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Compound Stochastic Seismic Vulnerability Analysis and Seismic Risk Evaluation for Super Large Cable-Stayed Bridge

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1. Introduction

Previous seismic disasters indicate bridge structures are the most vulnerable component of the road transportation system in seism, such as the Haiti earthquake and Tohoku earthquake. Bitter lesson of bridge damage leads to the development of seismic analysis theories for bridge such as seismic vulnerability analysis.

Generally, seismic vulnerability is the probability of different damage in different seismic levels, which combines the intensity measure of seism with damage index for bridge structure. Methods of seismic vulnerability analysis include expert vulnerability analysis, experience vulnerability analysis and theory vulnerability analysis. Nevertheless, only seismic randomness has been taken into account in most seismic vulnerability analysis (e.g. Shinozuka et al. 2000; Kiremidjian et al. 1997; Basoz et al. 1997; Yamazaki et al. 2000). Apart from seismic randomness, bridge structure parameters are also stochastic, such as material properties, bridge geometry, boundary condition and so on, which cause the randomness of structure seismic response. Therefore, seismic vulnerability for bridge structure should be determined by both the randomness of seism and that of structure parameters. Due to the complexity of bridge structure system, it is very difficult to gain the analytic solution of seismic response for stochastic structure. Since the stochastic numerical simulation is time consuming and inefficient, this method is suspended at the threshold of thought.

Now, based on traditional seismic vulnerability analysis method, Artificial Neural Network (ANN), Monte Carlo (MC) technologies combining with Incremental Dynamic Analysis (IDA) and PUSHOVER method, Compound Stochastic Seismic Vulnerability Analysis (CSSVA) method is developed to take both randomness of material and that of seism into account from the point of total probability, which not only gives full play to the ANN, MC, IDA and PUSHOVER,but also increases the the efficiency of analysis greatly (Feng Qing-hai 2009).

Generally, the damage of bridge might lead to more serious results and secondary damage than that of road, and the seismic risk level of bridge determines that of the whole road transportation system. Due to the above mentioned reasons, more and more scholars pay attention to the bridge seismic risk evaluation.

Safety is relative, risk is absolute. So far, bridge structure risk evaluation is only limited to that of transportation, maintenance, management and so on. Since paper or reports for seismic risk evaluation for bridge structure performance is few, the only essential aspect for bridge seismic risk evaluation by those paper or reports is the seismic risk according to the damage probability of a determined bridge structure (e.g. Furuta et al. 2006; Hays et al. 1998; Padgett et al. 2007). However, that is unilateral. The truth is the randomness of material and that of seism exist at the same time. Moreover, the bridge damage probability according to the seismic vulnerability is gained within seism happening. In order to overcome this shortage, a method of seismic risk evaluation based on IDA and MC is presented, which has taken the difference of site type, randomness of time, space and intensity into consideration. It has indeed reflects the seismic risk situation within any years.

So, by the aforementioned method for seismic vulnerability and risk assessment, more real performance state and seismic risk lever are gained, which are good for design, maintenance and earthquake insurance of long span bridge.

2. Method of compound stochastic seismic vulnerability analysis

2.1 Basic theory

The Damage Index(DI) of bridge is affected by many uncertainties such as randomness of parameters of structure, seism and so on, which makes it a complicated process in gaining the seismic vulnerability curve. The capability of bridge structure could be expressed in the form of $R(M,G,C,.....)$, M, G, C stand for variety of material, size and calculation methods, respectively. At the same time, the seismic response could be expressed as $P(IM)$. So, DI is the systemic combination of $R(M,G,C,.....)$ and $P(IM)$, which is shown as following.

$$DI = f\left(R(M,G,C,......),P(IM)\right) \tag{1}$$

Clearly, DI is also variable.

Easy to see, the calculation of DI for bridge structure is divided into several parts, the first is the statistic for capability of bridge structure itself, the second is the statistic for seismic response of bridge structure, and the final is the combination of them. The flow chart is shown in Figure 1.

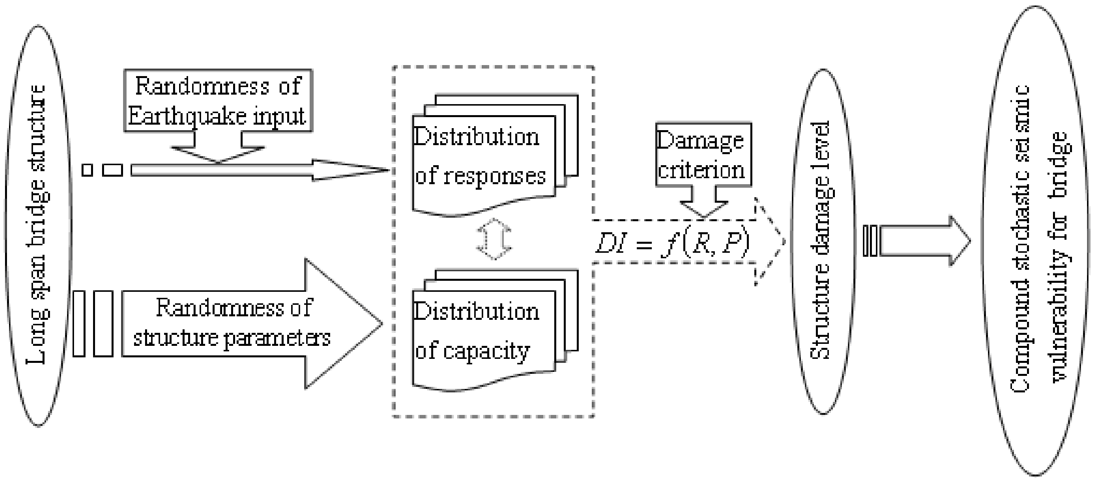


Fig. 1. Flow Chart for Compound Stochastic Seismic Vulnerability Analysis

2.2 Statistic for capability of bridge structure

Statistic for capability of bridge structure is analyzed based on method of PUSHOVER combining ANN and MC. The analysis process is shown in the following. Radial Basic Function Neural Network (RBFNN) is adopted in this method according to the conclusion of reference (Feng Qing-hai 2007).

