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Solution of Double Criterion Problem about Selecting Passive Control Device of Cable-Stayed Bridges

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ABSTRACT

Seismic control strategy of cable-stayed bridges is usually performed by implementing bearing devices in the connection point of deck and pylon. In this case, owners usually refuse to use superior seismic strategy because of its cost. In Mashhad cable-stayed bridge as a case study, Pot Bearing device has been used probably because of the lower costs, while it is not very effective in seismic behavior. However, Elastomeric Bearing Pads or Lead Rubber Bearings are more effective in absorbing earthquake's energy due to higher damping. Therefore, in this paper, we are going to thoroughly solve a double criterion problem about selecting bearing devices of Mashhad bridge considering the construction costs and earthquake losses. 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 the simultaneous analysis of costs and losses. To achieve this goal, 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 case. 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 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.

Keywords:
Mashhad cable-stayed bridge; Double criterion problem; Seismic risk assessment; Passive seismic control; Bearing device

1. Introduction

The bridges as an important means of transportation, must remain relatively undamaged for emergency disaster relief. Howbeit, about Chi-Lu cable-stayed bridge with two 120 m spans and a single tower, intense damages are reported during the Chi-Chi earthquake [1]. Their Long spans and low damping could be the cause of their vulnerability and hence some researchers focus on seismic risk assessment of this type of bridges [2-3]. In studying cable-stayed bridges, their nonlinear behavior due to the cables sagging [4], p-Δ effect and materials nonlinearity including concrete and reinforcement bars, must be considered [5].

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 [6]. The common approaches to obtain the fragility curves of structural components are lognormal distribution functions [6] or reliability-based approach [2]. Besides, the fragility curve of the whole bridge system is generated by employment of the jointly probabilistic model [7]. In order to apply the uncertainty of demand in seismic risk assessment, different methods such as Capacity Spectrum Method by Olmos et al. [8], Time History Analysis by Pang et al. [3], or Incremental Dynamic Analysis by Mander et al. [6] are generally used. Besides, the prevalent methods to consider the uncertainty of structural capacity is the Monte-Carlo simulation, or the Latin Hypercube Sampling (LHS) method or the Uniform Design (UD) method [3]. About the loss assessment, loss ratio obtained from experimental results is the common tool in researches framework [6].

On the other hand, one of the applications of seismic vulnerability or risk assessment is comparing different design schemes according to their fragility curves or seismic loss [9-10]. For example, Casciati et al. [2] examined the effectiveness of utilization of passive devices in cable-stayed bridges, by performing a comparison study only on the fragility curves of the bridge. However, fragility curves comparison or even the reduction of earthquake losses is not sufficient for the justifiable solution about seismic risk mitigation, and the construction costs must be taken into account too. 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 that 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 in Iran is selected as the case study. All the structural features remain the same, except the bearing device that is varied in three different cases including Pot Bearing (PB), Elastomeric Bearing (EB) and Lead Rubber Bearing (LRB). Then, the (EAL) can be obtained for different bearing devices usage by applying the seismic risk assessment process. Finally, using proposed method as Cost-Loss-Benefit (CLB) method, if economically justified, the proper decision is made about the improvement of passive control from the existing PB to another type.

2. Description of the Benchmarks and Three Different Passive Control Devices

Mashhad cable-stayed bridge with Pot bearing devices located in Iran, is selected as the case study (Figure 1) and will be designed with three different bearing devices including Pot Bearing (PB), Elastomeric Bearing (EB) and Lead Rubber Bearing (LRB).

The Mashhad cable-stayed bridge with 100 meters mid span, has two tower, each consists of two A-shaped concrete pylons with 37 meters height on both sides of the deck. The cross beam of the pylon is bold section with 2x2.8 m 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 cable-stayed.

Figure 1. View of Mashhad cable-stayed bridge.

The nonlinear 3D model of the bridge is developed based on [11-13]'s recommendations in SAP2000 v.15 software. It is notable that the utilization of SAP2000 software, can be seen in several researches such as [1, 8, 9, 14] in the field of seismic performance assessment of bridges.

