PERFORMANCE-BASED SEISMIC EVALUATION OF LONG-SPAN BRIDGES IN CHINA

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ABSTRACT :

The objective of this paper is to propose the methodology to evaluate the performance of long span bridges under a spectrum of earthquake ground motions, considering the difficulty and cost in inspection, reparability and replaceability. Based on the vulnerability analysis and the principle of minimum life-cycle cost, the optimum performance objectives are also proposed. The method and procedures presented in this paper can provide guidelines for the seismic design of major brides in the future.

KEYWORDS: Life cycle cost, performance-based seismic design, bridge, vulnerability analysis

1. INTRODUCTION

A total of 38 major bridges with main span over 400m have been built in China in the last two decades. With rapid economic development, more long-span bridges are being built in China. The long-span bridges are mainly in types of cable-stayed bridge, suspension bridge or long-span arch bridge. They are subjected to earthquake damage. For example, on September 21, 1999, an earthquake struck central Taiwan and caused damage to the cable-stayed bridge, the Chi-Lu bridge. The bridge was supported on a single pylon, which was connected to the center of the roadway by two rows of cables. Severe damage occurred in the deck on the southern side of the bridge. Additional damage occurred in the pylon (Chang et al. 2004).

The structural responses of long-span bridges subjected to earthquake are different from those of short to medium-span bridges. However, there are no specifications or codes to guide the seismic design or evaluation of long-span bridges. To ensure the safety of the bridges under earthquakes, seismic performances of long-span bridges are to be evaluated to ensure the bridges meet the desired performance levels. The objective of this paper is to investigate the performance of long-span bridges under a spectrum of earthquake ground motions and identify the key design parameters that affect their performance. As limited work has been done on evaluation of earthquake performance of cable bridges (Priestley et al. 1996; Chang et al. 1999; Khan et al. 2004; Vader and McDaniel, 2007), evaluation of a long-span cable bridges is proposed herein.

According to the differences in difficulty and cost in inspection, reparability and replaceability, key bridge components are described as those that are difficult to be inspected such as foundation and cables, or hard to be repaired or replaced such as towers and beams. The non-key components are those easy to be repaired or replaced, such as bearings and auxiliary piers. The level of damage of each component is classified as slight, moderate, or severe based on maximum stress level during the earthquake excitation. The probability of each component suffering certain degree of damage subjected to certain hazard level of earthquake is computed by nonlinear time history analysis using the ANSYS program. The cost of damage for component and replacement cost are estimated through literature review and survey. The optimum performance objectives of key-components and non-key components are proposed based on life-cycle cost analysis. The focus of this study is how to relate replaceabilty of bridge component to cost and design. Performance-based engineering is a methodology in which structural design or evaluation criteria are expressed in terms of achieving a set of performance objectives. These performance objectives can be related to various level of damage.