1. Main parameters which affect the capability of bridge structure most are analyzed. Distributions for each parameter are determined, too.
2. By the method of orthogonal design, A+B groups of finite element models of bridge structures are built.
3. The response of capability is derived by the method of PUSHOVER.
4. RBFNN is built, and trained by responses of A groups and checked by that of B groups.
5. Go on if the result of Step 4 is successful, or rebuild RBFNN from Step 4.
6. Plenty of responses of capability are simulated by inputting large number of structure model parameters generated by the method of MC and RBFNN.
7. The characteristic of capability of bridge structure is gained by statistics on all those responses of capability.

The analysis flow chart is shown in Figure 2.

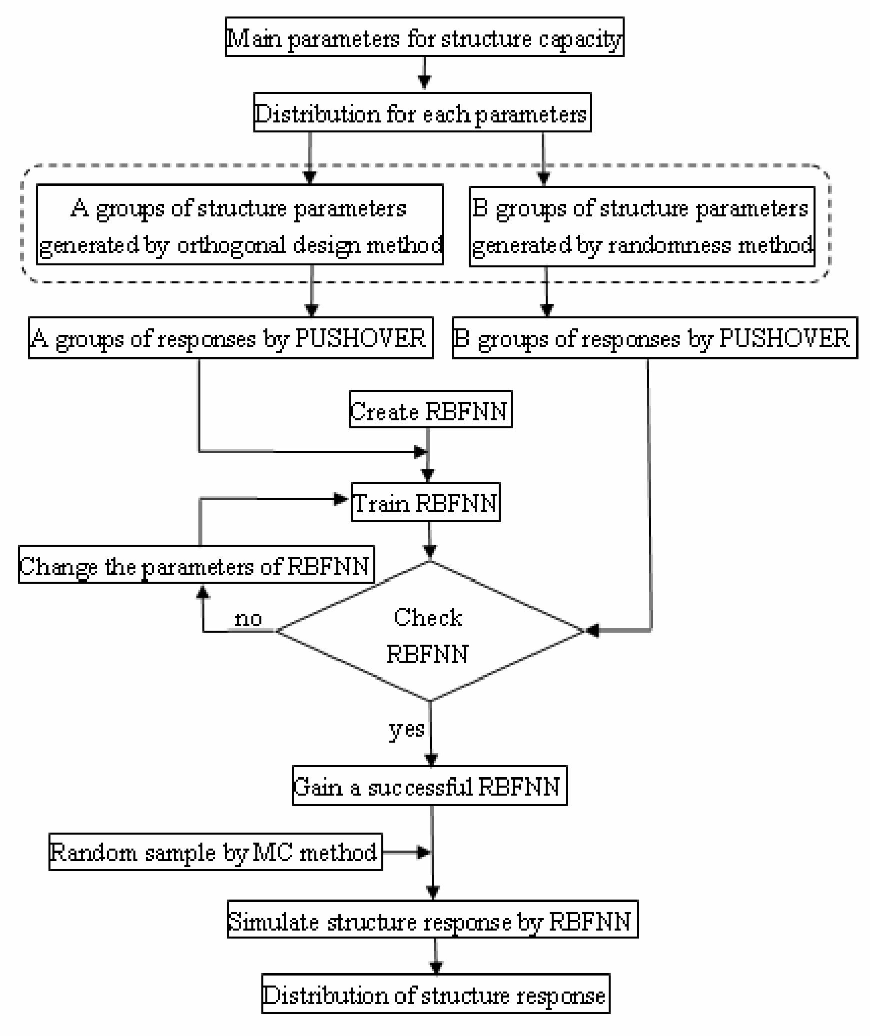


Fig. 2. Flow Chart for Stochastic Structure Capacity analysis

2.3 Statistic for seismic response of bridge structure

Seism is a ground motion of great randomness which might happen at anytime and anywhere. Therefore, it is very necessary to analyze the seismic response from the view of probability. While, the variability of bridge structure itself has a small effect on the seismic response when the randomness of both structure and ground motion are considered (Hu Bo 2000). In order to simplify the calculation method and reduce calculation time, only seismic randomness is taken into account in the statistic for seismic response of bridge structure in this paper.

Statistic analysis of seismic response is performed based on the method of IDA under multi-earthquake waves. The analysis process is shown in the following.

1. The finite element model of bridge structure is built.
2. Multi-earthquake waves are selected, and scaled to different intensities by scale factors (SF).
3. IDA is performed. Plenty of seismic responses are gained.
4. The characteristic of seismic responses of bridge structure is gained by statistic analysis on all those seismic responses.

The analysis flow chart is shown in Figure 3.