The materials including concrete and reinforcement bars, are defined based on [15]'s model, and ASTM model [11], respectively. The nonlinear sagging effects of cables, is considered using the equivalent elastic modulus based on the Eq. (1) [4].

$$E_{eq} = \frac{E}{1 + \frac{(L_0\gamma)^2(\sigma_1 + \sigma_2)}{24\sigma_1^2\sigma_2^2}E} \tag{1}$$

where for cables, E_{eq} is the equivalent elastic modulus, E is the elastic modulus of material, L_0 is the horizontal projection length, σ_1 and σ_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 [5, 12]. 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. Besides, the modeling of bearing devices including PB, EB and LRB are modeled based on the recommendations provided by Oladimeji Fasheyi [16], Makris and Zhang [17] and Agrawal et al. [18], respectively. The concrete slab of deck has been modeled by shell elements supported by a 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% [19-20]. The 3D model of bridge and location of bearing devices are shown in Figure (2).

Besides the existing pot bearing, Mashhad Bridge is designed with two other bearing devices. The design is performed using Guidelines provided by Tang [19] and conceptual seismic design of cable-stayed bridge proposed by Calvi et al. [14]. 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 for three 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 values in parentheses indicate the contribution percentage of the substructure in the total cost of the bridge.

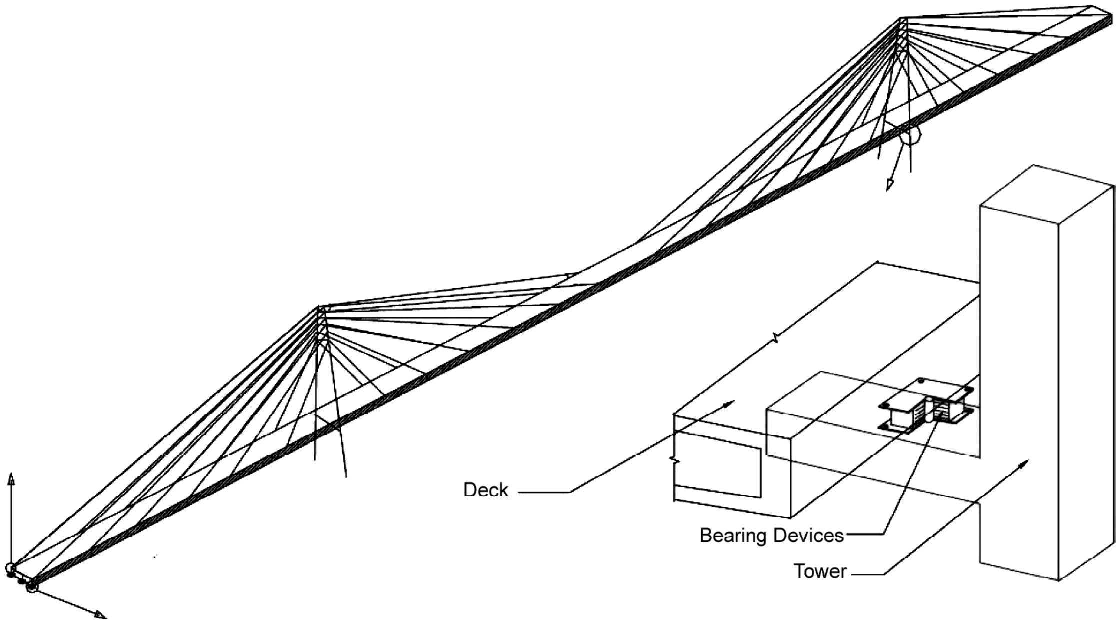


Figure 2. 3D Model of Mashhad cable-stayed bridge and bearing device location.

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 follows.

3. 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. Fragility assessment by developing fragility curves seems to be the most common method of assessing the vulnerability of structures in researches. Fragility curves report the probability of a component or the structure exceeding a certain damage state, for different intensity measures of the earthquake. Developing the fragility curve is done using Time History Analysis (THA) method and to consider the demand uncertainty, respectively [3]. Then, the loss assessment is performed by combining the fragility curves and the loss ratio. The mentioned process consists of the following steps that should be performed once for each benchmark and the results should be recorded.

3.1. 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 the uniform hazard spectrum (UHS) approach. These records were selected considering the seismicity of the region in which the Mashhad Bridge is located. Therefore, all the records are selected for moment magnitudes (Mw) 6.1 to 7.4 and 20 to 100 Km distance between the source and the site. For example, only the spectrums resulted from 15 records are plotted in Figure (3).