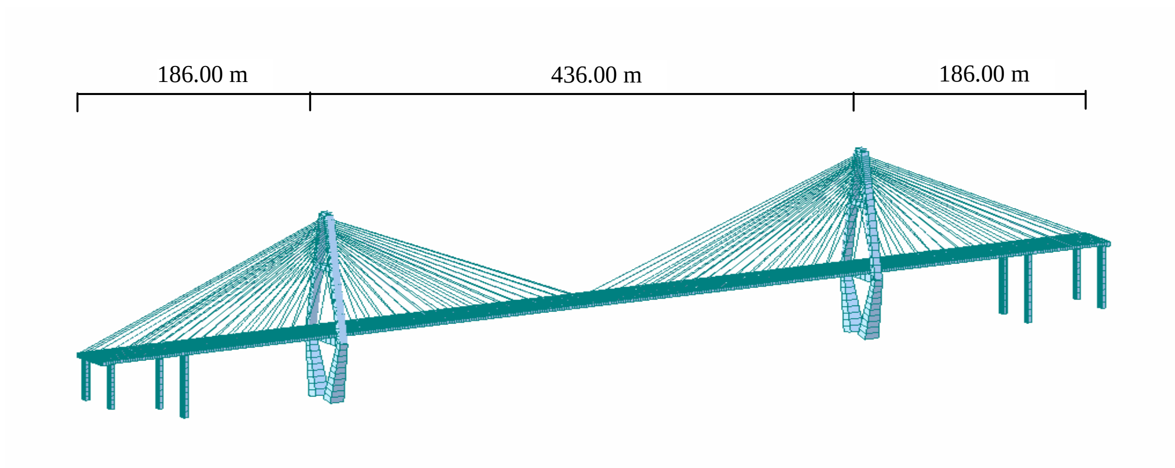

Figure 1 Overview of Chongqing Guanyinyan Bridge

2. BRIDGE CHARACTERISTICS AND MODELING

The Chongqing Guanyinyan Bridge is selected as an example to illustrate the concepts described above. The total length of the bridge is 808m, consisting three spans of 186m, 436m and 186m respectively. The fundamental period of the bridge is 11.8s. The cable is composed of high strength Φ7mm steel wire. The number of steel wire in a cable is from 150 to 350. The overview of the bridge is shown in Fig. 1. For the purpose of illustration, the focus of the analysis is on bridge towers, cables and beams. The details of tower and bridge beam are shown in Fig. 2 and 3, respectively. The slab is supported by H-shaped steel main girders with a height of 3.2m. Stress development of the components during moderate or severe earthquakes is examined. Vulnerability analysis is performed to evaluate seismic performance, and subsequently, optimal acceptable performance level is proposed.

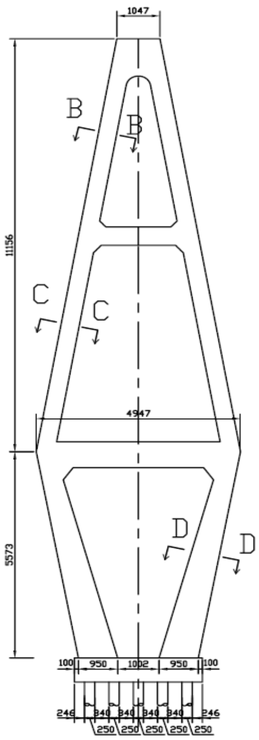

Figure 2 Reinforced concrete tower (unit: mm)

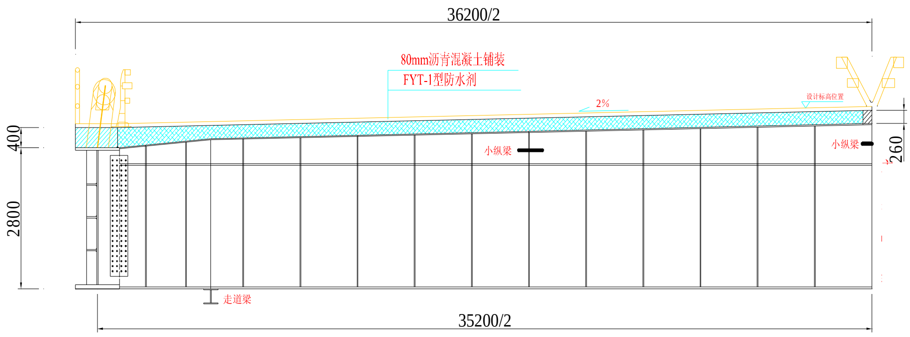

Figure 3 Cross section of bridge beam (unit: mm)

3. DAMAGE STATES

To determine acceptable performance objective is an important step in the seismic design for bridges. Once the seismic performance criteria is determined, the whole bridge, as well as each of its components should meet the criteria. However, the components composing a bridge can be classified as key (superstructure, substructure and connecting components) and non-key components (attachments). Key components can be classified further according to their inspectability and rehabilitability. The desired performance level for a bridged is: during the design life, the bridge should not collapse in severe earthquake, and it should be capable of resisting moderate earthquake without severe damage. Moreover, it is desirable that the damage caused by moderate earthquake be inspectable, hence a rehabilitation work can be applied. On the other hand, if the damage occurring at a member is not easily inspected, that member should be designed with higher seismic resistance to guarantee resisting moderate earthquake without suffering severe damage.