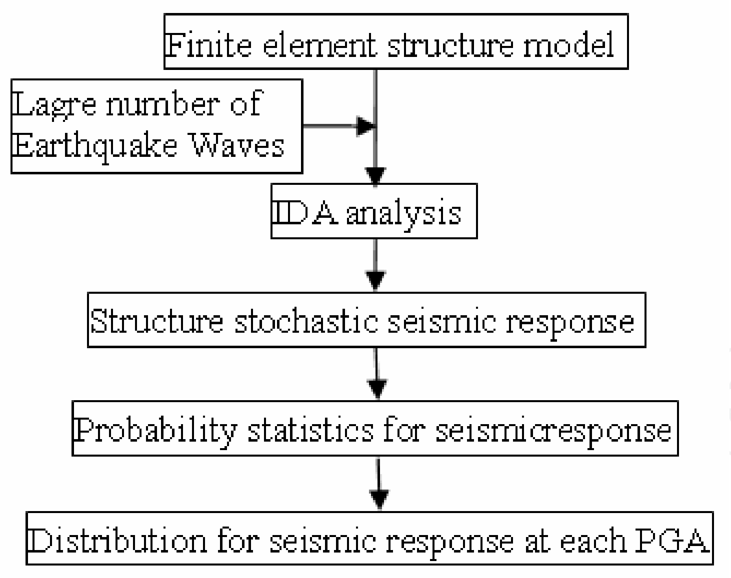


Fig. 3. Flow Chart for Stochastic Seismic Response Analysis

2.4 Methodology of CSSVA for bridge structure

Based on the theories mentioned in above sections, the distribution characteristic of capability and seismic response of bridge structure, CSSVA is performed combining with ANN-MC technology. The analysis process is shown in the following.

1. Get the distributions of capability and seismic responses of bridge structure, respectively.
2. Generate adequate numbers of capability and seismic responses by the method of MC and orthogonal design based on the distribution characteristic got in Step 1.
3. Two RBFNN are built, one for capability and the other for seismic response, then trained and checked by the data gained in Step 2.
4. Go on if the result of check is successful, or rebuild RBFNN from Step 3.
5. A large number of DI are gained according to Equation 1.
6. Select the damage criterion.
7. Compare DI with the damage criterion. The probability of damage is calculated at each IM.
8. The seismic vulnerability curves of bridge structure are drawn.

The analysis flow chart is shown in Figure 4.

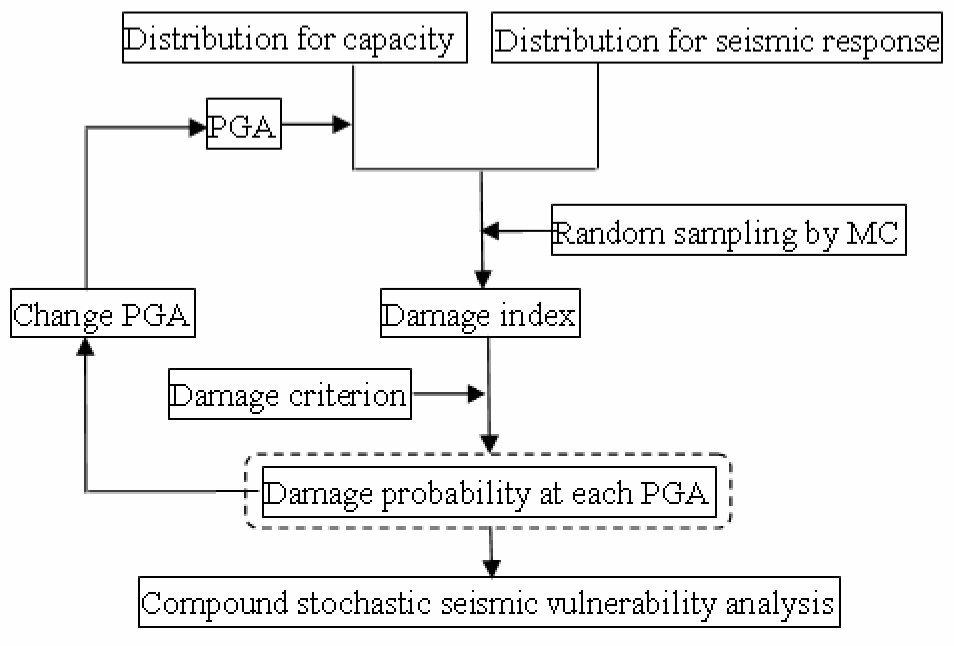


Fig. 4. Flow Chart for Compound Stochastic Seismic Vulnerability Analysis

2.5 Effect on seismic vulnerability by compound stochastic

Based on CSSVA, some examples are performed. For the limited space of paper, only part of results is drawn to display the effect on seismic vulnerability by compound stochastic. Seismic vulnerability curve of determination structure and that of compound stochastic are shown in Figure 5.

Easy to see, when structure stochastic are neglected, seismic vulnerability curves, which are gained by the method of two order spline curve fittings, are folded. Meanwhile, the curve deviate to the vulnerability point distinctly. By comparison, vulnerability curves of compound stochastic are smooth, and are getting through every vulnerability point. For the two curves, the PGA for beginning damage is the same. However, when damage probability is less than 80%, vulnerability value of determination structure is bigger than that of compound stochastic. When damage probability ranges from 80% to 95%, the contrary is the case.

In all, vulnerability curve of determination structure spreads around that of compound stochastic. Besides, the structure stochastic indeed affects the seismic vulnerability, although not too enormous. Compound stochastic reflects the seismic vulnerability of bridge structure better.

