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SEISMIC VULNERABILITY ASSESSMENT OF A LONG-SPAN CABLE-STAYED BRIDGE ISOLATED BY SMA WIRE-BASED LEAD RUBBER BEARING

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Abstract: The seismic performance of a newly developed smart isolation bearing, called shape memory alloy wire-based lead rubber bearing (SMA-LRB) has been studied in detail. In this regard, the efficiency of such smart isolation systems for the seismic response control of long-span cable-stayed bridges has also been verified. However, their reliability in isolating such huge structures has not been thoroughly investigated. The aim of this study is to evaluate the seismic fragility of a cable-stayed bridge isolated by SMA-LRBs. The Sutong Cable-stayed Bridge in China, with a main span of 1088 m, is taken as case study. A developed constitutive model of SMA-wire based rubber bearings was implemented in OpenSees and a 3D finite element model was generated in the same software. The pier, tower, and isolation system were chosen as 3 major vulnerable components. Results show that equipping lead rubber bearing with SMA wire increases the reliability of the bridge. The bridge system equipped with SMA-LRB undergoes damage with a smaller risk compared to LRB.

1 INTRODUCTION

In the last decades, cable-stayed bridges are gaining popularity throughout the world (Casciati et al., 2008; Ren and Obata, 1999). These bridges are built as the critical lifeline facilities of local and national transportation systems. Considering the flexibility and low inherent damping, cable-stayed bridges are vulnerable to seismic events (Pang et al., 2013; Chang et al., 2004). In this regard, it is crucial to protect such huge structures against earthquakes and investigate their functionality under different ground excitations. In order to improve the seismic performance of cable-stayed bridges, various dynamic control devices have been developed and used for such huge structures. Among different types of dynamic control mechanisms, base isolators such as natural rubber bearings (NRB), lead rubber bearings (LRB) and high damping rubber bearings (HDRB) are the simplest way and one of the most common used techniques in bridge structures (Alam et al., 2012). Due to the lateral flexibility and energy dissipation capacity, they can effectively isolate the structures and prevent them from damage during earthquakes. Using shape memory alloy wires incorporated with the isolators has also been proposed by several researchers (Attanasi et al., 2009; Choi et al., 2010; Hedayati Dezfuli and Alam, 2016; Ozbulut and Hurlebaus, 2010). The effectiveness of such smart isolation devices has been validated in different types of structures e.g. highway bridges and buildings. Considering the critical rule of cable-stayed bridge, if such bridge collapses during earthquakes, tremendous loss of life and property can be caused. Hence, the vulnerability of cable-stayed bridges should be evaluated carefully to make sure the safety of the structures.

The fragility curves are widely used to evaluate the conditional probabilities that a structural demand exceeds the limit-state capacity over a prescribed demand. Analytical approach has been widely adopted in the development of the fragility curves, when past damage data are absent or ground motions are insufficient or not available. There is limited works on the fragility analysis of cable-stayed bridges. Casciati et al. (2008) evaluated the fragility curves of a cable-stayed bridge retrofitted with hysteretic devices based on the analytical approach. Pang et al. (2014) proposed an alternative procedure for seismic fragility analysis based on the uniform design method. The fragility curves of different components considering different uncertainties were compared. The numerical results showed that the bridge system is more fragile than any component of bridges. Barnawi and Dyke (2014) assessed the vulnerability of a benchmark cable-stayed bridge equipped with magneto rheological (MR) dampers. The results of fragility relationships proved the efficiency of MR dampers in mitigating the effects of ground motions on the cable-stayed bridge. The same authors have thoroughly investigated the effectiveness of SMA wire-based rubber bearings in isolating cable-stayed bridges in the recent studies. However, the reliability of such smart isolation devices in isolating such huge structures has not been thoroughly investigated. Hence, extensive research work is necessary to be done on the assessment of vulnerability cable-stayed bridge equipped with SMA wire-based rubber bearings.

