IMPROVEMENT OF SEISMIC CONTROL OF CABLE - STAYED BRIDGE USING SIMULTANEOUS ANALYSIS OF COST AND LOSS

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Keywords: Mashhad Cable- Stayed Bridge, Seismic Risk Assessment, Passive Seismic Control, Bearing Device, Cost- Loss- Benefit (CLB) Method

ABSTRACT

In cable-stayed bridges, passive seismic control is usually performed by using bearingdevices in the place where deck and pylons connect to each other. However, owners usually refuse to use more expensive bearing devices despite their superior seismic behavior.In Mashhad cable-stayed bridge as a case study located in Iran, Pot Bearing device has been used which is not very effective in seismic behavior. While, Elastomeric Bearing Pads or Lead Rubber Bearings are more effective in absorbing earthquake's energy due to higher damping. Thus, the use of Pot Bearing was probably because of the lower costs compared to Lead Rubber Bearing.So in this paper, we are going to thoroughly compare the use of different bearingdevices in Mashhad bridge using simultaneous analysis of the construction costs and losses due to earthquake.Indeed, if economically justified, this paper tries to improve the passive seismic control device of the Mashhad bridge from its current Pot Bearing to another type. The economic justification is studied using seismic risk assessment process alongside simultaneous analysis of costs and losses. To achieve this purpose, it is necessary to design and control the bridge for seismic behavior with three aforementioned different bearing devices. Then, the seismic risk assessment process is performed for each cases. The final results of seismic risk assessment process are achieved as Total Loss Ratio curves. Then, the proposed Cost-Loss-Benefit (CLB) method will compare the three cases by defining Benefit Ratio (BR) as a profitability measure. The final results indicatethat both of the alternative cases increase the costs and decrease the losses compared to the existing Pot Bearings. However, simultaneously considering the costs and losses, the BR coefficient reveals the profitability of the use of Lead Rubber Bearings in Mashhad cable-stayed bridge.

INTRODUCTION

The bridges as an important means of transportation, must remain relatively undamaged for emergency disaster relief. Howbeit, about cable-stayed bridges as a good option for long spans, intense damages are reported during the Chi-Chi earthquake (Chang et al. 2004). Their Long spans and low damping could be the cause of their vulnerability and so some researchers focus on seismic risk assessment of this type of bridges (Casciati et al. 2008, Pang et al. 2013).

Seismic risk assessment is usually performed in two sections; vulnerability assessment in the form of fragility curves and loss assessment in the form of Expected Annual Loss (EAL) estimation (Mander et al. 2007). In order to apply the uncertainty of demand in seismic risk assessment, different methods such as Capacity Spectrum Method by Olmos et al. (2012), Time History Analysis by Pang et al. (2013), or Incremental Dynamic Analysis by Mander et al. (2007) are generally used.

However, one of the applications of seismic vulnerability or risk assessment is comparing different design schemes according to their fragility curves or seismic loss (Shinozuka et al. 2002, Kim et al. 2008).

But, the reduction of earthquake losses is not sufficient for the justifiable solution about seismic risk mitigation, and the construction costs also must be taken into account.Therefore, the purpose of this paper is to decide about the optimal passive control device of a cable-stayed bridge as a double criteria decision-making problem.The two criteria are construction costs and seismic losses which will be combined in the concept of economic justification. The economic justification is studied using seismic risk assessment process alongside simultaneous analysis of costs and losses. For the purpose of this paper, Mashhad cable-stayed bridge is selected as the case study. All the structural features remain the same, except the bearing device which is varied in three different cases include Pot Bearing (PB), Elastomeric Bearing (EB) and Lead Rubber Bearing (LRB). Then the (EAL) can be obtained for different bearing devices usage by applying seismic risk assessment process. Finally, if economically justified, the proper decision is made about the improvement of passive control from existing PB to another type using the proposed Cost-Loss-Benefit (CLB) method.