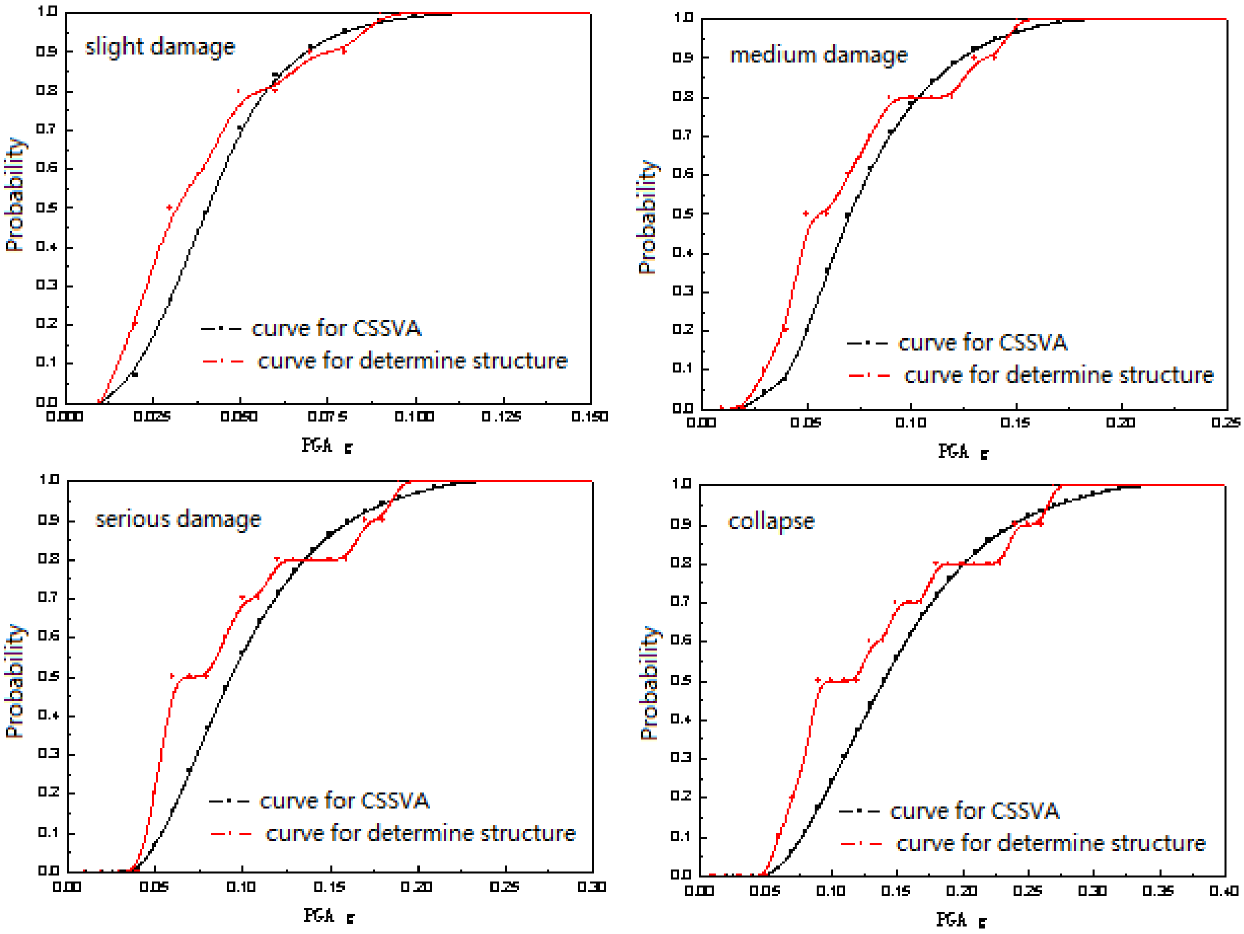


Fig. 5. Effect on Seismic Vulnerability by Compound Stochastic

3. Seismic risk probability evaluation for long span bridge

3.1 Concept for probability evaluation of seismic risk

Bridge seismic risk analysis involves two aspects, namely the probability of event occurrence and that of event consequence. The consequence mainly describes the damage severity and has no relationship with structure analysis. Risk analysis, usually said, is the probability of event occurrence without considering the consequence.

Seismic risk probability evaluation for bridge is one of the basis of risk analysis, which also involves two aspects, namely seismic risk and structure seismic vulnerability. Seismic risk probability evaluation for bridge could be expressed as following: the probability of different damage states with consideration of earthquake dangerous. It indicates that the reliability of bridge is threatened by both seism and structure seismic vulnerability during the same determined period.

Seism is regarded as a risk event, the sign is H. According to structure reliability thought, limit state function could be expressed as following (Alfredo H-S. ANG & Wilson H.Tang, 2007).

$$Z = R - S \tag{2}$$

in which, Z is the performance function, R is the comprehensive resistance, S is comprehensive response on structure induced by risk events. Then, the damage probability is expressed by expression as following.

$$P = P(R < S) = \int_R^{\infty} f(S)dS \tag{3}$$

in which, $f(S)$ is the probability density function of comprehensive effect induced by risk events. Clearly, S is closely related to H. The $f(S)$ should be expressed in the form of $f(S,H)$, namely the joint density function.

$$f(S,H) = f(S|H)f(H) \tag{4}$$

in which, $f(S|H)$ is the conditional probability density function for different damage states under given risk event H. $f(H)$ is the probability density function of risk event H. So, $f(S)$ is expressed as following.

$$f(S) = \int_{-\infty}^{+\infty} f(S|H)f(H)dH \tag{5}$$

then, the expression combining Equation 5 and Equation 3 is as following.

$$P = p(R < S) = \int_R^{+\infty}[\int_{-\infty}^{+\infty} f(S|H)f(H)dH]dS = \int_0^{+\infty}[\int_R^{+\infty} f(S|H)dS]f(H)dH \tag{6}$$

$$P = \int_0^{+\infty} F_S(H)f(H)dH \tag{7}$$

briefly,

$$P = \int_0^{+\infty} F_S(H)f(H)dH \tag{8}$$

in which, $F_S(H)$ stands for $\int_R^{+\infty} f(S \mid H)dS$.