3.2. 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

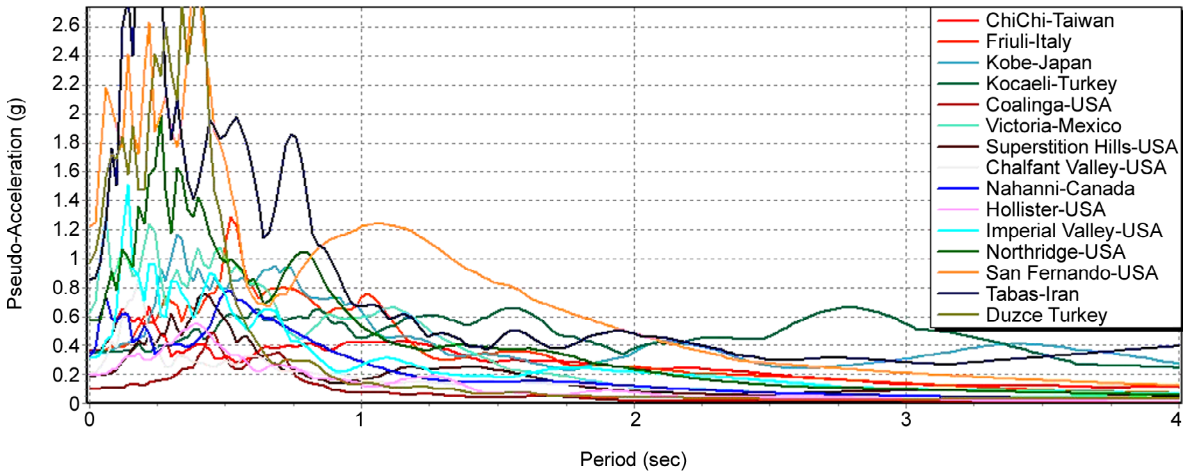
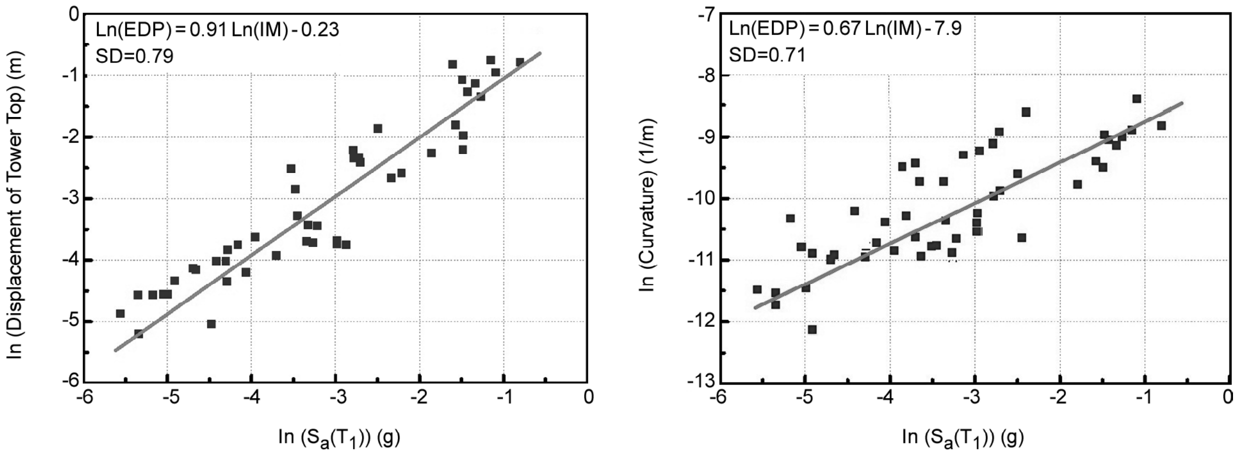


Figure 3. Record spectrums.

mentioned nonlinear models using time history direct integration method in SAP2000 v.15 software. Then, four seismic demands of the structure are monitored including pylon head displacement, critical pylon section curvature, cable tension, and critical stress on deck. In this paper, each record is applied separately in longitudinal and transverse directions, and 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 $(S_a(T_1))$ will be used as the intensity measure of the earthquake instead of PGA that is a high frequency measure. Therefore, it is necessary to determine the $S_a(T_1)$ value for each existing record provided in step 1. The maximum values of quadruple responses are obtained for each record in front of the corresponding $S_a(T_1)$, and thus, one point of the THA outputs is determined. Now, it is necessary to express seismic responses (THA outputs), as a Probabilistic Seismic Demand Model (PSDM), in order to explain the existing uncertainties. Thus, a common power relationship [3] is used to estimate the mean value of PSDM, and is demonstrated in Eq. (2).

