PROPOSE AN OPTIMAL CABLE CONFIGURATION FOR LALICABLE-STAYED BRIDGE USING SEISMIC RISK ASSESSMENT

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ABSTRACT

Generally, in order to reduce the amount of calculations, engineers analyse and design the structures using simple force based methods such as quasi-static or spectral methods. However, we can use seismic risk assessment to study the damage due to probable earthquakes, instead of investigating force or displacement responses which are the basis of simple design methods. About the main purpose of this paper, it should be said that selecting the cable configuration is always a challenge in cable stayed-bridges designing. It is because of that, the changing cable configuration in a cable - stayed bridge, firstly affects the period and damping of the structure, and secondly changes the forces in other components of the bridge which results in change of their required dimensions. Based on this, it can be concluded that a change in cable configuration will result in change in seismic risk, and a change in construction costs. So it is necessary to thoroughly investigate the common cable configurations in order to select the optimal option. In this paper, we will try to perform the seismic design on a cable - stayed bridge with Semi Fan and two other common configurations. So we will be able to relatively compare the dimensions and costs of three mentioned schemes. Then, the loss due to probable earthquakes can be obtained for each scheme using the Seismic Risk Assessment process performed in two steps: Fragility Assessment and Loss Assessment. In the end, by using the proposed Cost-Loss-Benefit (CLB) method and comparative-financial approach, the construction costs will be investigated simultaneously along with losses due to probable earthquakes. The CLB method will determine the optimal cable configuration by defining the Benefit Ratio (BR) as a profitability measure. Based on BR values, the Fan cable configuration is proposed as the optimal cable configuration for studied bridge.

INTRODUCTION

Generally, in order to reduce the amount of calculations, engineers analyze and design the structures using simplified methods such as quasi-static or code-based spectral methods. While there are more accurate methods such as Capacity Spectrum Method (CSM), Time History Analysis (THA) and Incremental Dynamic Analysis (IDA) for research purposes. Considering the accurate methods mentioned above, seismic risk assessment can be used to study the seismic damage and loss, instead of investigating force or displacement responses which are basis of code-based methods. Thus, a more accurate judgement can be made among possible structural variants designed by code-based methods.

Seismic risk assessment usually consists of two parts: fragility assessment in the form of damage probability, and loss assessment in the form of Expected Annual Loss (EAL) (Mander et al. 2007). In this regard, many researches have been conducted in seismic fragility assessment of bridges as a life line of transportation. On the other hand, in some earthquakes, cable-stayed bridges are severely damaged, such as Chi-Lu Bridge in Taiwan during the Chi-Chi earthquake (Chang et al. 2004). Consequently, some of the recent researches examine the seismic vulnerability assessment of this type. In this field, the fragility relationships of a benchmark cable-stayed bridge are presented by Barnawi and Dyke (2014), or Casciati et al. (2008) examined the effectiveness of utilization of passive devices in these bridges, by performing a comparison study on the fragility curves of the bridge.

About the common cable configuration of cable-stayed bridge as the main issue of this paper, Kawashima et al. (1993) have demonstrated that the period and damping of the cable-stayed bridge depend heavily on the type of cable configuration. Also it is obvious that changing the cable configuration affects the forces in structural components of the bridge, thus changing their required dimensions. So In this study, three different benchmarks with different cable configurations for an existing cable-stayed bridge will be designed, and the required dimensions and construction costs of the three benchmarks have been compared. Then, the EAL can be obtained using the common process of Seismic Risk Assessment, for all of benchmarks. Finally, the decision-making process is conducted by developing the mentioned common process to select the optimal cable configuration.

MODELING THE BENCHMARKS AND CONDUCTING RELATIVELY COST ANALYSIS (RCA) ON THEM

The case study of paper as the basis for generation of benchmarks, is the Lali cable-stayed bridge which is located in Iran. The important parts of Lalibridge are plotted in Figs. 1(a)-(c).