Some members are inspectable, but not replaceable. For cable-stayed bridge, the inspectability and rehabilibility of bridge towers and beams are good, but their replacability is not that good. In comparison, it is more difficult to inspect and rehabilitate cable, while replace the cable is feasible. Therefore, according to the accessability, the seismic performance criteria of superstructure component could be proposed as those in Table 1.

Table 1 Acceptable performance level of superstructure components

	Moderate Earthquake	**Severe Earthquake**
Tower	Light/moderate damage	severe damage but no collapse
Cable	No damage	severe damage but no collapse
Beam	Light/moderate damage	severe damage but no collapse

A reasonable design philosophy would be: when subjected to moderate earthquake, each component suffers certain degree of damage, but it can be rehabilitated. The acceptable damage degree will be determined by vulnerability analysis, which balances the rehabilitation cost and construction cost to generate the optimum criteria for design. The life-cycle cost in this study only includes initial construction cost and the cost due to damage from earthquake. By minimizing the life-cycle cost, the optimal design criteria could be obtained. The life cycle cost is shown as:

$$C = C_{\text{construction}}(\text{design level}) + C_{\text{Failure}}(\text{design level}) \tag{1}$$

Where:

$$C_{Failure} = \sum_i C_i P(\text{design level})_i \tag{2}$$

Both construction cost $C_{\text{construction}}$ and failure cost C_{Failure} depend on the bridge's performance level, that is, the higher the design level, the larger the $C_{\text{construction}}$, the lower the C_{Failure}, and vice versa.

The damage state depends on structural responses. There are several damage classifications and associated structural responses (for example, Park and Ang 1985; Meyer et al 1988; Powell and Allahabadi 1988; Cosenza et al 1993; Williams and Sexsmith 1995; Rodriguez and Aristizabal 1999), but the common characteristics for damage classifications are as follows: If the response remains elastic, there is usually no damage; If the internal force reaches the ultimate strength capacity, significant deformation and structural failure will be caused. Between the state of "no damage" and "failure", herein, "moderate" and "severe" states are defined in Fig. 4 for towers and beams. The definitions of damage states of Tower, beam and cable are summarized in Table 2.

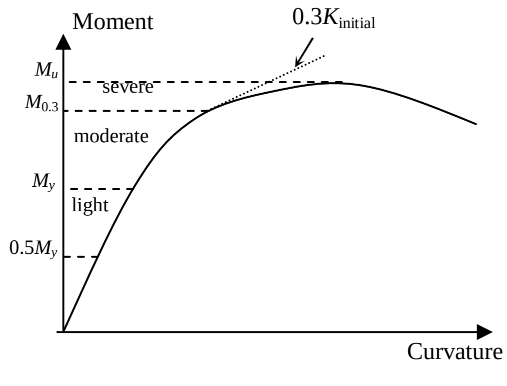

Figure 4   Damage states defined corresponding to internal moment

Once damage occurs, the reparation and rehabilitation costs, as well as the costs due to closing of the bridge and fatality associated with severe damage are summarized in Table 2, which are obtained by the damage survey and expert consulting in China (Qin 2002). Associated with light damage are mainly reparation cost; costs due to closing of bridge become significant once moderate damage occurs, and fatality cost is the most significant cost when severe damage occurs.

Table 2. Damage definition and associated cost of components of cable-stay bridges

Damage states / Components	Light		Moderate		Severe	
	Definition	Cost	Definition	Cost	Definition	Cost
Tower	$0.5M_y < M < M_y$	0.05C	$M_y < M < M_{0.3}$	0.3C	$M_{0.3} < M < M_u$	10C
Beam	$0.5M_y < M < M_y$	0.1C	$M_y < M < M_{0.3}$	0.3C	$M_{0.3} < M < M_u$	5C
Cable	$0.5N_y < N < N_y$	0.05C	$N_y < N < N_u$	1.0C	$N_y < N < N_u$	1.0C

Note: C denotes the construction cost of the bridge

4. ANALYSIS RESULTS

There are no earthquake records associated with the location of the bridges. Therefore, for the purpose of illustration, we utilize a set of 30 recorded ground motions (La01~La30) from the SAC projects (2000), The ground motion ensembles have probabilities of 10% of being exceeded in 50 years (la01-20) and 2% of being exceeded in 50 years (la21-30), which are abbreviated as 10/50 and 2/50, respectively. Nonlinear dynamic analysis is performed using ANSYS program to investigate the seismic performance of this bridge subjected to the suite of ground motion excitations.

