi \sqrt{\frac{W}{g K_b}} = 2\pi \sqrt{\frac{250}{9.81(4,092)}} = 0.496 \text{ sec}$

Using the response spectrum from Example 12-1, Figure 2, the maximum displacement for rock sites is given as

$$\Delta_{\text{rock}} = S_d = 0.2(100)(0.496) = 9.92 \text{ mm (0.39 in)}$$

$$\Delta_{EQ} = S \cdot \Delta_{\text{rock}} = 1.2(9.92) = 11.9 \text{ mm (0.47 in)}$$

Because $\Delta_{EQ} > \Delta_y$, the lead yields under earthquake excitation. The earthquake-induced force may now be calculated as follows:

$$F_r = k_r \Delta_{EQ} = 1,159(11.9) = 13,792 \text{ N (3.1 kip)}$$

$$F_{EQ} = F_L + F_r = 19.63 + 13.79 = 33 \text{ kN (7.42 kip)}$$

By increasing the bearing height, the value of seismic forces has dropped to half of its previous value.

This system of lead-rubber bearing has been extensively used in buildings and bridges worldwide over the past three decades. Many real-life examples from the United States, Japan and New Zealand are cited by Skinner et al., 1993. Some of these examples include, for example, Salt Lake City and County Building in Utah, and Sierra Point Bridge in California (US 101) in the United States, and Moonshine Bridge in Upper Hunt in New Zealand.

Appendix 1

Sheet 1 Material Properties of Elastomeric Bearings

Table 1. Elastomer Properties at Different Hardness Levels According to the AASHTO Code

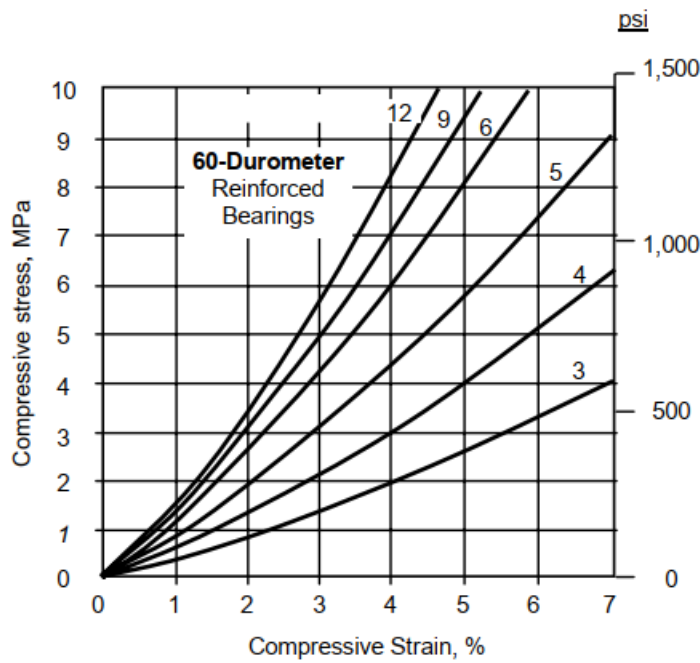
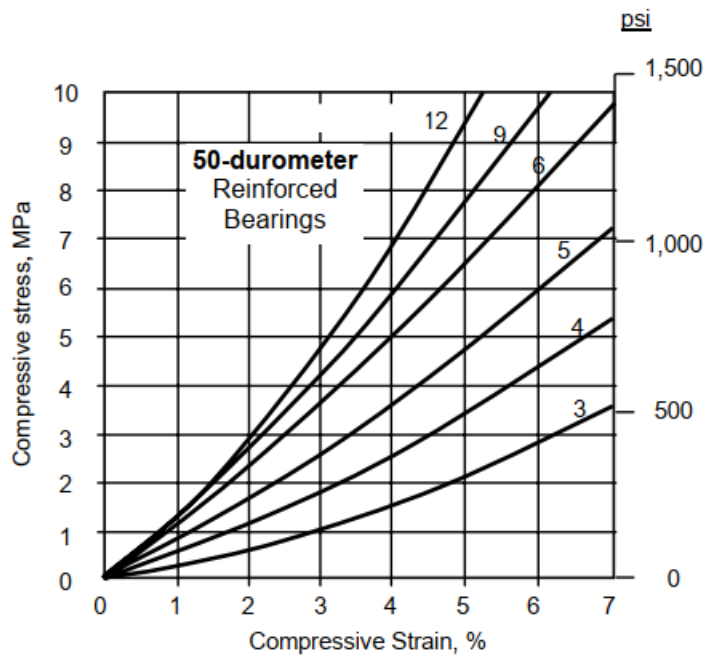
Hardness	50	60	70
Shear modulus, G: at 23° C. (MPa) at 73° F. (psi)	0.68 – 0.93 (95 – 130)	0.93 – 1.43 (130 – 200)	1.43 – 2.14 (200 – 300)
Creep deflection at 25 years as percentage of instantaneous deflection	25%	35%	45%

As a material, lead exhibits ideal elasto-plastic behavior in shear. The lead properties in shear are given in Table2.

Table 2. Properties of Lead Material

Shear modulus, G	130 MPa (18.85 ksi)
Yield stress in shear, τ_y	10 MPa (1.45 ksi)

Sheet 2 Stress-Strain Relationship of Elastomer at Hardness 50 and 60



References

1. AASHTO, “Standard Specifications for Highway Bridges”, Division I-A, 15th ed., American Association of State Highway and Transportation Officials, Washington, DC, 1992.
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5. ICC, “International Building Code”, International Code Council, Washington, DC, 2006.
6. Skinner, R. I, Robinson, W. H., and McVerry, G.H., An Introduction to Seismic Isolation, Wiley, New York, 1993.