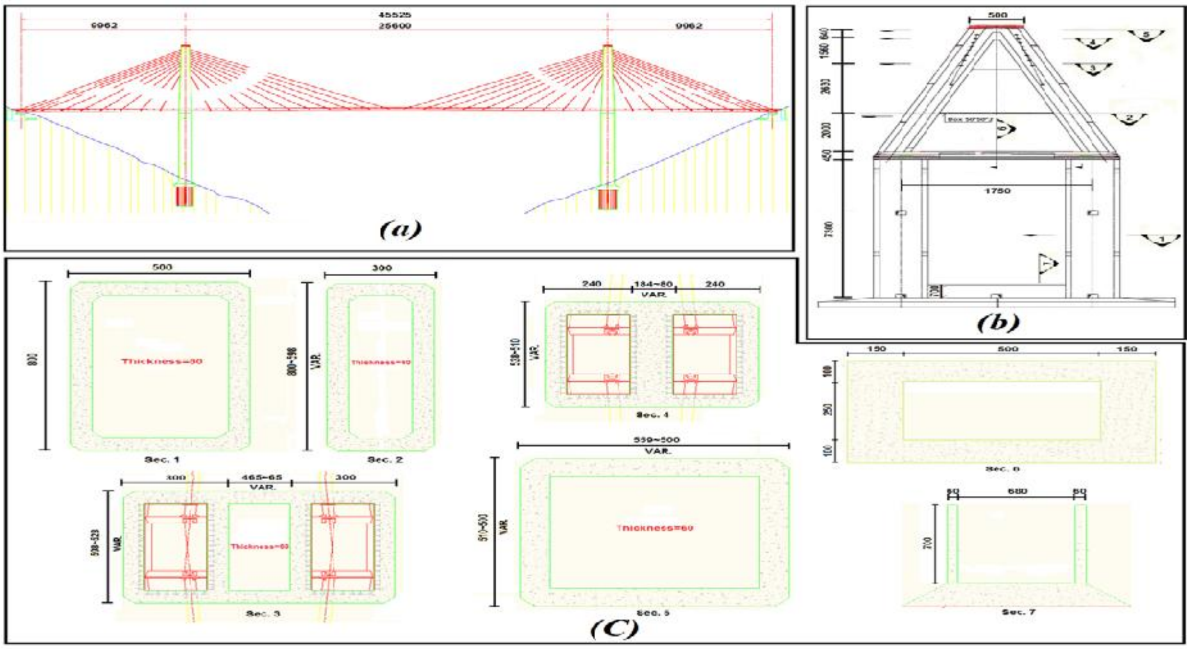

Figure 1.(a) Bridge elevation, (b) Tower side view, (c) Cross sections. Measurements in (cm)

In this study, like many researches in the field of seismic performance assessment of bridges such as (Chang et al. 2004, Calvi et al. 2010, Jara et al. 2013), SAP2000 software has been selected to perform seismic analysis of the studied bridge. Finite element modeling in SAP2000v15 was done with the help of recommendations of Aviram et al. (2008), and SAP2000 software manual (Computers and Structures Inc., 2005). Also different aspects of nonlinear behavior were considered as follows: Due to the nonlinear effects caused by sagging, the cables are modeled by truss element with equivalent elastic modulus based on the Eq. (1) (Pang et al. 2013).

$$E_{eq} = \frac{E}{1 + \frac{w(L)^2}{12T^3} EA} \tag{1}$$

Where for cable, Eeq is the equivalent elastic modulus, E is the elastic modulus of the material, "L" is the horizontal projection length, A is the cross sectional area; and T is the tension force.

The materials including concrete and reinforcement bars, are defined by Mander et al.(1998) model, and ASTM model (Caltrans 2004), respectively. The towers have been simulated by assigning distributed plasticity fiber model to the nonlinear beam-column element (Aviram et al. 2008). A bending plastic hinge is also added to both endpoints of the cross beam of tower. The deck concrete slab, the girders, and the side span piers aremodeled by shell elements, elastic beam-column element, and nonlinear link element, respectively. Meanwhile, because of the large geometric dimensions of the structure, the nonlinear P-Δ effect is taken into account. Also, LRB connection between deck and beam can be considered as an isolator link element with a bilinear relationship.