DESCRIPTION OF THE CASE STUDY AND MODELLING WITH THREE DIFFERENT PASSIVE CONTROL DEVICES

Mashhad cable-stayed bridge with Pot bearing devices located in Iran, is selected as the case study (Fig. 1) and will be modelled with three different bearing devices

Figure 1. View of Mashhad cable-stayed bridge

The Mashhad cable-stayed bridge with 100 meters mid span, has two tower that each consists of two A shape concrete pylons with 37 meters hight on both sides of the deck. The cross beam of the pylon is bold section with 2*2.8m dimensions and is connected to deck by Pot Bearing. The composite deck of the bridge includes concrete slabs and steel box girders. The cables have semi fan configuration, and 50 meters side spans are also cables-stayed. The nonlinear 3D model of the bridge is developed based on (Caltrans, S. D. C. 2004, Aviram et al. 2008, Computers and Structures Inc. (CSI) 2005) ’s recommendations in SAP2000 v15 software. It is notable that utilization of SAP2000 software, can be seen in several researches such as (Shinozuko et al. 2002, Chang et al. 2004, Calvi et al. 2010, Olmos et al. 2012,) in the field of seismic performance assessment of bridges.

The materials including concrete and reinforcement bars, are defined based on (Mander et al. 1988)'s model, and ASTM model (Caltrans S. D. C. 2004), respectively. The nonlinear sagging effects of cables, is considered using equivalent elastic modulus based on the Eq. (1) (Ren and Obata 1999).

$$E_{eq} = \frac{E}{1+\frac{(L_0\text{¥})^2(\pm_1+\pm_2)}{24\pm_1^2\pm_2^2}E} \qquad (1)$$

Where for cables, Eeq is the equivalent elastic modulus, E is the elastic modulus of material, "L0" is the horizontal projection length, $\pm_1$ and $\pm_2$ are tension stresses in a certain loading process.

Considering the nonlinear behavior and axial force-bending moment interactions, the pylons are simulated by assigning distributed plasticity fiber model to the section of nonlinear beam-column element (Nazmy and Abdel-Ghaffar 1990, Aviramet al. 2008). The nonlinear effect of P-Δ is considered, due to the large geometric dimensions of the structure. The pylon cross beam and side span pier, are modeled using bending plastic hinge and nonlinear link element, respectively. Also the modeling of bearing devices including PB, EB and LRB are modeled based on recommendations provided by Oladimeji Fasheyi(2012), Makris and Zhang (2002) and Agrawal et al. (2012), respectively. The concrete slab of deck has been modeled by shell elements supported bya plane frame of steel girders. It is notable that since the girders must remain elastic, they are modeled using elastic steel beam-column element. Considering the cable configuration, damping of the structure is assumed to be 3% (Tang 1992, Kawashima et al. 1993).

Besides the existing pot bearing, Mashhad bridge is designed with two other bearing devices. The design is performed using Guidelines provided by Tang (1992) and conceptual seismic design of cable-stayed bridge proposed by Calvi et al. (2010). The results show that designing the bridge with different bearing devices, causes changes in design forces and consequently in dimensions of the three main substructures of the bridge including pylon, deck and cables. After performing the design process, the volume of used material forthree different design schemes can be stated relatively. If the material usage for the Mashhad bridge (with Pot Bearing) is stated by the value "1", then the material used for other three cases is given relatively for different substructures in Table 1. Besides, the valuesin parentheses indicate the contribution percentage of the substructure in the total cost of the bridge.

Table 1. Relatively Cost Analysis (RCA) data

Bearing devices	Inputs				Outputs
	Material Volume Coefficient of Substructures				relative construction costs
	Bearing	Deck	Cable	Pylons	
Pot Bearing	1(10%)	1(38%)	1(22%)	1(30%)	1
Elastomeric Bearing	1.3(14%)	0.97(34%)	1.19(24%)	0.91(28%)	1.053
Lead Rubber Bearing	1.45(16%)	0.97(35%)	1.16(23%)	0.86(26%)	1.064

As mentioned before, all three schemes are designed by considering code-based methods which are generally quick and simple methods for engineer utilization. Hence, we need a more astute tool such as seismic risk assessment to study the structure performance more accurately as following.