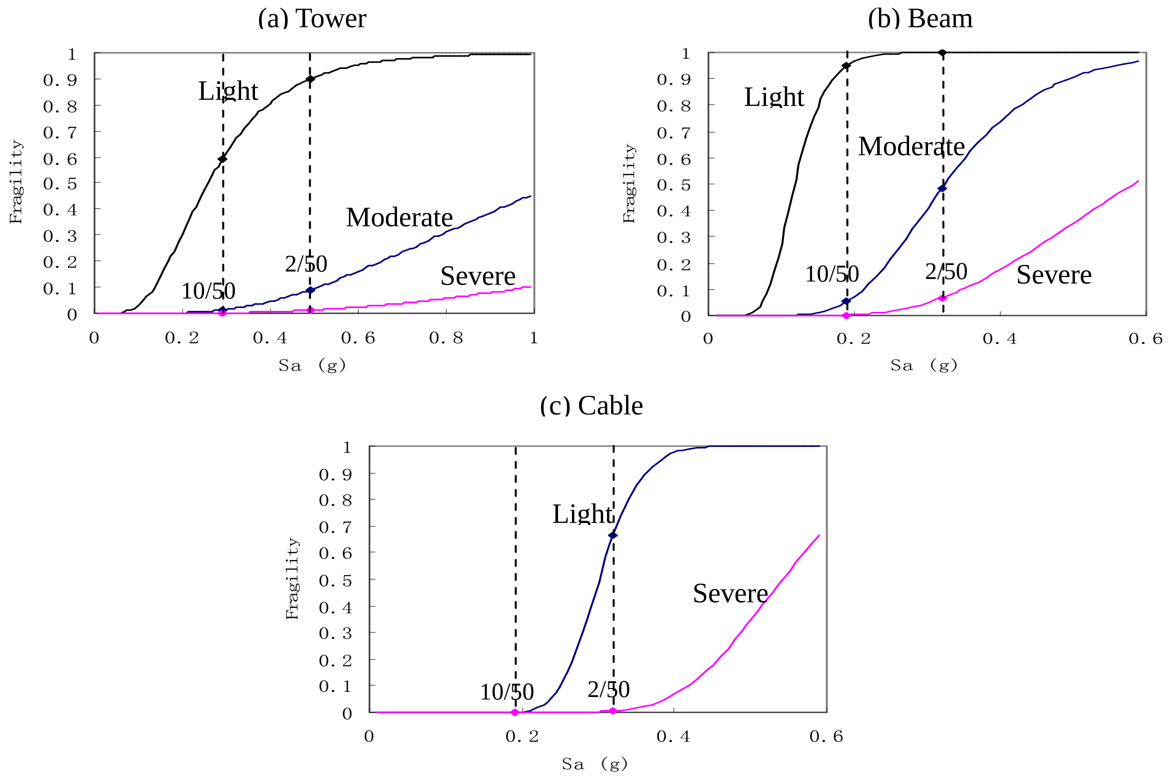

Figure 5. Fragility curves of tower, beam and cable

Based on the nonlinear dynamic analysis of each key component, the fragility curves of Tower (fundamental Period: 2.23s), Beam (fundamental Period 3.55s) and Cable are shown in Fig. 5.

Under 10/50 ground motion excitation, the tower and beam will suffer slight damage, but the probability of moderate damage is very small, while the cable will keep elastic. In comparison, under 2/50 ground motion excitation, the probability of tower suffering moderate or severe damage increases slightly. For the beams, moderate damage is likely to occur, but the probability of severe damage is small. The cable suffers only light damage regardless the severity of the ground motions.