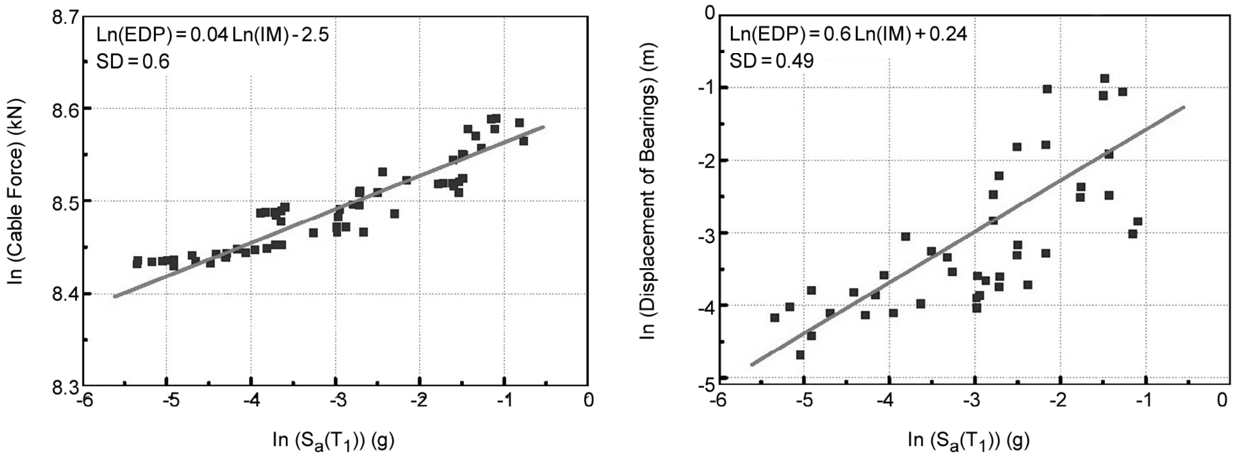
$$EDP = a((IM)^b) \tag{2}$$

where *EDP* is the Engineering Demand Parameter that consists of the monitored responses, *IM* is the intensity measure of the earthquake $S_a(T_1)$, and both a and b are the scaling coefficient. The scaling coefficient of PSDM mean, and Standard Deviation (SD) of the responses about their mean can be calculated using regression analysis of responses. Therefore, finally instead of THA results for each response, a PSDM consisting of mean curve and standard deviation will be determined and plotted in Figure (4). It is notable that this figure shows the results when using pot bearing device in Mashhad bridge.



(a) Pyion Head Displacement

(b) Pylon Section Curvature



(c) Cable Tension

(d) Bearing Displacement

Figure 4. PSDM of Mashhad cable-stayed bridge with Pot Bearing.

3.3. Step 3: Defining the Damage Criterion for Cable-Stayed Bridge

Bridge damages are classified in four states: Slight, moderate, extensive and collapse [3, 6]. 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. [3]. These criteria considered as damage limit states are presented in Table (2).

3.4. Step 4: Fragility Curves Estimation

Fragility curves indicate the probability of exceeding a damage state for different values of intensity measure of the earthquake. The fragility of a component for damage state '*i*' is defined based on Eq. (3):

$$P_f = P[D \ge Cc_i \mid IM] \tag{3}$$

where P_f is the probability of exceedance of damage state *i*, *D* is the seismic demand of the structure, Cc_i is the capacity criterion of the structure in damage state *i* which is obtained from Table (2), and *IM* is the 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. (4):

$$P_f = \phi\left[\frac{\ln\left(\frac{\mu_D}{\mu_{Cc}}\right)}{\sqrt{\beta^2_{\ln D} + \beta^2_{\ln Cc}}}\right] \tag{4}$$

where ϕ is the standard normal cumulative distribution function, and if P_f is the probability of exceedance of damage state *i*, then μ_D and $\beta^2_{\ln D}$ are mean and standard deviation of the PSDM, respectively. Besides, μ_{Cc} and $\beta^2_{\ln Cc}$ are mean and standard deviation of capacity criterion in damage state *i*, respectively.

Then, this definition is used 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. (5) [7, 21].

$$P_f[bridge_{system}] = \bigcup_{j=1}^{n} P_f[component_j] \tag{5}$$

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 j^{th} component (monitored response) exceeding the damage state *i*, *n* is the number of effective components on the behavior of the bridge, and $\bigcup$ is the probability union function.

The process of step 1 to step 4 is done for Mashhad Bridge with different bearing devices, which 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 Figures (5) to (6), and the fragility curve of the whole bridge system is presented in Figure (7).

