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# DESIGN OF BASE-ISOLATED HIGHWAY BRIDGES

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## SUMMARY

An optimum seismic design for highway bridges should provide a reasonable balance between the shear forces transmitted to the supports and tolerable deck displacements. A simple design procedure is proposed for base-isolated highway bridges using the inelastic response spectra approach. Simplified charts are presented which provide a design aid for new bridges as well as the retrofitting and upgrading of existing ones. The method is shown to be simple and reasonably accurate. It takes into account the flexibility of the pier and is suitable for code type approach.

## INTRODUCTION

Highway bridges are an essential link in the transportation lifeline system. They are required to remain in service during and after an earthquake event. The majority of highway bridges are two to four lanes, simple span or continuous over a number of supports with fairly rigid decks in the horizontal plane. Long span bridges, bridges with curved decks or suspension bridges are normally regarded as special cases. Recent earthquakes caused substantial structural damage to highway bridges. As a result, much stricter codes of bridge design are now in use. The main seismic design approaches are the New Zealand Code (Highway bridge design brief, 1978) (Ref. 1) and the Caltrans (California Transportation) criteria which was recently adopted by AASHTO (1983) (Ref. 2). Although the design philosophy and procedures are quite different in the two codes, the resulting designs are similar. In the current design philosophy for highway bridges it is recognized that it is uneconomical to design the bridge to behave elastically during a major earthquake. The ductile approach to bridge design is not without its problems. Some of the difficulties encountered in the ductile design include the need for complex inelastic analysis, proper detailing of sections during design and construction, concerns for stability and permanent deformation.

Base-isolation techniques provide an alternative approach for seismic design of many new bridges as well as a convenient way of upgrading existing bridges. When appropriate, the use of special energy dissipating devices between the superstructure and the substructure can significantly reduce the forces induced in the bridge structure as compared to non-isolated bridges. An example of the efficient base-isolation system is the lead-rubber bearing (Ref. 3) shown in fig. 1. The main function of the base-isolation technique is to decouple the structure from the support. The flexibility of the bearing pads cause a period shift for the structure normally to the longer period range. Some base-isolation systems provide energy dissipation mechanisms through the hysteresis behaviour of the bearing. With base-isolation, the bridge pier can be designed to remain elastic during a severe earthquake and at the same time achieve an economic design. Most base-isolation devices can be easily replaced after a damaging earthquake by jacking up the superstructure.

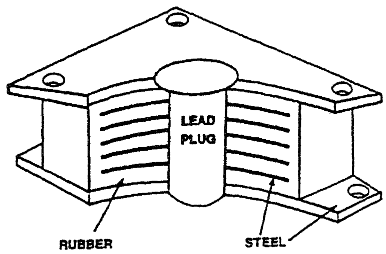


Fig. 1: Typical square lead-rubber bearing

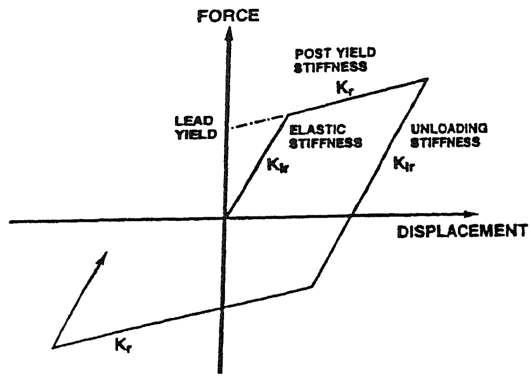


Fig. 2: Idealized force-displacement relationship

The objective of this investigation is to develop a simple method for the seismic design of highway bridges with lead-rubber base-isolation system. The design procedure is applicable to a wide range of bridges and takes into account the pier flexibility and location of bearings.

## APPROACH TO DESIGN

The process of seismic design of highway bridges using lead-rubber base-isolation involves the determination of the following:

- the size and location of the elastomeric bearing and lead inserts
- the seismic forces for pier and abutment design
- the maximum displacement of the bridge deck and bearings.

The proposed design method is developed using the inelastic response spectrum approach. The bridge system is represented by an equivalent single degree of freedom oscillator. The spring stiffness of the equivalent system is taken to be bilinear where the elastic and post-elastic stiffnesses are termed $K_1$ and $K_2$, respectively.

The equivalent elasto-plastic behaviour of the system was adopted based on experimental evidence of the force-displacement relationship of the lead-rubber bearing (Refs. 3 and 4). A reasonable description of the hysteresis loop assumes a post-elastic stiffness equal to the elastomeric stiffness $K_r$, and the initial elastic (i.e., unloading stiffness) $K_{lr} = 10\ K_r$, as shown in fig. 2. The yield level of the equivalent one degree of freedom system is taken to be equal to 5% of the superstructure weight W. This is a commonly used ratio that defines the shear resistance at yield of all the lead plugs in the bearings. A viscous damping ratio of 5% of critical damping is assumed for the system.