On the other hand, damping of a cable-stayed bridge can be estimated using an analytical process which has been proposed by Kawashima et al. (1993). Thus, the bridge was divided to three substructures including tower, deck and cable anchoring and bearing device which are the main sources of energy dissipation. Then the free oscillation test was applied to each substructure. Finally, based on superposition principle about energy, damping ratio of bridge has been determined.

Now the conceptual seismic design of cable-stayed bridges provided by Calvi et al. (2010) was used, to check the existing bridge with Semi-Fan configuration and generate two other benchmarks with Fan and Harp cable configurations. The common cable configurations are shown in Figure2.

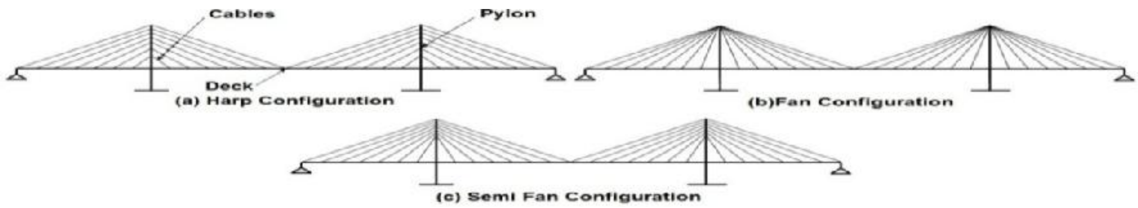

Figure 2. Three common types of cable configuration

The designed benchmarks show that a change in cable configurations, causes changes in design forces and consequently in required dimensions of the three main substructures which are tower, deck and cables. So, Relatively Cost Analysis (RCA) can be conducted using material volume which is used in different benchmarks, as follows: If the material usage in different benchmarks is expressed relatively, then based on contribution percentage of substructures in total cost of the bridge, the cost construction of different benchmarks can be estimated, relatively. Accordingly, the material usage for the existing bridge is stated by the value "1", and the relative material usage for the two other benchmarks is given in Table 1 for different substructures. The values in parentheses indicate the contribution percentage of the substructure in the total cost of the bridge. Finallythe relative construction costs of benchmark bridges are calculated based on the aforementioned descriptions.

Table 1. RCA inputs and outputs

Cable configuration	Inputs				Outputs
	Material Volume Coefficient of Substructures				relative construction costs
	Towers	Deck	Cables	Others	
Semi-Fan	1(22%)	1(39%)	1(20%)	1(19%)	1
Fan	0.97(21%)	1.18(42%)	1.08(21%)	1(16%)	1.086
Harp	0.98(19%)	1.35(45%)	1.27(24%)	1(12%)	1.219

DEVELOPED SEISMIC RISK ASSESSMENT (DSRA) PROCESS AND CONDUCTING IT ON BENCHMARKS

Different configurations can be affected the other mechanisms such as gravitational behavioror seismic force transition mechanism. Sothe probable loss calculated for each design scheme alongside its construction cost have to be studied usingproposed process of Developed Seismic Risk Assessment (DSRA) consisting of following (a) to (c) parts:

A) FRAGILITY ASSESSMENT

In this study, CSM-based fragility assessment is applied to obtain the fragility curves. The CSM method is selected because it requires less computation than THA and IDA methods, While its accuracy in generating fragility curves for bridges has been proven by Banerjee and Shinozuka (2007).

Step 1: Ground motion selection

In order to perform the seismic analysis in probabilistic domain, based on uniform hazard spectrum approach, 100 records from PEER ground motion Database were selected considering the seismicity of the region in which the Lalibridge is located.