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. However, the critical response of bridge with PB and LB is the pylon section curvature. The other results that are concluded from fragility curves will be reported in

Table 2. Definition of damage limit states.

Damage Criterion (CC)		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

conclusion section.

3.5. Step 5: Expected Annual Loss (EAL) Estimation

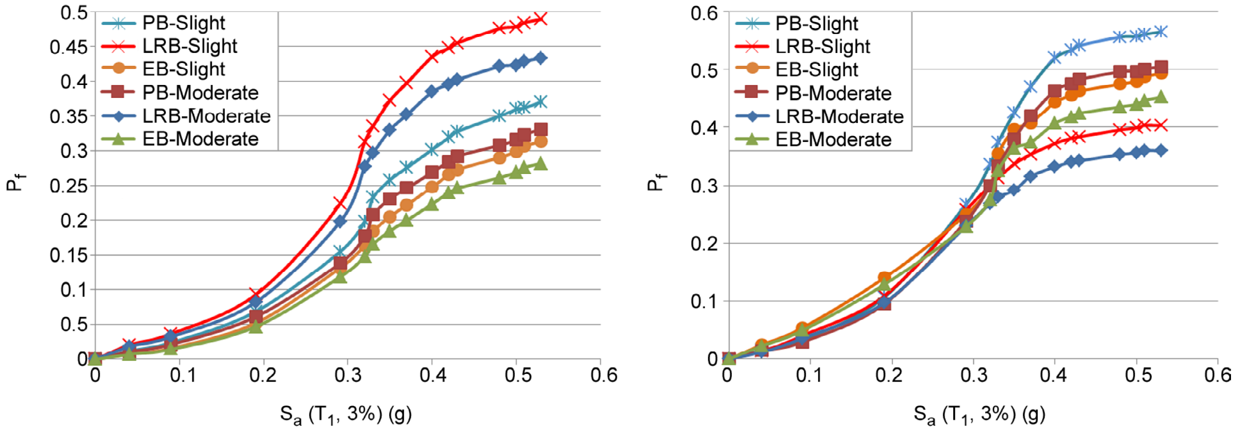
The Expected Annual Loss (EAL) due to probable earthquakes can be obtained for each bearing device employment using the loss assessment. First, the total loss ratio will be obtained by combining the damage probability of the bridge system and Loss Ratio (LR), which is proposed for each damage state in literature review. The LR is defined as the ratio of repair costs to replacement costs. Thus, total loss ratio is calculated for different values of the intensity measure ($S_a(T_1)$) considering the fragility curves of the whole bridge system and the loss ratio of each damage state using Eq. (6):

$$Total\ Loss\ Ratio\,(IM = im) = \sum_{i=1}^{4}[P(DS_i \mid im) - P(DS_{i+1} \mid im] \times LR_i \tag{6}$$

where DS_i is the i^{th} damage state, and LR_i is the loss ratio in i^{th} damage state, that was defined by Mander et al. [6] in each damage state as the repair costs to replacement costs ratio.

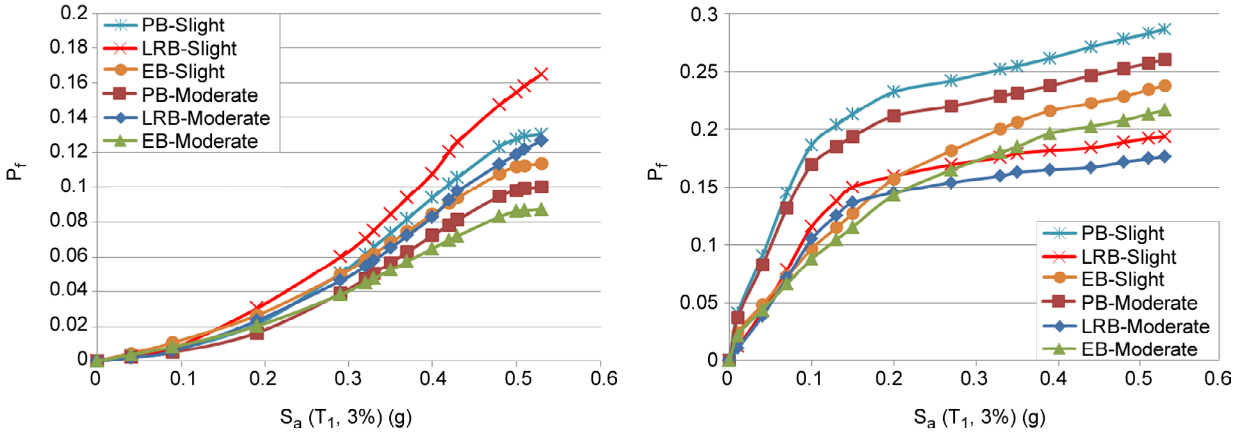
Calculated total loss ratio is generally reported versus the annual frequency of corresponding intensity measure [6]. To obtain the annual frequency of intensity measure, it is necessary to present the hazard curve of the studied bridge region according to seismological studies performed by Gholipour et al. [22]. Note that the seismological results are presented for PGA parameter. While the results of this paper, as mentioned before, are obtained based on $S_a(T_1)$ as the intensity measure of the earthquake. Transformation of PGA into the corresponding $S_a(T_1)$ is done by the spectrums of Figure (3).