The objective of this study is to evaluate the seismic vulnerability of cable-stayed bridges isolated by smart lead rubber bearings in which SMA wires are wrapped around LRBs in a double-cross configuration. The new type of smart bearing was introduced by Hedayati Dezfuli and Alam (2015). However, its effect on the seismic fragility of cable-stayed bridges has not been investigated. In this regard, a long-span cable stayed bridge is taken as a case study. SMA wire-based LRBs are used as the isolation systems. 3D dynamic analytical models are generated in OpenSees (McKenna et al., 2000) software. The fragility curves of two major vulnerable components, i.e. tower sections and bearings, are generated based on incremental dynamic analyses (IDA). A total of 20 near-fault ground motions with peak ground acceleration (PGA) values ranging from 0.4g to 1.58g are chosen as the seismic input.

2 BRIDGE CHARACTERISTICS AND DYNAMIC ANALYTICAL MODEL

A second-longest cable-stayed bridge in the world, i.e. Sutong Cable-stayed Bridge (SCB) with a central span of 1088 m connecting Suzhou and Nantong cities in China, is taken as an example in this study. It consists of two inverted-Y pylons, 272 cable members with double plane fan configuration, a streamlined flat steel box girder and 4 auxiliary piers in each side span. The configuration of the bridge is presented schematically in Figure 1. The existing dampers in this bridge are not considered. In order to validate the effectiveness of SMA wire-based LRB in improving the seismic performance of the bridge, a total of 54 isolators have been designed according to the recommendation from AASHTO (2014) and Earthquake Engineering Handbook (2003) and arranged along the longitudinal direction, including 3 and 9 isolators at each pier and tower location, respectively. The smart rubber bearing used in this study consists of lead rubber bearing and double cross configuration of SMA wires (DC-SMAW) (See Figure 1). The corresponding constitutive models have been proposed by Hedayati Dezfuli and Alam (2015). According to the newly proposed model, a computer code was implemented in OpenSees and a new element representing the seismic behavior of such smart bearing was generated in the library of OpenSees. The lead rubber bearings have the plan area of 850 mm by 850 mm with identical thicknesses of rubber layers (266 mm). A Ferrous SMA material, i.e. FeNiCoAlTaB, was utilized and the cross sectional diameter was 14 mm. The mechanical properties of the smart rubber bearings are given in Table 1.

Two different configurations of cable-stayed bridges are adopted in this study, i.e. one is the bridge isolated by LRBs; another one is the system isolated by SMA-LRB (SMA-LRBS) in which SMA-based isolators are used. A three dimensional finite element model of SCB was developed in OpenSees. The steel girders and transverse diaphragms are assumed to remain in elastic stage under earthquake and are modeled using elastic beam-column element. The girder is discretized based on the suspended points of the stayed cables. 3D tension-only truss elements using Ernst method are used to model the cables. Girders are divided into a number of small discrete segments. The mass of each segment is equally distributed between two adjacent nodes in the form of point mass. The fiber elements are used to model the towers and piers. Chang and Mander (1994) uniaxial steel model simulates the behavior of the reinforcements. Concrete 01 is used to model the unconfined and confined concrete. It is assumed that the bridge is supported by bedrock. The soil-structure interaction effects are neglected.

Table 1: Mechanical properties of the LRB and DC-SMA wire.

LRB bilinear model		DC-SMAW model	
Initial stiffness, K_0 (kN/mm)	14.8	Initial stiffness, $K_{0,w}$ (kN/mm)	4.66
Yield force, F_y (kN)	150	Intermediate stiffness, K_i (kN/mm)	16.42
Post-yielding hardening ratio, *r*	0.152	Re-centering stiffness, K_r (kN/mm)	2.31