The piers of the base-isolated bridge are assumed to behave elastically. The deck of the highway bridge is treated as a rigid diaphragm. Recent analysis by Ghobarah and Ali (Ref. 5) demonstrated that the rigid deck assumption does not result in any significant loss of accuracy in the analysis of most bridges. Rigid deck assumption enables the designer to use the design procedures to assess either the longitudinal or transverse bridge response.

The response of the inelastic single degree of freedom system to a given strong motion earthquake record is determined numerically. The Newmark-β step by step numerical integration method is used in the analysis.

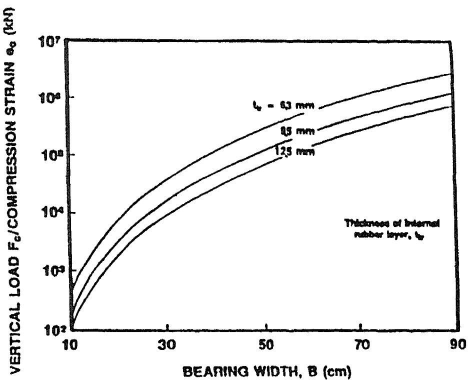


Fig. 3: Square rubber-bearing design

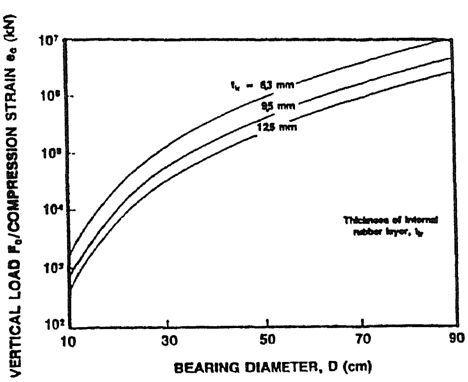


Fig. 4: Circular rubber bearing design

## DESIGN PROCEDURE

The proposed design procedure consists of two parts. Firstly, the lead- rubber bearing pad is selected and secondly the shear forces transmitted to the piers and abutments as well as the deck displacement are calculated. The procedure is best described in the following point form:

STEP 1:

The weight of the superstructure W, is calculated and the reactions due to dead plus live loads at the abutment and at the piers are determined.

STEP 2:

A suitable compression strain for bearing $e_c$ is chosen. The compression strain should be less than 7% for AASHTO (Ref. 2) and 4% for the Ontario Code (Ref. 6), as examples. The maximum bearing compression load $F_c$, can be determined by dividing the total of the dead and live loads by the total number of bearings $N_b$. The required plan dimensions B, for square shape or diameter D, for a circular bearing can be obtained from figs. 3 and 4 for some selected internal rubber layer thicknesses (also see Ref. 7).

STEP: 3

The number of rubber layers $N_l$ is selected. The selection of the total rubber thickness $t_r = N_l t_{ir}$ should be guided by the stability conditions recommended by the codes

$$t_r \leq B/3 \text{ for rectangular bearings}$$
$$\leq D/4 \text{ for circular bearings}$$

where $t_{ir}$ is the selected internal rubber layer thickness.

STEP 4:

The shear stiffness of the elastomeric bearings located at the abutment $K_{ar}$, is:

$$K_{ar} = \Sigma (G_r A_b/t_r) M_{ka} \quad (1)$$

where $G_r$ is the shear modulus of rubber = 0.7 MPa, $A_b$ is the area of the bearing and $M_{ka}$ is a modification factor:

$$M_{ka} = (1 + 0.5\, e_{ca}) / (1 - e_{ca})$$

where $e_{ca}$ is the compression strain of bearings at the abutment.

Following a similar procedure, the shear stiffness of the elastomeric bearings at the pier $K_{pr}$, can be calculated by the formula

$$K_{pr} = \Sigma\, (G_r\, A_b/t_r)\, M_{kp} \tag{2}$$

where $M_{kp} = (1 + 0.5\, e_{cp}) / (1 - e_{cp})$ , $e_{cp}$ is the compression strain of bearings at the pier.

STEP 5:

The equivalent post-elastic spring stiffness for flexible piers is determined by the formula

$$K_2 = \sum_n K_{ar} + \sum_m \frac{K_{pr} K_c}{K_{pr} + K_c} \tag{3}$$

where n and m represent the number of abutments and piers, respectively. The stiffness of the pier as a cantilever is $K_c$. The equivalent elastic spring stiffness is written as:

$$K_1 = \sum_n \mu_{ar} K_{ar} + \sum_m \frac{\mu_{pr} K_{pr} K_c}{\mu_{pr} K_{pr} + K_c} \tag{4}$$

where $\mu_{ar} = U_s R_{ar}$ and $\mu_{pr} = U_s R_{pr}$ where $U_s$ is the unloading stiffness ratio of the lead rubber bearing (to be taken = 10 or to be determined experimentally).
$R_{ar}$ and $R_{pr}$ are the ratios of bearings having lead plugs to the total bearings, at the abutment and at pier, respectively. In eqn. 4, $R_{ar} = 1$ for the case of no lead plugs at the pier and $R_{pr} = 1$ for the case of no lead plugs at the abutment.