Step2: Generation of Probabilistic Seismic Demand Model (PSDM) using CSM

In this step, seismic analysis is done in the form of CSM process which is using capacity curve alongside demand spectrum to determine the Performance Point (PP). To determine the capacity curve, pushover analysis is conducted based on the procedure of Coupled Nonlinear Static Pushover (CNSP) the philosophy of which is provided by Camara and Astiz (2012) shown in Figure3.

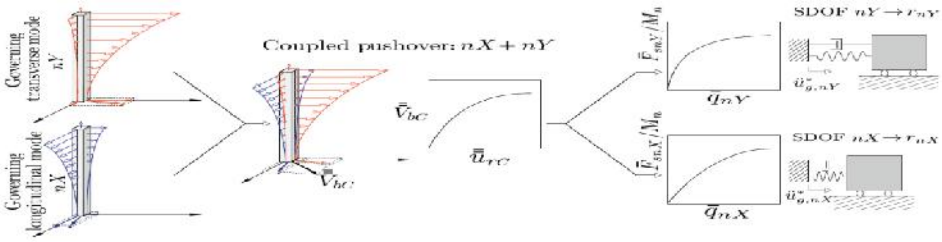

Figure 3. Summary philosophy of CNSP (Camara and Astiz 2012)

In this process, the weighted total of load distribution patterns of X and Y directions, is obtained tocoupled push the structure. Thus, the capacity curves are obtained as base shear versus displacement of the control point in horizontal and vertical directions based on Camara and Astiz's(2012) recommendations. On the other hand, the demand spectrum as the indicator of the effects of earthquake records on the structure, should be generated from record spectrum which is described in step 1. The capacity and demand curves should be converted to Acceleration- Displacement Response Spectra (ADRS) format using existing procedures(Banerjee and Shinozuka 2007). In the occurrence moment of performance point, maximum of four structural responses including tower head displacement, critical tower section curvature, cable tension, and critical stress on deck, have been recorded. Now, it is necessary to express seismic responses, as a Probabilistic Seismic Demand Model (PSDM), in order to explain the existing uncertainties. Soa common power relationship (Barnawi and Dyke 2014), 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 $S_a(T_1)$, and both *a* and *b* are the scaling coefficient.

Step 3- Defining the Damage Criterion (DC) for cable-stayed bridge

Damage states of bridges are classified into four levels: Slight, Moderate, Extensive, and Collapse (Mander et al. 2007). In order to control the exceeding of a monitored response from a damage state, Damage Criterion (DC) is defined as a two parameter lognormal distribution proposed by Khan et al. (2006) and Pang et al. (2013),and are given in Table 2.

Table 2. 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 development

Considering the lognormal distributions assigned to the PSDM and DC, the probability of exceeding the damage state *i* can be calculatedbased on Eq. (3):

$$P_f = 1 - \Phi\left[\frac{\ln\left(\frac{\mu_{EDP}}{\mu_{DC}}\right)}{\sqrt{\beta_{EDP}^2 + \beta_{DC}^2}}\right] \tag{3}$$

Where $\emptyset$ is the standard normal cumulative distribution function, if P_f is the probability of exceedance of damage state *i*, then μ_{EDP} 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 DC in damage state *i*, respectively.

Then, fragility of the whole bridge is calculated based on component level approach which has been proposed by (Nielson and Desroches 2007). Based on their study, if a component exceeds a certain damage state, it means that the whole bridge is experiencing the state. Thus, the bridge fragility can be obtained using probability union principle and based on Eq. (4) (Nielson and Desroches 2007).

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

Where $P_f[bridge_{system}]$ is the probability of the 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*, *j* is the number of monitored response of the bridge, and is the probability union function.

This process, consisting of steps 1 to 4, is done for three benchmarks which are designed in section 2. Thus, the fragility curves of the components and bridge system for different damage states, alongside differentcable configurations employment can be obtained. Fragility curves of the components and whole bridge system are plotted in Figures. 4-5 and Fig. 6, respectively.