3.2 Method of seismic risk probability evaluation for bridge based on IDA-MC

In order to avoid complicated calculation, IDA is applied in association with MC. The specific procedure is interpreted at the following sections.

3.2.1 Probability distribution of seismic intensity and according PGA

Seismic dangerous analysis is the basis of seismic risk probability evaluation, which reflects the probable maximum effect of seismic damage for a bridge in a district within determined coming period. The effect could be depicted in many ways. Since bridges designed in China are based on the design criterion of seismic intensity, probability distribution of seismic intensity introduced in reference (Gao Xiao-wang et al. 1986) is adopted as the seismic dangerous, namely:

$$F_{III}(x) = \exp(-(\frac{\omega - x}{\omega - \varepsilon})^K) \tag{9}$$

in which, ω is the upper limited value of intensity, usually equals to 12. ε usually satisfied with the equation of $1 - e^{-1} = 0.632$. K is form parameter. From the point of engineering application, K equals to the value of intensity according to the seismic probability of 10%.

If the probability distribution of seismic intensity for 50 years is determined, then the probability distribution in any limited period could be expressed as the following.

$$F_i(i) = [F_T(I)]^{t/T} = [\exp(-(\frac{\omega - i}{\omega - \varepsilon})^K)]^{t/T} = \exp(-\frac{t}{T}(\frac{\omega - i}{\omega - \varepsilon})^K) \tag{10}$$

According to the existing seismic records, PGA according to a determined intensity are of big discreteness. In order to be convenient for calculation, A has the relationship to I as following.

$$A = 10^{(I \cdot Log2 - 0.01)} \tag{11}$$

in which, A and I is the value of PGA and seismic intensity, respectively. The unit for A is gal. Here, it is very necessary to illuminate that, A is a continuous value only for the necessary of statistic.

3.2.2 Method and steps

1. To build a finite element analysis model of bridge structure, and choose enough seismic waves.
2. IDA is performed. Seismic response according to every wave is recorded to form IDA curve.
3. Determine design reference period (prior to a small one) and the probability distribution.
4. According to MC, a great lot of I are generated.
5. According to Equation 11, the same number of A are gained based on Step 4.

6. Based on A, corresponding seismic responses are gained from the IDA curve.
7. Structure damage probability is gained by statistics based on damage criterion.

The analysis procedures are shown in Figure 6.