It is notable that, all the calculated values for EAL and the Total Loss Ratio are related to the structure value, obviously. The hazard curve along with total loss ratio and their corresponding EAL, which are calculated by the aforementioned approaches, are illustrated for the three benchmarks



(a) Pylon Head Displacement

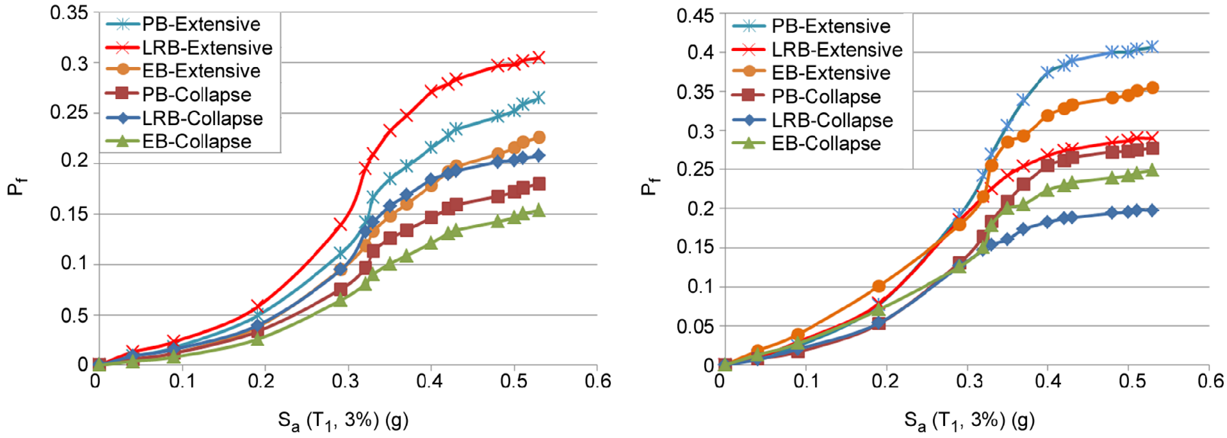
(b) Pylon Section Curvature



(c) Cable Tension

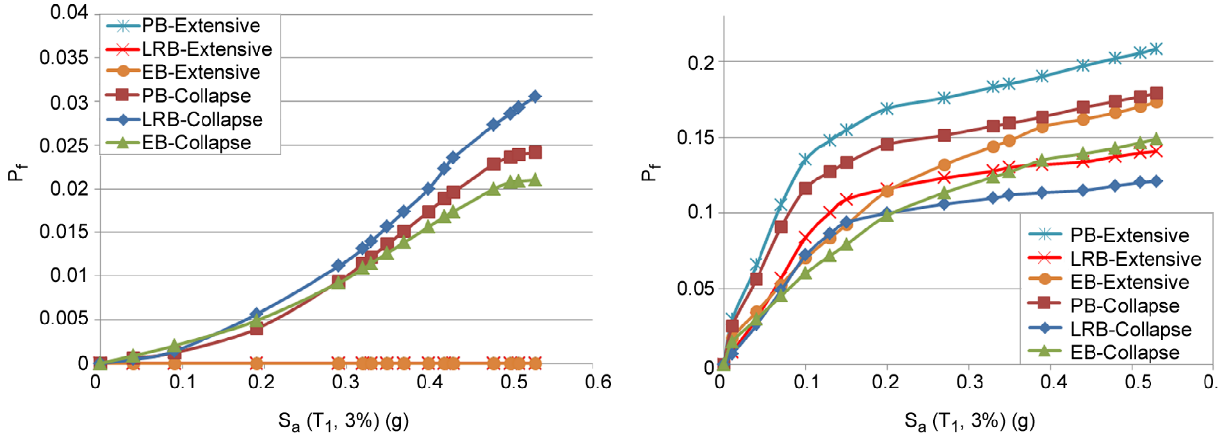
(d) Bearing Displacement

Figure 5. Fragility curves of components (Slight and Moderate).