Next, we perform the vulnerability analysis. Based on the principle of point estimates by Rosenblueth (1975), the probability distribution of seismic intensity can be sample by two samples: 10/50 and 2/50. The total damage cost due to earthquake is:

$$C_{Damage} = \sum_k kP[k \text{ earthquakes occur with hazard level of } 2\%/50\text{yrs}] \cdot C_{Failure|2/50} + \sum_k kP[k \text{ earthquakes occur with hazard level of } 10\%/50\text{yrs}] \cdot C_{Failure|10/50} \quad (3)$$

where $C_{Failure|10/50}$ and $C_{Failure|2/50}$ represent the expected cost due the damage induced by an earthquake with hazard level of 10/50 and 2/50, respectively.

$$C_{Failure|10/50} = \sum_{\text{component i}} \sum_{\text{damage j}} C_{ij} P_{ij|10/50} (1+r)^{-t} \quad (4)$$

where r denotes the interest rate (10%), t denotes the time (year) after the construction of the bridge when earthquake occurs.

Corresponding to 10/50 hazard level, the failure probability ($P_{ij|10/50}$) and cost (C_{ij}) are listed in Table 3.

Table 3. Failure probability of each component and estimated cost subjected to 10/50 seismic hazard

	Light (1)	Moderate (2)	Severe (3)
Tower (1)	0.59, 0.05C	0.0123, 0.3C	0.00125, 10.0C
Beam (2)	0.95, 0.1C	0.053, 0.3C	0.0026, 5.0C
Cable (3)	0.00717, 0.05C	0, 1.0C	

Similarly,

$$C_{Failure|2/50} = \sum_{\text{component i}} \sum_{\text{damage j}} C_{ij} P_{ij|2/50} (1+r)^{-t} \quad (5)$$

Corresponding to 2/50 hazard level, the failure probability ($P_{ij|2/50}$) and cost (C_{ij}) are listed in Table 4:

Table 4. Failure probability of each component and estimated cost subjected to 2/50 seismic hazard

	Light (1)	Moderate (2)	Severe (3)
Tower (1)	0.898, 0.05C	0.0899, 0.3C	0.0114, 10.0C
Beam (2)	1, 0.1C	0.485, 0.3C	0.068, 5.0C
Cable (3)	0.662, 0.05C	0.0046, 1.0C	

Supposing a service life of 100 years, we have

$$C_{Total} = C_{\text{construction}} + C_{\text{Failure}} = 1.062C \quad (6)$$

Which means the seismic damage cost is insignificant because of the conservative design.

Next, capacities of the key elements are changed to investigate the contribution of components to overall vulnerability. If the capacity of cable, beam and tower is modified to 70%, 80% and 75% of its original design, the construction cost would decreases to 0.77C. According to the fragility curves shown in Fig. 6, the failure probabilities are list in Table 5 and Table 6

Table 5. Failure probability of each component subjected to 10/50 seismic hazard

	Light (1)	Moderate (2)	Severe (3)
Tower (1)	0.919	0.109	0.0155
Beam (2)	0.997	0.262	0.0235
Cable (3)	0.63	0.0043	

Table 6. Failure probability of each component subjected to 2/50 seismic hazard

	Light (1)	Moderate (2)	Severe (3)
Tower (1)	0.993	0.372	0.0791
Beam (2)	1	0.827	0.246
Cable (3)	1.0, 0.05C	0.429	