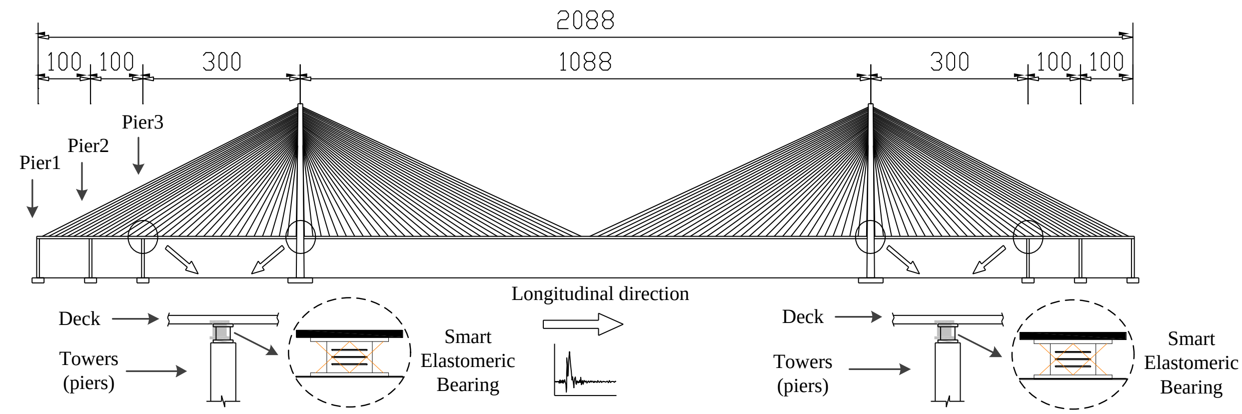

Figure 1: The configuration of the SCB (meters)

3 FRAGILITY FUNCTION METHODOLOGY

Fragility theory is used to investigate the probability levels that the seismic demand of a structure, D, exceeds the capacity of the structure, C. The level of seismic loading can be specified as a specified intensity measure (IM). The vulnerability of a structure can be defined as Eq. 1 (Hwang et al. 2001).

$$F = P[LS|IM] = P[D \geq C|IM] = \Phi\left[\frac{\ln(S_d/S_c)}{\sqrt{\beta_{D|IM}^2 + \beta_c^2}}\right] \tag{1}$$

where LS is limit state of a bridge component; Φ is the cumulative distribution function of the standard normal distribution, S_d and S_c are the median estimates of the demand and the capacity, respectively, and $\beta_{D|IM}$ and β_c are logarithmic standard deviations of the demand and the capacity, respectively.

In this study, the correlation between the engineering demand parameters, EDPs, and the ground intensity measures, IMs, is established according to a probabilistic seismic demand model (PSDM). The scaling approach is used to develop the PSDM (Bhuiyan and Alam 2012; Zhang and Huo 2009). In this method, the ground motions are scaled to selective intensity levels and an incremental dynamic analysis (IDA) is conducted at each intensity level. It is assumed that the relationship of EDP and IM is represented by a two-parameter lognormal probability distribution (e.g. a power model) (Song and Ellingwood 1999).

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

where *a* and *b* are regression coefficients and can be determined from the nonlinear time history response of the structure. In fragility analysis, limit states (LS) are used to provide a qualitative representation for a bridge component, which can be classified to slight, moderate, extensive, and collapse (FEMA 2003). In this work, the towers and isolation bearings are assumed as the main vulnerable components of the cable-stayed bridge. The drift ratio, *θ*, for the tower and the shear strain, *γ*, for the isolation bearings are chosen as damage indices to capture the limit states. The damage states or limit states of the bridge components are shown in Table 2. The fragility function of component level is not accurate to represent the system level fragility function. The first order reliability theory can be utilized to determine the system fragility according to Eq. 3.

$$\max_{i=1}^{n}\left[P\left(F_i\right)\right] \le P\left(F_{system}\right) \le \prod_{i=1}^{n}\left[1-P\left(F_i\right)\right] \quad (3)$$

where $P(F_i)$ and $P(F_{system})$ are the probabilities of reaching the prescribed limit of damage state for the component and system, respectively.