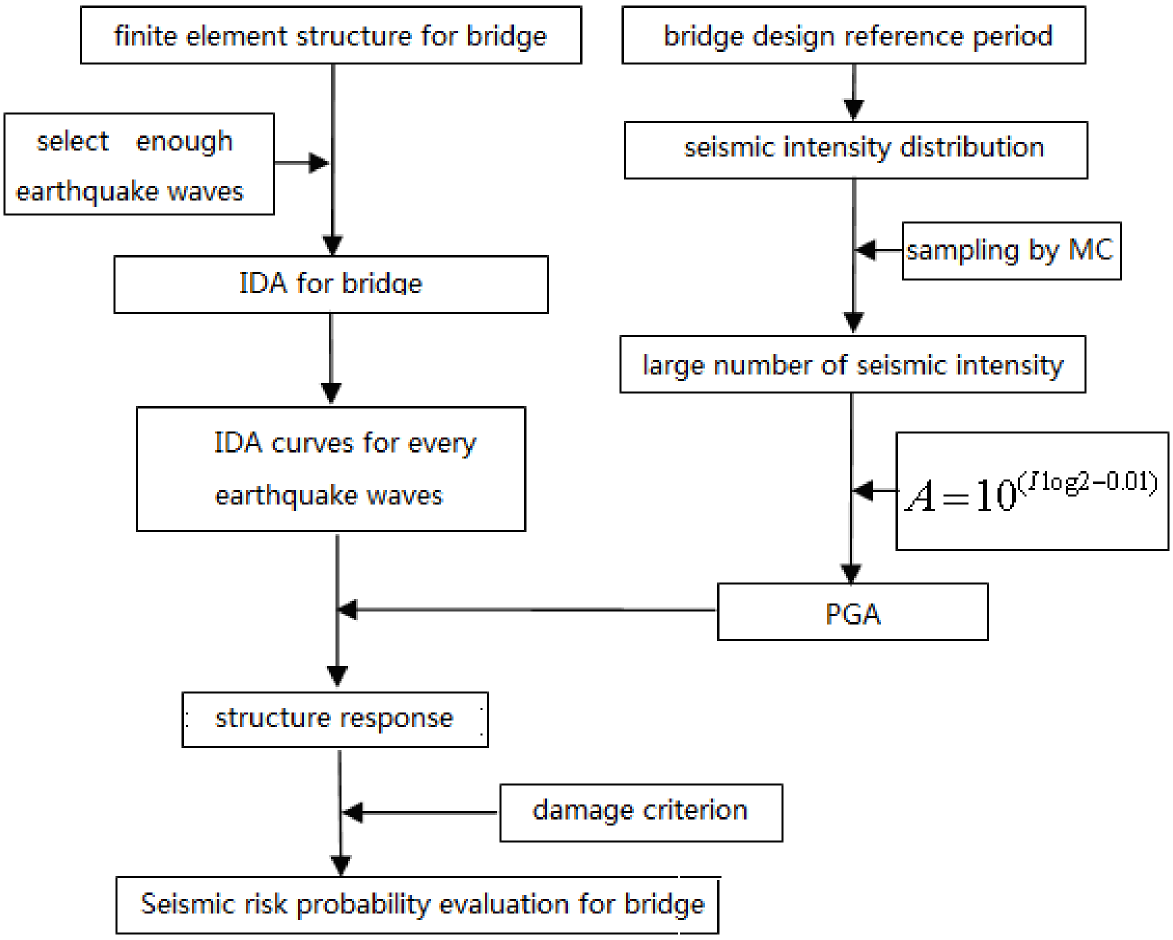


Fig. 6. Seismic risk probability evaluation for bridge

3.3 Example analysis

3.3.1 Analysis model for floating system cable-stayed bridge

According to reference (Yan Hai-quan and Wang Jun-jie 2007), floating cable-stayed bridge could be simplified to a main tower with a lumped mass on the top of main tower, and the tolerance of results are acceptable. In this section, simplified models are adopted and only longitudinal cases are analyzed. The refined finite element model for main tower is built by OpenSees as shown in Figure 7, main tower is divided into 3 parts, namely upper tower, middle tower and low tower. In consideration of the strengthening at the upper tower by steel pile casting, the upper tower is regarded elastic. Fiber element is adopted in middle tower and low tower.

Main tower is 300m in height, 90m for upper tower, 150m for middle tower and 60m for low tower, respectively. Tower is divided into 30 elements of 10 meters in vertical direction, and every element and joint is numbered from 1 to 30 and 1 to 31, respectively. The bridge site belongs to 3rd type, the seismic intensity is 8 and design period is 50 years.

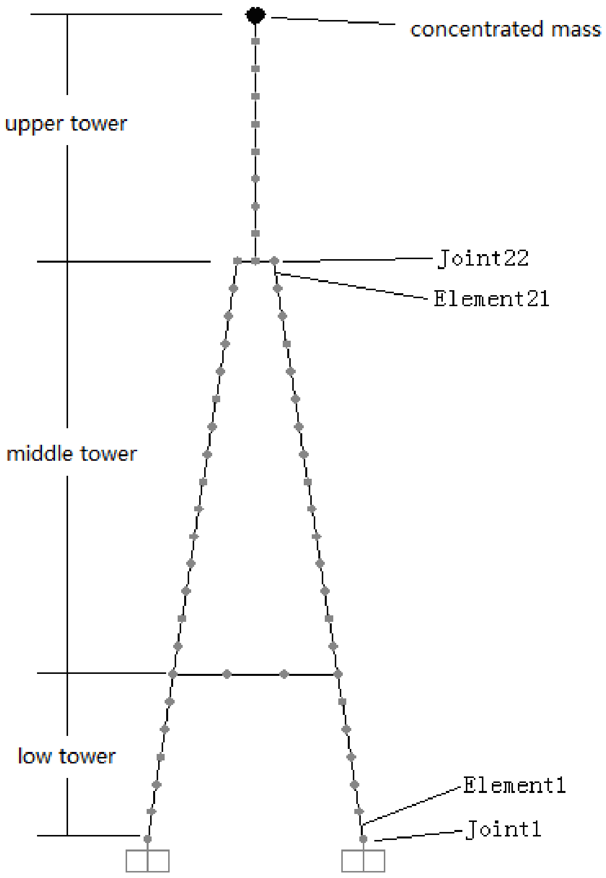


Fig. 7. Finite element model for main tower

3.3.2 Damage criterion

Double control damage criterion put forward by Park and Ang are adopted, which is shown as following:

$$DI = f\left(\delta_m, \delta_u, Q_y, \int dE_h, \beta\right) = \frac{\delta_m}{\delta_u} + \frac{\beta}{\delta_u Q_y}\int dE_h \tag{12}$$

in which, the signal and suggestion value are illuminated particularly in reference (Fan Li-chu and Zhuo Wei-dong 2001). The relationship between damage levels, damage state and DI described by Park, Ang and Wen (H. Hwang et al. 2001) is shown in Table 1.

Damage level	*Damage character*	*Park-Ang DI*
1 no damage	Some slight fracture at local part	$DI < 0.1$
2 slight damage	Slight fracture distributed widely	$0.1 \le DI < 0.25$
3 medium damage	Serious fracture or spall partly	$0.25 \le DI < 0.4$
4 serious damage	Concrete crushed or steel break	$0.4 \le DI < 0.8$
5 collapse	collapse	$DI \ge 0.8$

Table 1. Damage Character and Damage Index at Each Level

3.3.3 IDA for main tower

Only longitudinal case is studied. IDA is performed with PGA being scaled from 0.1g to 1.0g with step of 0.1g. Seismic responses such as moment, curvature, hysteretic energy are recorded. Representative response distributions along main tower are described in Figure 8, 9,10, respectively..