SEISMIC RISK ASSESSMENT PROCESS

After developing the three different bridge models, the seismic risk assessment process must be separately performed on each of them. This process will be performed in two parts including seismic fragility assessment and loss assessment. Developing the fragility curve is done using Time History Analysis (THA) method (Pang et al. 2013)to consider the demand uncertainty. Thenthe loss assessment is performed by combining fragility curves and loss ratio. Process steps explained below.

Step 1: Choosing the earthquake records

Based on the seismicity of studied region, a set of 60 records are provided for this research through PEER strong ground motion Database (http://peer.berkeley.edu/smcat) which are modified based on uniform hazard spectrum (UHS) approach.

Step 2: Seismic analysis and estimation of Probabilistic Seismic Demand Model (PSDM)

In this step, first the developed models in the previous step are analyzed under the dead load, and second the earthquake records are applied to the deformed model. Each record is applied to the mentioned nonlinear models using time history direct integration method in SAP2000 v15 software. Then four seismic demands of the structure are monitored include pylon head displacement, critical pylon section curvature, cable tension, and critical stress on deck. All demands are monitored for critical response between longitudinal and transverse excitations. Considering the fact that cable-stayed bridges have long periods, spectral pseudo acceleration of the fundamental period (Sa(T1)) will be used as intensity measure of the earthquake instead of PGA that is a high frequency measure. So, it is necessary to determine the Sa(T1) value for each existing record provided in step 1.Now, it is necessary to express seismic responses, as a Probabilistic Seismic Demand Model (PSDM), in order to explain the existing uncertainties. So a common power relationship (Pang et al. 2013), is used to estimate the mean value of PSDM, and is demonstrated in Eq. (2).

$$EDP = a((IM)^{b}) \tag{2}$$

Where EDP is the Engineering Demand Parameter which consists of the monitored responses, IM is the intensity measure of the earthquake Sa(T1), and both a and b are the scaling coefficient. The scaling coefficient of PSDM mean, and standard deviation of the responses about their mean can be calculated using regression analysis of responses. So, finally instead of THA results for each response, a PSDM consisting of mean curve and standard deviation will be determined.

Step 3: Defining the Damage Criterion for cable-stayed bridge

Bridge damages are classified in 4 states; Slight, moderate, extensive and collapse. (Mander et al. 2007, Pang et al. 2013). It is necessary to define each of these damage states using a capacity criterion in order to control the monitored responses exceeding the damage states. The criterion controlling the seismic responses of a cable-stayed bridge in each damage state is presented as a two parameter lognormal distribution by Pang et al. (2013). These criteria which are considered as damage limit states are presented in Table 2.

Table 2. Definition of damage limit states

Damage Criterion (DC)		Lognormal Distribution of Damage Limit States							
Component	Damage index	Slight		Moderate		Extensive		Collapse	
		M*	SD**	M*	SD**	M*	SD**	M*	SD**
Tower	Curvature Ductility	1.5	0.2	3	0.2	5.5	0.2	7.5	0.2
Tower Head	Drift	0.011	0.2	0.02	0.2	0.038	0.2	0.06	0.2
Deck	Stress (f_y)	0.125	0.2	0.25	0.2	0.375	0.2	0.5	0.2
Cable	Tension(MN)	5.5	0.11	6.9	0.11	1.1	0.11	1.35	0.11

* M: Mean, ** SD: Standard Deviation

Step 4: Fragility curves estimation

Fragility curves indicate the probability of exceeding a damage state for different values of intensity measure of the earthquake. Considering the lognormal distributions assigned to the seismic demand and damage criterion of the structure, the probability of exceeding the damage state i is calculated based on the prevalent first-order reliability formulation of Eq. (3):

$$P_f = \Phi\left[\frac{\ln\left(\frac{\mu_D}{\mu_{Cc}}\right)}{\sqrt{\beta_{\ln D}^2 + \beta_{\ln Cc}^2}}\right] \tag{3}$$