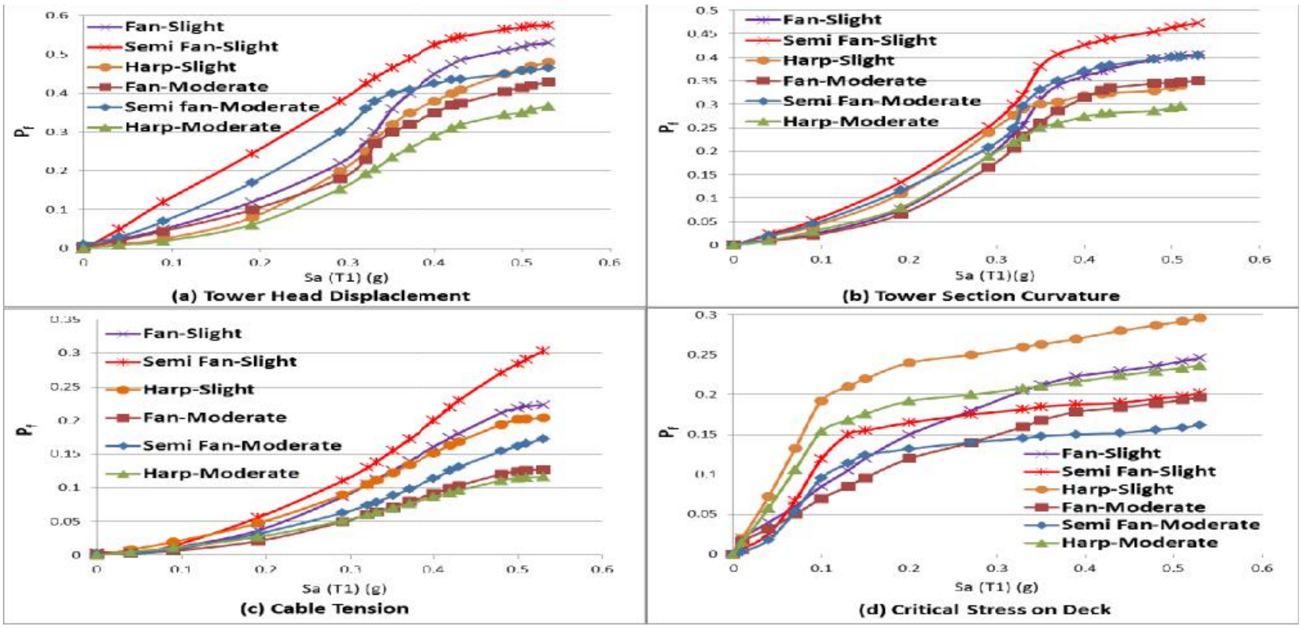

Figure 4. Fragility curves of components (Slight and Moderate damage state)

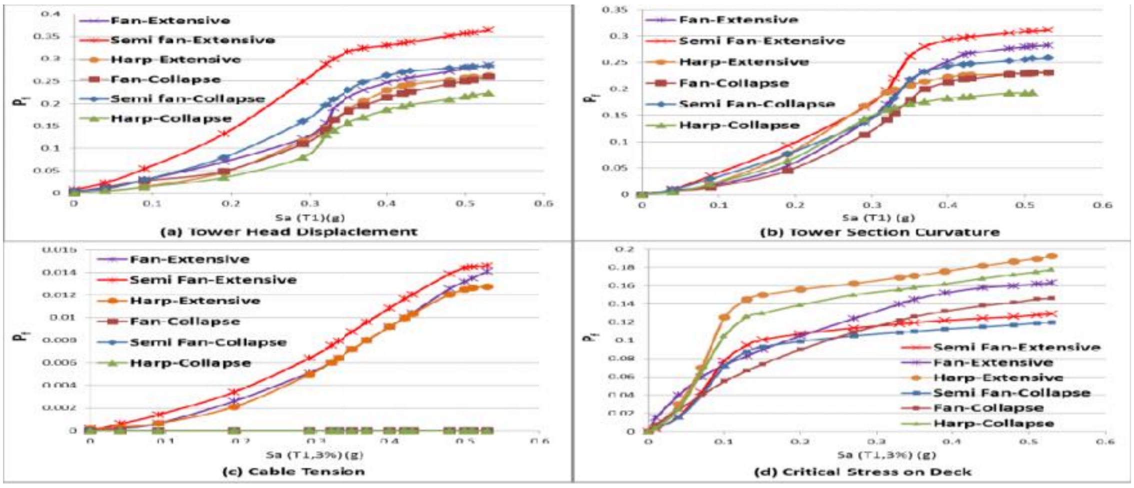

Figure 5. Fragility curves of components (Extensive and Collapse damage state)