STEP 6:

The maximum response values are determined for various effective periods of the isolated bridge which is taken to be in the practical range of 1 to 2 seconds. The effective period T, is defined as the period at maximum displacement considering the tangent stiffness

$$T = 2\pi \sqrt{W/(g\, K_2)} \tag{5}$$

Steps 3 to 5 should be repeated until an appropriate rubber thickness is selected according to the degree of isolation required.

STEP 7:

The thickness of the internal steel plates may be selected to be up to 3.2 mm (Ref. 7). The thickness could be increased if desired but this would affect the overall height of the bearing. Stresses in the steel plates $f_{st}$, can be determined as follows (Ref. 8)

$$f_{st} = 0.75\, (F_c/A)\, (t_1 + t_2)/t_s \tag{6}$$

where A is the area of steel plate,
$t_1$ and $t_2$ are the thickness of two adjacent rubber layers, and
$t_s$ is the thickness of the steel plate

STEP 8:

The lead plug diameter d, can be determined by taking the total yield force of the lead plugs to be 5% of the total dead weight of the bridge

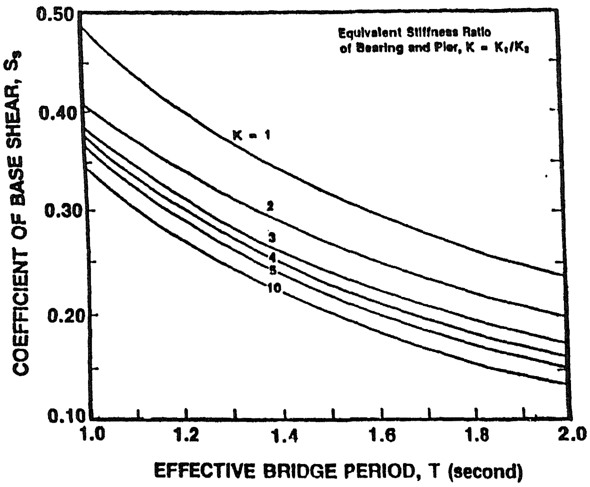

Fig. 5: Coefficient of base shear

$$d = 2\sqrt{0.05\ W/(\pi N_p f_{y\ell})} \tag{7}$$

where $f_{y\ell}$ is the yield stress of lead = 10 MPa and $N_p$ is the number of lead plugs used in the bridge bearings.

In order to ensure that the lead plug is subjected to pure shear, it is recommended (Ref. 7) that the diameter be selected within the following limits:

$B/6 \leq d \leq B/3$ for rectangular bearing
$D/6 \leq d \leq D/3$ for circular bearing
$d \leq 0.67$ of the bearing height

If the plug diameter does not satisfy these conditions, the bearing dimensions (Steps 1 to 8) should be modified.

STEP 9:

The total base shear V, can be determined using the formula

$$V = S_s W \tag{8}$$

where $S_s$ is the coefficient of base shear given by fig. 5 for different cases of bilinear stiffness ratio $(K_1/K_2)$ against the effective period T. The force on the abutment $V_a$, the shear in the pier $V_p$ and the deck displacement $u_d$, can be determined by considering the stiffness of each element as follows

$$V_a = 0.05\ \psi_{ab} W + (V - 0.05\ W)(K_{ar}/K_2) \tag{9}$$

where $\psi_{ab}$ is the ratio of yield strength of lead plugs placed at the abutment to the yield strength of all lead plugs

$$V_p = V - V_a \tag{10}$$

$$u_d = (V_a - 0.05)\ W/K_{ar} \tag{11}$$

The bearing displacement $$u_{pd} = u_d - V_p/K_c \tag{12}$$

STEP 10:

The shear strain for each bearing, determined by dividing the lateral displacement by the total thickness of rubber layers $t_r$, should be checked to be less than 50% as specified by AASHTO and the Ontario Highway Bridge Design Code (Ref. 2 and 6). Also the compression stress should not violate the code limits.

The described design method reduces to special cases of superstructures supported on elastomeric bearings without lead inserts by using $K_1/K_2 = 1$. The case of a simple span bridge supported on lead-rubber bearings can be obtained by using very flexible piers and $K_1/K_2 = 10$ for unloading stiffness ratio of ten. The design charts are simple but cover the different possibilities of lead plug locations, pier flexibility and stiffnesses of the elastomeric bearings at abutments and piers. The El Centro earthquake record has been used in the dynamic analysis of the present work. Ideally, a sufficient number of earthquake records should be chosen as input with the average of the response being used to develop general design charts.

## CONCLUSIONS

A simple and reasonably accurate method is presented for the design of highway bridges with lead-rubber base-isolation system. The method is a code type approach and is suitable for most design applications. The method is applicable to typical symmetrical highway bridges with rigid decks. The pier's flexibility is taken into consideration. Actual values for the unloading stiffness of the bearings, as determined by testing, can be used in the design. In addition, the design procedure can accommodate variations in the bearing stiffness at the pier and abutments and different lead plug locations.

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