Table 2: Damage/limit states of tower and elastomeric bearing

Bridge Component	EDP	Limit States				Reference
		Slight	Moderate	Extensive	Collapse	
Tower	Drift Ratio	0.015> θ>0.007	0.025> θ>0.015	0.050> θ>0.025	θ>0.050	Yi et al. 2007
Elastomeric Isolator	Shear Strain	γ>100%	γ>150%	γ>200%	γ>250%	Zhang and Huo 2009

Table 3: Description of the near-fault ground motions used in the analysis

Earthquake	Station, Component	Rrup (km)	PGA (g)	PGV (cm/s)
1999 Chi-Chi	TCU052-NS	1.84	0.45	172.34
1999 Chi-Chi	TCU065-EW	2.49	0.78	132.29
1999 Chi-Chi	TCU068-EW	3.01	0.51	279.88
1999 Chi-Chi	TCU071-EW	4.88	0.53	69.83
1999 Chi-Chi	TCU084-EW	11.48	1.03	128.8
1994 Northridge	SCE-281	5.19	0.45	61.50
1994 Northridge	Olive View-360	5.30	0.84	130.37
1994 Northridge	Rinaldi-275	6.50	0.84	174.79
1994 Northridge	PUL-104	7.01	1.58	55
1994 Northridge	PUL-194	7.01	1.29	54.92
1971 San Fernando	Pacoima Dam(upper left)	1.81	1.22	114.20
1978 Tabas	Tabas-L1	2.05	0.85	121.22
1989 Loma Prieta	LGPC-00	3.89	0.56	94.71
1992 Cape Mendocino	Petrolia-90	8.18	0.66	90.16
1995 Kobe	JMA-NS	0.96	0.85	105.2
1995 Kobe	TAK090	1.47	0.67	123.15
1992 Landers	LCN-260	2.19	0.73	133.1
1979 Imperial Valley	E06140	1.0	0.44	66.7
1979 Imperial Valley	E07230	0.56	0.47	113.0
1986 N. Palm Springs	NPS210	4.04	0.69	65.8

Note: Rrup is the closest distance to fault rupture; PGA and PGV are the peak ground acceleration and peak ground velocity, respectively.

4 GROUND MOTIONS

The bridge is expected to be functional without any damage under low- or medium-intensity earthquakes. Based on this background, a set of 20 near-fault records with high peak ground acceleration values from 0.4g to 1.58g are chosen as the input from PEER strong motion database (PEER). The basic properties of the ground motions are listed in Table 3. The selected ground motion records are applied in the longitudinal direction. The PGA is recognized as one of the widely used intensity measures to describe the severity of the ground motion (Padgett and DesRoches 2008). Hence, IM is measured by PGA in this study.

5 RESULTS AND DISCUSSIONS

5.1 Fragility of Components

As aforementioned, two engineering demand parameters (EDPs), i.e. drift ratio for the tower and shear strain for the elastomeric isolation system, should be evaluated. Drift ratio is defined as the rotation of the bridge tower. Shear strain is defined as a ratio of the lateral displacement to the total thickness of rubber layers. According to the previous study, the rubber bearings at pier-deck location experience the maximum lateral displacement, and they are used in the fragility analyses. The coefficients of PSDMs are determined based on the regression analyses, as shown in Table 4.

Table 4: Regression coefficients of PSDMs for bridge components

Bridge Component	Drift Ratio, θ			Shear Strain, γ		
	a	*b*	$\beta_{D/PGA}$	*a*	*b*	$\beta_{D/PGA}$
LRB	0.008	0.937	0.320	93.6	1.152	0.695
SMA-LRB	0.008	0.932	0.322	73.9	1.140	0.660

Figure 2 shows the fragility curves of the tower and rubber bearing when LRB and SMA-LRB are used as different isolators. As can be observed, SMA-LRB can decrease the probability of damage of the tower at slight, moderate, and extensive limit states compared to LRB. For example, the probabilities of slight damage at a PGA of 1.0g, moderate damage at a PGA of 2.5g, and extensive damage at a PGA of 4.0g are 67%, 57%, and 10%, respectively, while in the case of SMA-LRB, the corresponding probabilities are 60%, 49%, and 8%, respectively. It means that the capacity of the tower equipped with smart bearings increases and the tower becomes less vulnerable to the seismic records. The reason is that the SMA-LRB can dissipate a higher amount of earthquake's energy. When the PGA increases above 1.5g, the tower may experience a moderate damage. It can make a conclusion that the tower could remain functional without a severe damage under strong earthquakes. Additionally, when the PGA is smaller than 4.0g, the towers are not possible to collapse. It is in accordance with the fact that considering the critical rule as a life-line facility, the bridge is designed to against any earthquakes without collapse.