(a) Pylon Head Displacement

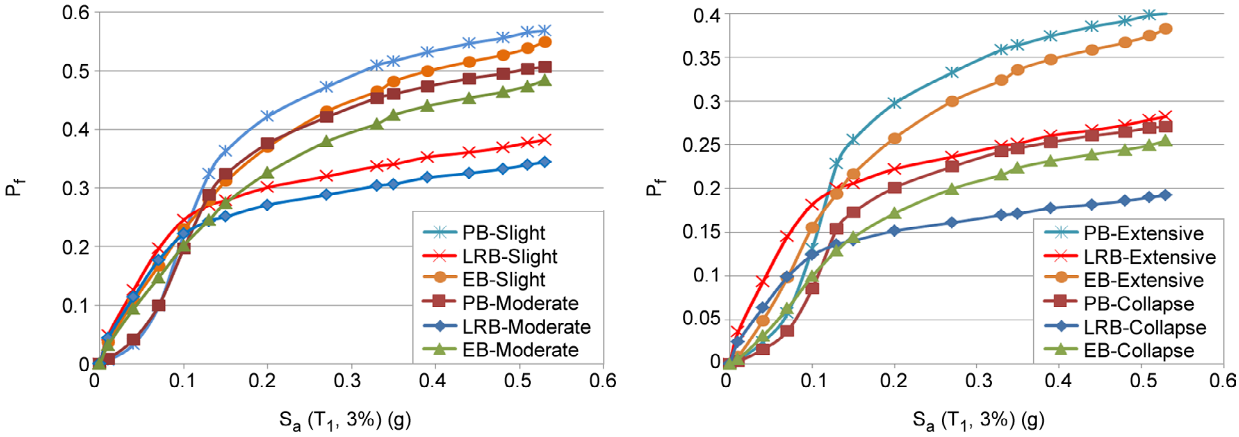
(b) Pylon Section Curvature



(c) Cable Tension

(d) Bearing Displacement

Figure 6. Fragility curves of components (Extensive and Collapse).



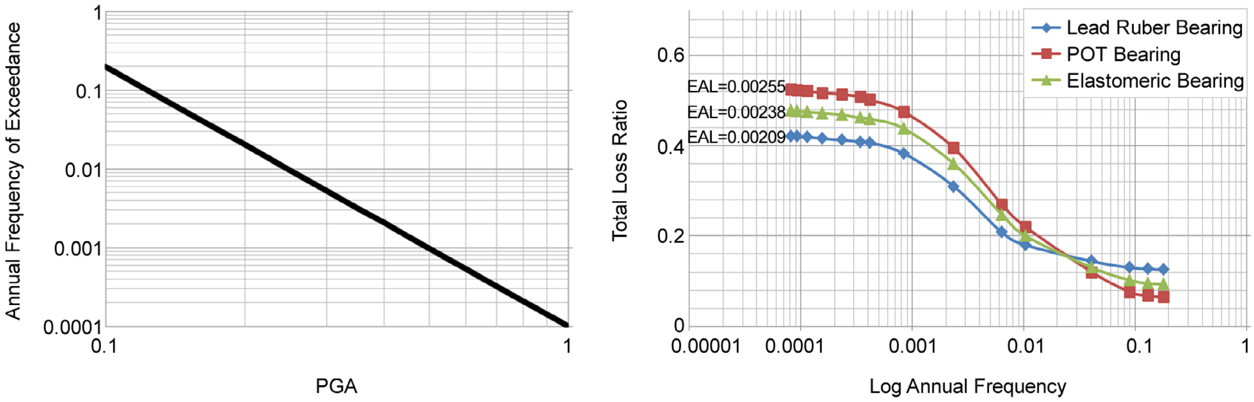
(a) Slight and Moderate

(b) Extensive and Collapse

Figure 7. Fragility curves of the whole bridge system.

in Figure (8).

However, according to Figure (8), usually LRB usage leads to the lower total loss ratios. Moreover, a more accurate judgment is required for absolute decision-making about the improvement of seismic control of Mashhad cable-stayed bridge considering the 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 the following section.