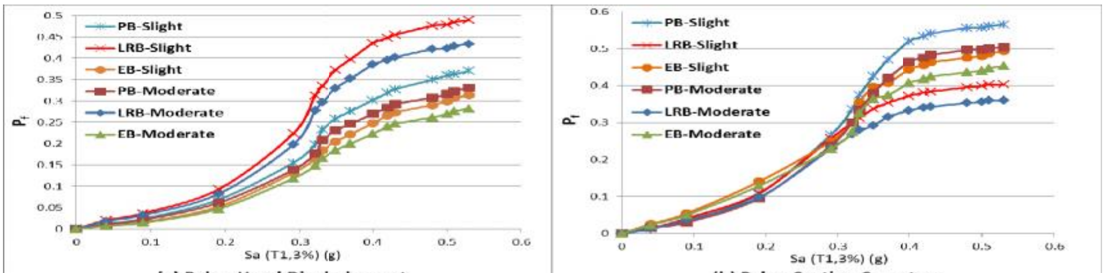
Where if Pf is the probability of exceedance of damage state i, then $\mu_D$and $\beta_{\ln D}$ are mean and standard deviation of the PSDM, respectively. And μ_{DC} and $\beta_{\ln c_c}$are mean and standard deviation of capacity criterion in damage state i, respectively.

Then, we use this definition to calculate the fragility of the whole bridge system: “if a component exceeds a certain damage state, it means that the whole bridge is experiencing the state”.Considering this definition, the fragility curve for the bridge system can be obtained based on Eq. (4) (Nielson and DesRoches 2007, Ross 2009).

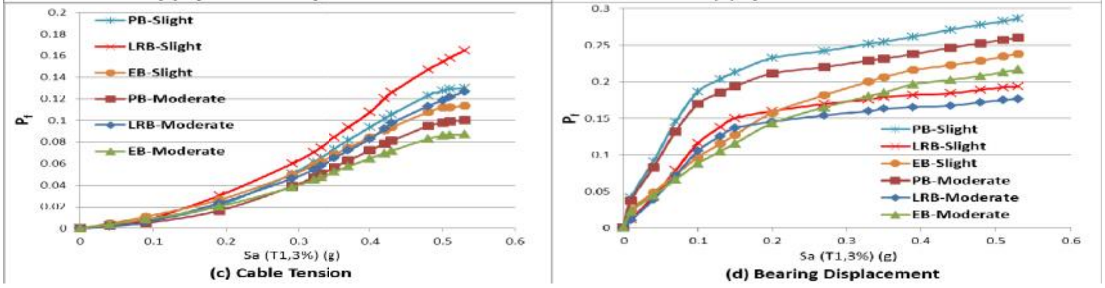
$$P_f[bridge_{system}] = \bigcup_{j=1}^{n} P_f[component_j] \tag{4}$$

Where $P_f[bridge_{system}]$ is the probability of the whole bridge system exceeding the damage state i, $P_f[component_j]$ is the probability of the jth component (monitored response) exceeding the damage state i, n is the number of effective components on the behavior of the bridge.

The process of step 1 to step 4 is done for Mashhad bridge with different bearing deviceswhich are designed previously. Thus, the fragility curves of the components and bridge system for different damage states alongside different passive control usage are illustrated in Figs.2-3 and the fragility curve of the whole bridge system is presented in Fig. 4.