Figure 2b shows the fragility curves of LRB and SMA-LRB. It can be seen that the inclusion of SMA wire in the elastomeric isolation system causes significant decrease in the seismic fragility of the LRB for the given damage states. In fact, using SMA wires with superior self-centering capacity and a flag-shaped hysteresis could effectively reduce the shear strain demand of SMA-LRBs by increasing the lateral stiffness of elastomeric isolators. Hence, SMA wires can prevent the regular bearings from over-displacement and consequently, improve their dynamic stability.

Comparing the fragilities of the tower and isolation systems indicates that the towers possess more seismic vulnerability than the isolation bearings (LRB and SMA-LRB) at slight damage states for PGA values higher than 0.88g, and at moderate damage for PGA values higher than 2.53g. The tower is less vulnerable at extensive and collapse damage states compared to the elastomeric bearings.

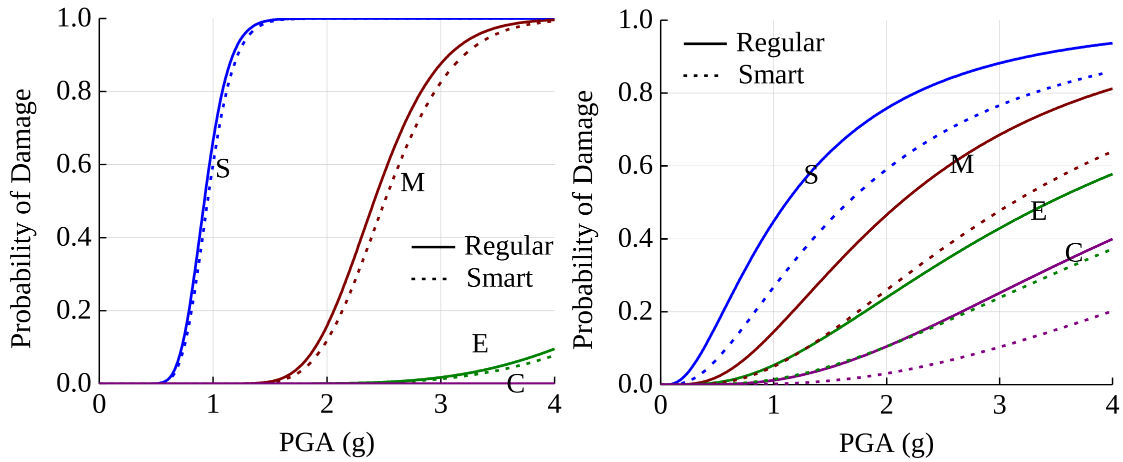

Figure 2: Fragility curves of (a) tower and (b) rubber bearing when different isolation systems (LRB and SMA-LRB) are used

5.2 Fragility of Bridge System

The fragility functions of the bridge system can be obtained from the combination of fragility curves of tower and isolation system. As mentioned before, the upper bound in the first order reliability theory is utilized to estimate the fragility of the cable-stayed bridge system. Figure 3 shows the fragility curves of the bridges isolated by LRB and SMA-LRB at different damage states.

As can be seen from Figure 3 that the bridge isolated by LRB is more vulnerable to seismic ground motions. The reason is that SMA wires with superior energy dissipation capacity can effectively decrease the seismic force and limit the displacement of the isolation bearings. It can also be observed that the different between fragilities becomes noticeable at moderate, extensive, and collapse damage states compared to the slight damage state. In other words, the SMA-LRBs are more efficient when the bridge system is at moderate, extensive, and collapse damage states.