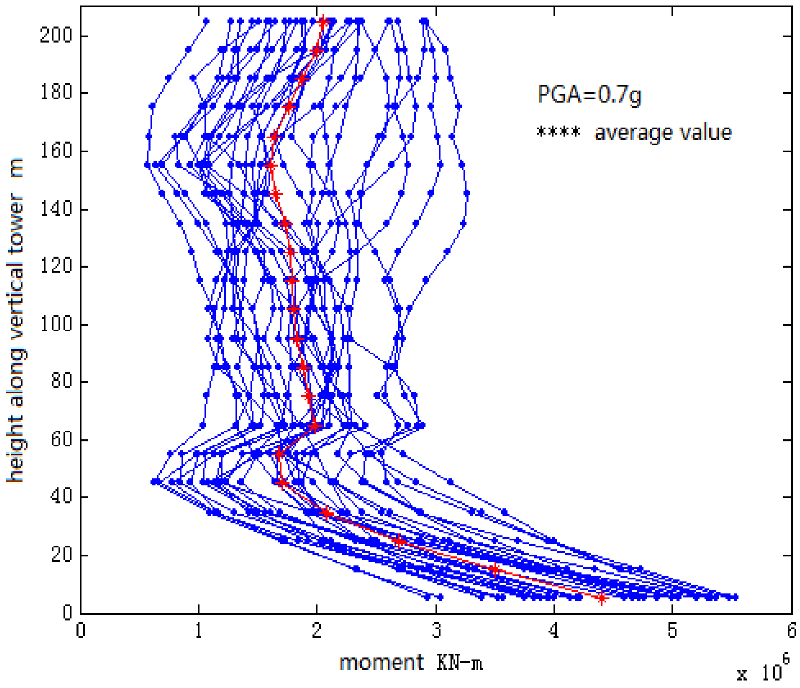


Fig. 8. Moment distribution along vertical tower

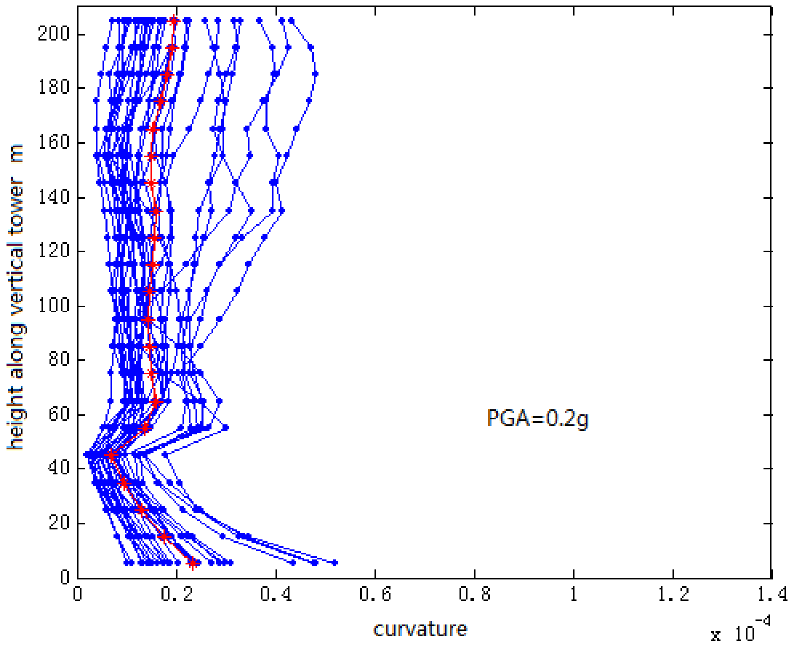


Fig. 9. Curvature distribution along vertical tower

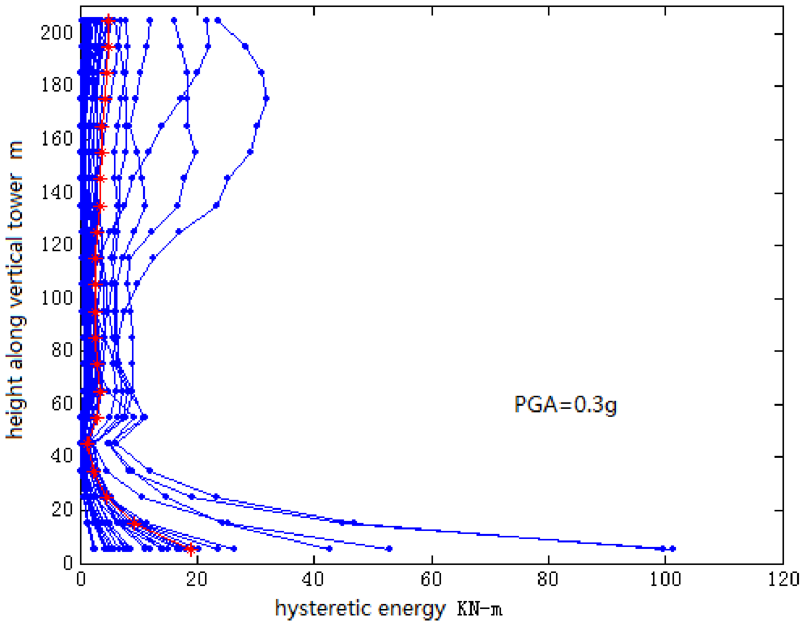


Fig. 10. Hysteretic energy distribution along vertical towe

3.3.4 Stochastic sampling for PGA

According to reference (Ye Ai-jun 2002) combining the site type, design period and seismic intensity, K is determined as following:

$$1-0.1=\exp(-(\frac{12-8}{12-6.45})^{K}) \tag{13}$$

According to Equation 13, the K=6.87. Then, the seismic intensity probability distribution within t years is

$$F_t(i)=\exp(-\frac{t}{50}(\frac{12-i}{5.55})^{6.87}) \tag{14}$$

When t=1, and according to the method of MC, 50000 random intensity value are generated, numbered $Rand(1)$ to $Rand(50000)$. Then, the according PGA numbered from $RandPGA(1)$ to $RandPGA(50000)$ which reflect the seismic random from time, space and intensity are gained as following.