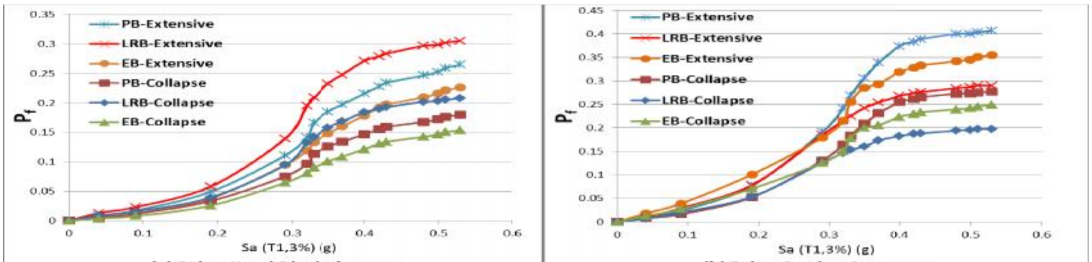


(a) Pylon Head Displacement (b) Pylon Section Curvature

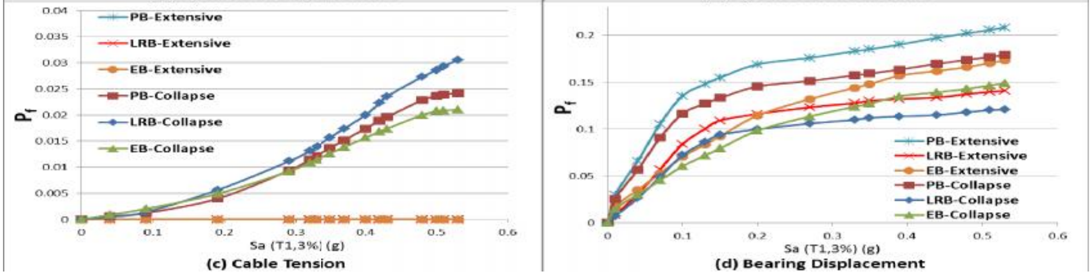


(c) Cable Tension (d) Bearing Displacement

Figure 2. Fragility curves of components (Slight and Moderate)

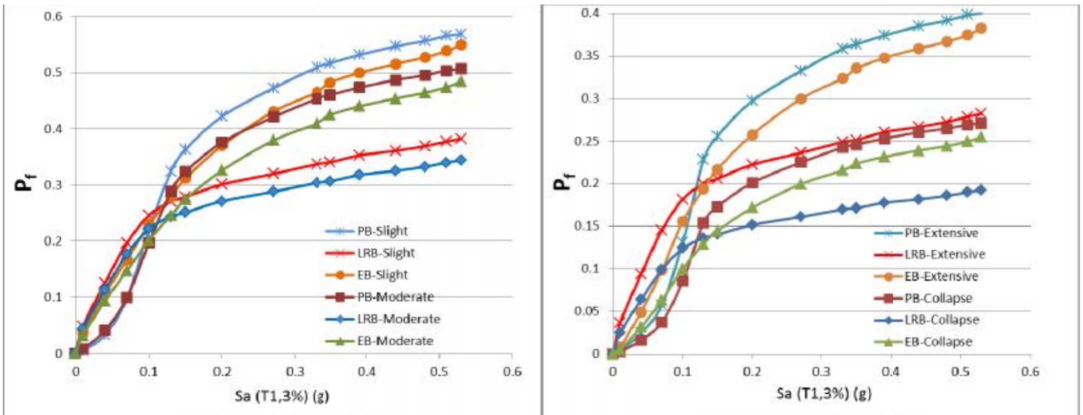


(a) Pylon Head Displacement (b) Pylon Section Curvature



(c) Cable Tension (d) Bearing Displacement

Figure 3. Fragility curves of components (Extensive and Collapse)



(a) Slight and Moderate (b) Extensive and Collapse

Figure 4. Fragility curves of whole bridge system

The results which are concluded from fragility curves will be reported in conclusion section.