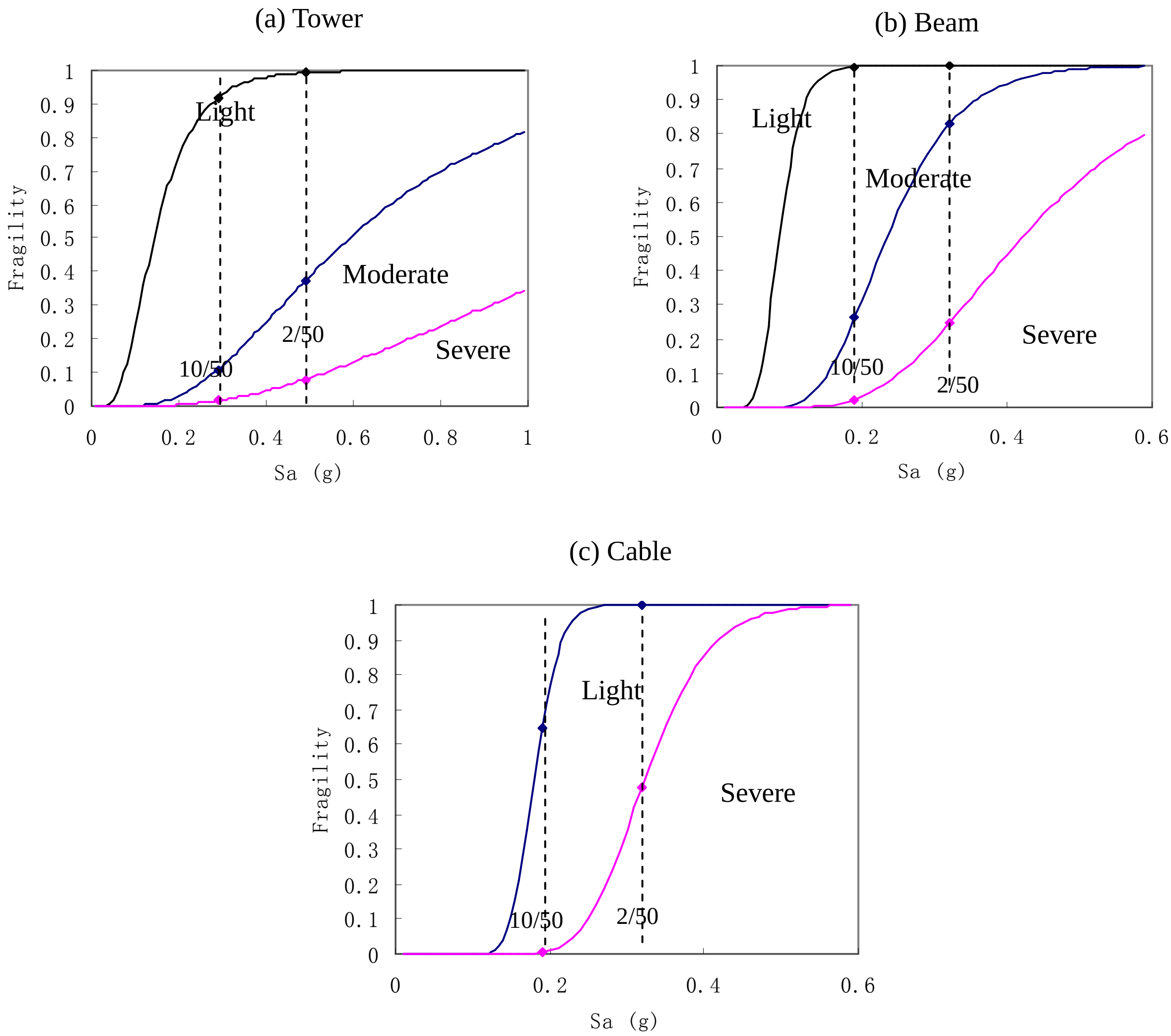

Fig 6. Fragility curves of tower, beam and cable

Thus, we have the total cost to be:

$$C_{Total} = C_{\text{construction}} + C_{\text{Damage}} = 0.77C + 0.19C = 0.96C \quad (7)$$

The total cost drops about 10%.

Next, we decrease the capacity of each component further, to half of its original. The construction cost decreases to 0.61C, but the damage cost increases to 0.79C. Thus,

$$C_{Total} = C_{\text{construction}} + C_{\text{Damage}} = 0.61C + 0.79C = 1.40C \quad (8)$$

As a result, the total cost will increase 40%.

So the optimum design level, according to the principle of minimum life-cycle cost , is listed in Table 7

Table 7. Suggested performance level of superstructure components

	Moderate Earthquake (10/50)	Severe Earthquake (2/50)
Tower	light damage	moderate damage
Cable	No damage	moderate damage
Beam	light damage	moderate damage

Conclusions

Long-span bridges play an important role in the rapid economic development in China. As many of the bridges are exposed to earthquake hazard, there is a need to investigate the seismic performance level of the bridges. The performance levels should be related to the cost of bridge construction and the cost of potential seismic damage. This study proposes performance-based evaluation of long-span bridges based on accessiblity and damage cost of superstructure components, using a cable-stayed bridge as an example. Based on vulnerability analysis, the optimum seismic performance levels of different superstructure component are suggested.

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