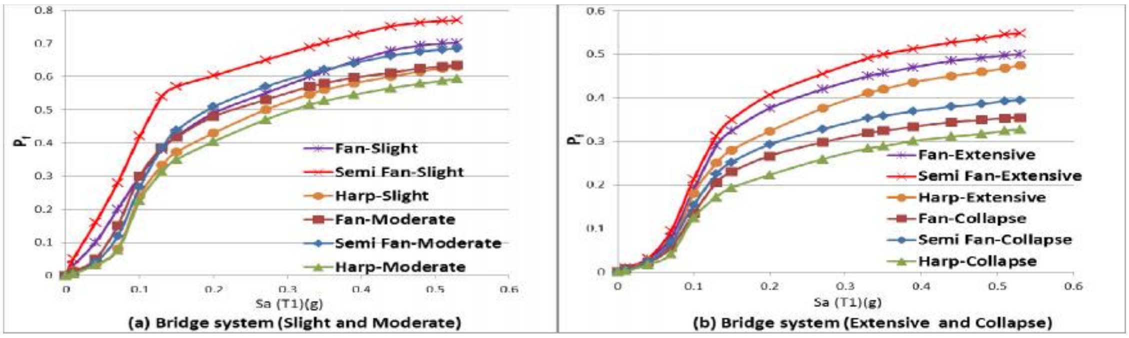

Figure 6. Fragility curves of whole bridge system

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

B) LOSS ASSESSMENT OF BENCHMARKS

In this part, First, the total loss ratio will be obtained for different values of intensity measure, by combining the damage probability of the bridge system and Loss Ratio (LR), based on Eq. (5).

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

Where P is the probability function, DSi is the ith damage state, im is the earthquake intensity measure and LRi is the loss ratio in ith damage state which is assumed based on (Mander et al. 2007)

Total loss ratio is generally reported versus the annual frequency of corresponding value of the intensity measure. The annual frequency can be obtained based on hazard curve of the studied bridge region (Gholipour et al. 2008). Note that the Sa(T1) must be transformed into the corresponding PGA based on the record spectrums. EAL is obtained by calculating the area beneath total loss ratio curve. The hazard curve along with total loss ratio and their EAL, are illustrated for the benchmarks in Fig. 7.

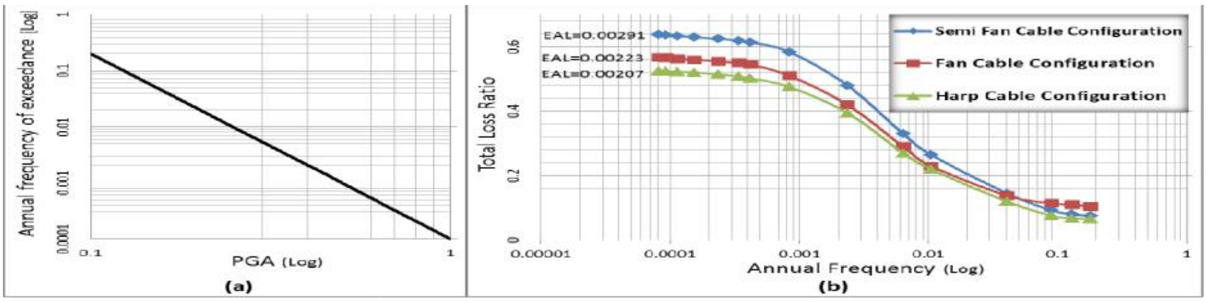

Figure 7. (a) Hazard curve, (b) Total Loss Ratio curves

It can be deduced from Fig. 9 that utilization of Harp, Fan, and Semi-Fan cable configurations increases the seismic loss in that order. However, solely considering the loss is not sufficient for selecting the optimal configuration and it is necessary to consider the construction costs, simultaneously using final step of the proposed DSRA process as following description.