Step 5: EAL estimation

Total loss ratio is calculated for different values of intensity measure ($Sa(T_1)$) considering the fragility curves of the whole bridge system and loss ratio of each damage state. using Eq. (5):

$$Total\ Loss\ Ratio(IM = im) = \sum_{i=1}^{4}[P(DS_i|im) - P(DS_{i+1}|im)] \times LR_i \tag{5}$$

Where DSi is the ith damage state, and LRi is the loss ratio in ith damage state, Which was defined by Mander et al.(2007) in each damage state as the repair costs to replacement costs ratio.

Calculated total loss ratiois generally reported versus the annual frequency of corresponding intensity measure (Mander et al. 2007). To obtain the annual frequency of intensity measure, it is necessary to present the hazard curve of the studied bridge region according to seismological studies performed by Gholipour et al. (2008). Also, EAL can be obtained by calculating the area beneath total loss ratio curve. The hazard and total loss ratio curves and calculated EAL are plotted in Fig. 5.

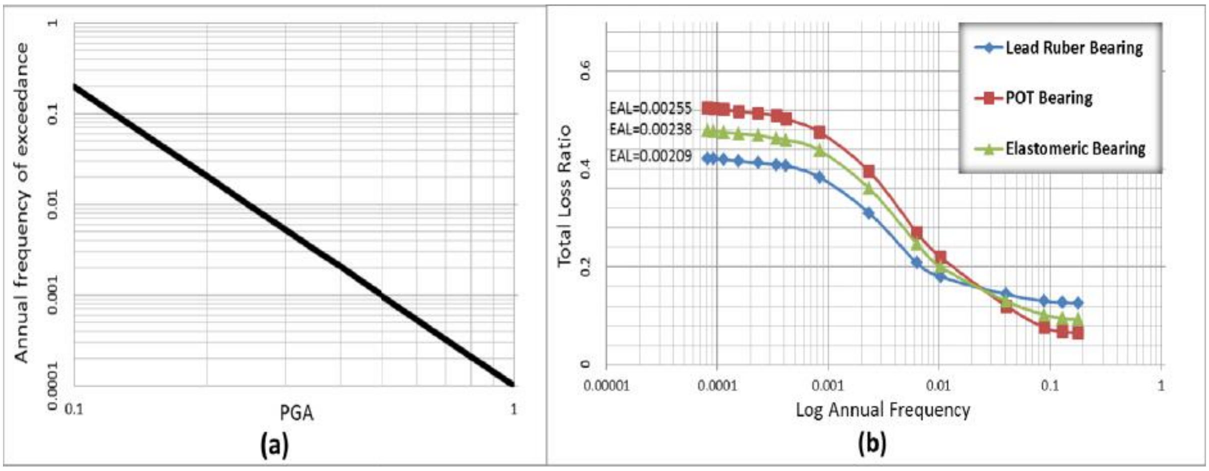


Figure 5. (a) Hazard curve, (b) Total Loss Ratio curves

However, according to Fig.5, usually LRB usage leads to the lower total loss ratios. But, a more accurate judgment is required for absolute decision-making about improvement of seismic control of Mashhad cable-stayed bridge considering economic justification. Because, up to this part of the discussion only the first criterion (loss) has been considered; while it is necessary to consider the construction costs as the second criterion as well, with using proposed process in following section.

Simultaneously analysis of cost and loss using proposed method

The seismic risk assessment process of previous section, as a perfect decision-making tool of this paperis developed using the Cost-Loss-Benefit (CLB) method. Meaning that, we can decide between different feasible passive control system using the results of this simple method. Hence, decision-making about the optimal improvement of seismic controlof case-study, can be done by simultaneously considering the construction costs and probable earthquake losses.Also, considering the currency value differences in different countries, the advantage of the CLB method is that it uses relative values. In the CLB method, the existing Mashhad bridge with Pot Bearing must be selected as benchmark and then two other schemes can be evaluated relatively. For this purpose, a factor called Benefit Ratio (BR) is calculated for each bearing device usage based on Eq. (6):

$$BR_s = \left(\frac{C_{s=1}}{C_s}\right) \times \left(\frac{Loss_{s=1}}{Loss_s}\right) \tag{6}$$

Where C_s and $Loss_s$ are the absolute construction cost and absolute expected annual loss for Sth scheme, respectively, and $s=1$ indicates the benchmark. Also,$Loss_s$ can be achieved based on Eq. 7.

$$Loss_s = EAL_s * C_s \tag{7}$$

Where EAL_s is the EAL of the Sth scheme which has been shown in Fig. 5(b), previously.