The possibilities of damage states at four values of PGA, i.e. 1.0g, 2.0g, 3.0g and 4.0g are listed in Table 5. The relative differences between the possibilities at each level are compared. It can be seen that the difference between the possibilities decreases with the increase of the peak ground motions at moderate, extensive, and collapse limit states. At a PGA of 2.0g, using LRB in place of SMA-LRB increases the fragility of the cable-stayed bridge by 36%, 54% and 70% at moderate, extensive, and collapse level, respectively.

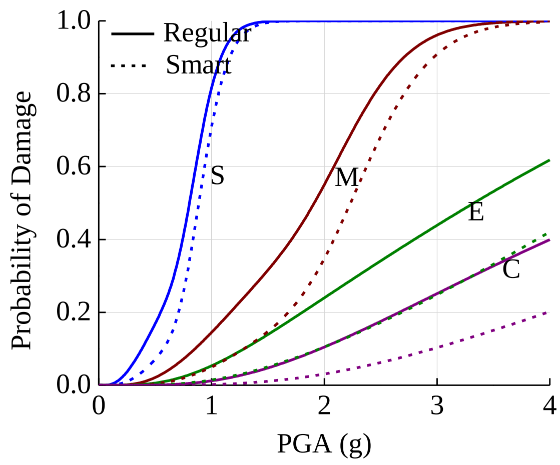

Figure 3: Fragility curves of the bridge system isolated by LRB and SMA-LRB

Table 5: Damage probabilities of the bridge system isolated by LRB and SMA-LRB

PGA (g)	EDP	Slight		Moderate		Extensive		Collapse	
		*P**	Δ*	*P**	Δ*	*P**	Δ*	*P**	Δ*
1.0	SMA-LRB	0.71	-	0.05	-	0.01	-	0.00	-
	LRB	0.82	13%	0.14	64%	0.05	80%	0.00	0%
2.0	SMA-LRB	1.00	-	0.35	-	0.11	-	0.03	-
	LRB	1.00	0%	0.55	36%	0.24	54%	0.10	70%
3.0	SMA-LRB	1.00	-	0.91	-	0.25	-	0.10	-
	LRB	1.00	0%	0.96	5%	0.44	43%	0.25	60%
4.0	SMA-LRB	1.00	-	1.00	-	0.42	-	0.20	-
	LRB	1.00	0%	1.00	0%	0.62	32%	0.40	50%

P: damage probability

Δ: relative difference between damage probabilities of SMA-LRB AND lrb

6 CONCLUSIONS

The objective of this study was to assess the fragility of a super-span cable-stayed bridge equipped with a new generation of smart elastomeric bearings under near-fault ground motions. Two different types of isolation systems, i.e. leas rubber bearing (LRB) and SMA wire-based LRB (SMA-LRB), were implemented in this bridge. The tower and the isolation systems were chosen as the major vulnerable components to develop the fragility curves of the bridge. Incremental dynamic analyses (IDA) was conducted to obtain the structural responses. A set of 20 near-fault ground motions containing non-pulse records and impulsive records were chosen as the seismic input. The main conclusions are summarized as follows:

1. Compared to LRB, SMA-LRB can dissipate more seismic energy and as a result, the towers are less vulnerable at different limit states.

2. Using SMA wires with superior self-centering capacity and a flag-shaped hysteresis could effectively improve the dynamic stability of the elastomeric isolators by increasing the lateral stiffness. Consequently, SMA wires could reduce the vulnerability of regular bearings.

3. Using SMA-LRB instead of LRB makes the bridge system less vulnerable. SMA-LRBs are more efficient when the bridge system experiences large amplitude vibration.

Here, in order to obtain the fragility of the cable-stayed bridge, the present study considers only one bridge model without considering the geometrical and material uncertainties. Therefore, in order to assess the fragility of such huge structure accurately, several factors such as the effect of soil-structure interaction, uncertainties in geometry and material properties, and the characteristic of near-fault records should be conducted in the future works.

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