C) COST-LOSS-BENEFIT (CLB) ASSESSMENT

A definitive decision making about optimal cable configuration is only performed when the construction cost for each scheme is analyzed alongside its probable seismic loss. So, the CLB assessment using the results of RCA process and EAL values to select the optimal cable configuration for the Lalibridge, by defining a criterion called Benefit Ratio (BR) as a profitability measure. The BR value shows the total profitability resulted from using an alternative design scheme instead of existing design scheme, considering changes in construction cost and in seismic losses, simultaneously.So, the BR value for the existing Lalibridge with Semi-Fan cable configuration is assumed to be 1 and the BR value for other benchmarks can be obtained based on the Eq. 6.

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

Where Cs and Losss are the absolute construction cost and absolute expected annual loss for Sth benchmark, respectively, Cs=1 and Losss=1 are the mentioned items for the expected benchmark with Semi-Fan cable configuration. Also, Losss can be achieved based on Eq. 7.

$$Loss_s = EAL_s * C_s \quad (7)$$

Where EAL_s is the EAL of the *S*th benchmark which has been shown in Fig. 7(b), previously.

Using 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:

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

Where $EAL_{s=1}$ is the EAL of the benchmark with Semi-Fan cable configuration.

Thus, by combining the three factors ofcost, loss, and benefit, the CLB assessment achieves the optimal cable configuration. Notice that, a BR value for a benchmark greater than 1 indicates that the benchmark is relatively more beneficial than the existing scheme. The output of this including BR values are reported in Table 3 along with its inputs including RCA results and loss assessment results.

Table 3. The CLB inputs and outputs of Lali cable-stayed bridge

Cable configuration	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
Semi Fan	1	1	1	1
Fan	1.086	0.921	1.305	1.107
Harp	1.219	0.820	1.406	0.945

Based on BR values, the fan cable configuration has been recognized as the optimal cable configuration for Lali cable-stayed bridge. Mathematically, using the fan type instead of Semi Fan type in Lali Bridge caused a 23 percent reduction of loss due to earthquake, while it only increased the construction cost by 10%.

CONCLUSION AND REMARKS

This paper has investigated the simultaneous effect of cable configuration of cable-stayed bridges on construction cost and seismic risk. This was done by conducting Relatively Cost Analysis (RCA) alongside Developed Seismic Risk Assessment (DSRA), with a Financial-Comparative (FC) approach. In the end, the most important results of the paper are explained as follows:

1- Proposed relations by Kawashima et al. (1993) were accurate enough for estimating the parameters related to structural damping of the studied cable-stayed bridge.
2- The order of cable configurations in which the structural damping of cable-stayed bridge increases is: Semi Fan, Fan, and Harp.
3- The amount of material needed for designed cable-stayed bridge with different cable configurations increases in accordance with the order mentioned in the item number 2. In other words, increase in structural damping is associated with increase in construction costs. So it was necessary to investigate how much this increase in damping can contribute to reduction in seismic losses, and if the increase in construction costs was economically justifiable.
4- Damage probability of three responses of tower head displacement, tower section curvature and Cable tension, decreases in accordance with the order mentioned in item number 2. And damage probability of stress on deck increases in accordance with the order mentioned in item number 2.It is because stress on deck depends on vertical displacement and consequently vertical damping which decreases in this order:Semi Fan, Fan, and Harp cable configuration.
5- Fragility curves show thatTower head displacement is the critical response of the structure.which was predictable considering the low stiffness of “A” shape tower.
6- The changing trend of damage probability of the bridge system is similar to the three responses mentioned in item number4.
7- The effect of cable configuration on fragility curves is stronger for earthquakes with higher intensity measures.This is due to the fact that by changing the cable configuration, the structural damping also changes, and damping factor becomes more prominent in more intense earthquakes.
8- (EAL) decreases in accordance with the order mentioned in item number 2.
9- The employmentof Fan type instead of existing Semi Fan type in Lali Bridge caused a 10.7 percent increase in total profitability measure (BR value).
10- The employment of Harp type instead of existing Semi Fan type in Lali Bridge caused a 5.5 percent reduction in total profitability measure (BR value).
11- This paper indicates that selecting the Fan cable configuration instead of Semi Fan or Harp type is an economically justifiable decision for cable-stayed bridges with middle spans approximately 250 meters long.