(a)

(b)

Figure 8. (a) Hazard curve and (b) Total loss ratio curves.

4. Simultaneously Analysis of Cost and Loss Using Proposed Method

It should be noted that, although the fragility and loss curves provide a more accurate judgment than comparing seismic responses, they still do not provide perfect judgments. Deciding between different structural schemes is only justified when the construction cost for each scheme is examined alongside its probable loss due to an earthquake. The seismic risk assessment process of previous section, as a perfect decision-making tool of this paper is developed using the Cost-Loss-Benefit (CLB) method. Meaning that, we can decide between different feasible passive control systems using the results of this simple method. Hence, decision-making about the optimal improvement of seismic control of case-study, can be done by simultaneously considering the construction costs and probable earthquake losses. Moreover, 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. (7):

$$BR_s = \left(\frac{C_{s=1}}{C_s}\right) \times \left(\frac{Loss_{s=1}}{Loss_s}\right) \tag{7}$$

where C_s and $Loss_s$ are the absolute construction cost and absolute expected annual loss for S^{th} scheme, respectively, and $s = 1$ indicates the benchmark. Besides, $Loss_s$ can be achieved based on Eq. (8).

$$Loss_s = EAL_s * C_s \tag{8}$$

where EAL_s is the EAL of the S^{th} scheme shown in Figure (8b), previously.

Considering the Eqs. (7) and (8), 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:

$$BR_s = \left(\frac{C_{s=1}}{C_s}\right)^2 \times \left(\frac{EAL_{s=1}}{EAL_s}\right) \tag{9}$$

where $EAL_{s=1}$ is the EAL of the existing Mashhad cable-stayed bridge with Pot bearing device.

Take 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 (3) along with its inputs including RCA data and loss assessment data.

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.

Table 3. The CLB data and results.

Bearing Device	CLB Inputs			CLB Output
	Material Volume Coefficient from RCA	Bridge System $\left(\frac{C_{s=1}}{C_s}\right)$	$\left(\frac{EAL_{s=1}}{EAL_s}\right)$ 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

5. Conclusions

In this paper, the common process of seismic risk assessment is developed using simultaneously analysis 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:

- 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, the improvement of seismic control device is associated with an increase in construction costs. Therefore, it was necessary to analyze how much this improvement can contribute to the reduction in seismic losses, and if the increase in construction costs was economically justifiable.
- Fragility curves show that, the critical responses of the bridge with LRB is the pylon displacement and it was not unexpected considering free movement of LRB for damping release mechanism. Besides, the critical response of bridge with PB and LB is the pylon section curvature.
- Damage probability of pylon head displacement and the cable tension increases in accordance with the order mentioned in item number 1. Moreover, damage probability of pylon section curvature and bearing displacement decreases in accordance with the aforementioned order.
- Damage probability of the whole bridge system decreases in accordance with the order mentioned in item number 1.
- 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.
- Expected annual loss decreases in accordance with this order: Pot Bearing, Elastomeric Bearing, Lead Rubber Bearing.
- From item 1 and 6, it can be concluded that the decrease in seismic loss is associated with the increase in construction costs. Thus, it was necessary to investigate how much this increase in cost can contribute to the reduction in seismic losses, and if the increase in construction costs was economically justifiable. This issue checked out in this paper using simultaneous analysis of the costs and losses. The results of this comparison analysis presented in the following remarks.
- The change of seismic control device from the existing Pot Bearing to Elastomeric Bearing in Mashhad bridge caused a 5.3 percent increase in construction costs and 6.6 percent decrease in expected annual loss.
- Simultaneously considering the costs and losses shows that, the change of seismic control device from the existing Pot Bearing to Elastomeric Bearing in Mashhad bridge caused 3.3 percent decrease in total profitability measure (BR value).
- The improvement of seismic control device from the existing Pot Bearing to Lead Rubber Bearing in Mashhad Bridge caused a 6.4 percent increase in construction costs and 18 percent decrease in expected annual loss.
- Simultaneously considering the costs and losses shows that the change of seismic control device from the existing Pot Bearing to Lead Rubber Bearing in Mashhad Bridge caused a 7.8 percent increase in total profitability measure (BR value).
- This paper indicates that the improvement of seismic control device from the existing Pot Bearing to Lead Rubber Bearing is an economically justifiable decision for cable-stayed bridges with middle spans approximately 100 meters long such as Mashhad cable-stayed bridge.

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