Considering the Eqs. (6) and (7), BR value can be calculated based on the relative EAL_s parameter and relative C_s value, independent of the absolute $Loss_s$parameter and absolute C_s values:

$$BR_s = \left(\frac{C_{s=1}}{C_s}\right)^2 \times \left(\frac{EAL_{s=1}}{EAL_s}\right) \tag{8}$$

Where EALs=1 is the EAL of the existing Mashhad cable-stayed bridge with Pot bearing device.

Notice that, a BR value for a benchmark greater than 1 indicates that the improvement scheme is relatively more beneficial than the existing scheme. The outputs of method including BR values are reported in Table 6 along with its inputs including RCA data and loss assessment data.

Table 3: The CLB data and results

Bearing device	CLB Inputs			CLB Output
	Material Volume Coefficient from RCA	Bridge system $(\frac{C_{s=1}}{C_s})$	$(\frac{EAL_{s=1}}{EAL_s})$ from loss assessment	BR_s
Pot Bearing	1	1	1	1
Elastomeric Bearing	1.053	0.95	1.071	0.967
Lead Rubber Bearing	1.064	0.94	1.22	1.078

The final results indicate that both of the alternative cases increase the costs and decrease the losses compared to the existing Pot Bearings. However, simultaneously considering the costs and losses, the BR coefficient reveals the profitability of the use of Lead Rubber Bearings in Mashhad cable-stayed bridge. Expressing in more detail, the use of LRB instead of Pot Bearing caused an 18 percent reduction of loss due to earthquake, while it only increased the construction cost by 6 percent.

CONCLUSION AND REMARKS

In this paper, the common process of seismic risk assessment is developed using simultaneously analyze of cost and loss. Thus, economic justification of different schemes for improvement of seismic control of Mashhad cable-stayed bridge has been studied by authors. The results of the problem solving process are summarized as follows:

1- The amount of material needed for designed cable-stayed bridge with different bearing devices increases in accordance with this order: Pot Bearing, Elastomeric Bearing, Lead Rubber Bearing. In other words, Improvement of seismic control device is associated with increase in construction costs. So it was necessary to analyze how much this improvement can contribute to reduction in seismic losses, and if the increase in construction costs was economically justifiable.
2- Fragility curves show that, the critical responses of bridge with LRB is the pylon displacement and it was not unexpected considering free movement of LRB for damping release mechanism. Also the critical response of bridge with PB and LB is the pylon section curvature.
3- Damage probability of pylon head displacement and cable tension increases in accordance with the order mentioned in item number 1. Also Damage probability of pylon section curvature and bearing displacement decreases in accordance with the order mentioned in item number 1.
4- Damage probability of the whole bridge system decreases in accordance with the order mentioned in item number 1.
5- The effect of improvement of seismic control to LRB device on fragility curves is stronger for earthquakes with higher intensity measures. This is due to the fact that LRB damping releases mostly in more intense earthquakes.
6- (EAL) decreases in accordance with the order mentioned in item number 1.
7- The Change of seismic control device from existing Pot Bearing to Elastomeric Bearing in Mashhad bridge caused a 3.3 percent decrease in total profitability measure (BR value).
8- The improvement of seismic control device from existing Pot Bearing to Lead Rubber Bearing in Mashhad bridge caused a 7.8 percent increase in total profitability measure (BR value).
9- This paper indicates that the improvement of seismic control device from existing Pot Bearing to Lead Rubber Bearing is an economically justifiable decision for Mashhad cable-stayed bridge.

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