REFERENCES

Aviram A, Mackie K and Stojadinovic B (2008)Guidelines for nonlinear analysis ofbridge structures in California, Pacific Earthquake Engineering ResearchCenter(PEER), University of California, Berkeley

Banerjee S and Shinozuka M (2007) Nonlinear static procedure for seismic vulnerability assessment of bridges. *Computer-Aided Civil and Infrastructure Engineering*, 22(4): 293-305

Barnawi W and Dyke S (2014) Seismic fragility relationships of a cable-stayed bridge equipped with response modification systems, *J. Bridge Eng.* 19

Caltrans SDC (2004)Caltrans Seismic Design Criteria version 1.3, California Department of Transportation, Sacramento, California

Calvi GM, Sullivan TJ and Villani A (2010) Conceptual Seismic Design of Cable-Stayed Bridges.*Journal of Earthquake Engineering*, *14*(8): 1139-1171

Camara A and Astiz MA (2012) Pushover analysis for the seismic response prediction of cable-stayed bridges under multi-directional excitation.*Engineering Structures*, 41: 444-455

Casciati F, Cimellaro GP and Domaneschi M (2008) Seismic reliability of a cable-stayed bridge retrofitted with hysteretic devices, *Comput. Struct.*, 86(17): 1769–1781

Chang KC, Mo YL, Chen CC, Lai LC and Chou CC (2004) Lessons learned from the damaged Chi-Lu cable-stayed bridge, *J. Bridge Eng.*, 9(4): 343–352

Computers and Structures Inc. (CSI) (2005)SAP2000-Linear and nonlinear static and dynamic analysis and design of three-dimensional structures: basic analysis reference manual, CSI, Berkeley, California

Gholipour Y, Bozorgnia Y, Rahnamaa M and Berberian M (2008)Probabilistic seismic hazard analysis, phase I-Greater Tehran Regions , Technical Report, College of Engineering, University of Tehran

Jara JM, Galván A, Jara M and Olmos B (2013) Procedure for determining the seismic vulnerability of an irregular isolated bridge, *Structure and Infrastructure Engineering,* 9(6): 516-528

Kawashima K, Unjoh S and Tunomoto M (1993) Estimation of Damping Ratio of Cable-Stayed Bridges for Seismic Design. *J. Struct. Eng.*, 119(4): 1015–1031

Khan RA, Datta TK and Ahmad S (2006) Seismic risk analysis of modified fan type cable stayed bridges, *Engineering structures*, 28(9): 1275-1285

Mander JB, Priestley MJN and Park R (1988) Theoretical stress-strain model for confined concrete, *J. Struct. Eng.*, 114(8): 1804–1826.

Mander JB, Dhakal RP, Mashiko N and Solberg KM (2007) Incremental dynamic analysis applied to seismic financial risk assessment of bridges, *Engineering Structures*, 29(10): 2662-2672

Nielson BG and DesRoches R (2007) Seismic fragility methodology for highway bridges using a component level approach, *Earthquake Eng. Struct. Dynam.*, 36(6): 823–839

Pang Y, Wu X, Shen G and Yuan W (2013) Seismic fragility analysis of cable-stayed bridges considering different sources of uncertainties, *J. Bridge Eng.*, 19(4)