$$RandPGA(i)=10^{(Rand(i)\log(2)-0.01)} \tag{15}$$

3.3.5 Bridge structure seismic risk probability evaluation within 1 year

Based on the stochastic PGA and IDA curve, responses for every element in any stochastic PGA are gained, the total number is 560000. Based on the damage criterion, the damage time for every element in different damage levels are accounted. For example, the damage number for slight damage at the bottom of main tower is 7649. Then the damage probability is

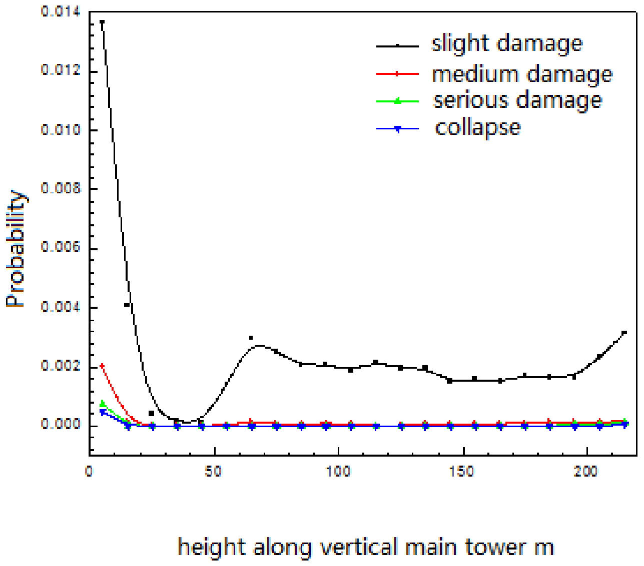
$$\frac{7649}{560000}\times 100\%=1.37\% \tag{16}$$

Damage probability distribution along main tower in different damage level is shown in Figure 11(a). Easy to see, in different damage levels, the damage probability is different, especially damage probability of the bottom is larger than that of the others, there are two main reasons for this phenomenon as following:

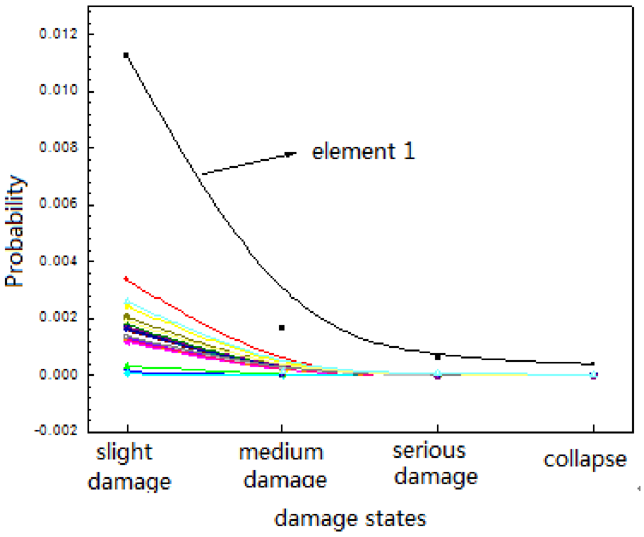
Firstly, the main tower is the most important component of large long span bridge, any damage could cause devastating damage for the bridge. So in the design, main tower is conservatively designed. Not only stiffness but also strength is strengthened.

Secondly, when the bottom element begins to be damaged, the upper elements are protected.

Based on the thought of structural reliability, the main tower is a series of structure, so the total damage probability is the biggest one in different damage levels.



(a) Damage probability distribution along vertical tower at different states



(b) Element damage probability at different damage states

Fig. 11. Element damage probability at different damage states

3.3.6 Bridge structure seismic risk probability evaluation within any years

With different years, the seismic risk is different, and so does the seismic intensity distribution. According to the method as in Section 3.3.5, seismic risk probability from 10 to 100 years with interval of 10 years are calculated, as shown in Figure 11(a).

In order to get a reasonable cognition, risk levels are shown in Table 2. Combining figure 11(a) with Table 2(Basoz, Nesrin, Kiremidjian & Anne S, 1997), the log curve for main tower seismic risk is shown in Figure 11(b).

Grade	Risk Description	Probability Range	Intermediate Value
1	Very unlikely	＜0.0003	0.0001
2	Impossible	0.0003－0.003	0.001
3	Occasional	0.003－0.03	0.01
4	Possible	0.03－0.3	0.1
5	Very likely	＞0.3	1

Table 2. Risk Probability Description

Easy to see from Figure 11(b), for main tower, within 1 year, slight damage and medium damage is impossible, and serious damage will never happen. Within other years, especially over 30 years, slight damage is possible, medium damage and serious damage will be occasional, and collapse will never happen.

4. Conclusion

Compound stochastic seismic vulnerability analysis for bridge structure is presented, in which double damage criterion is adopted. The effect of compound stochastic on seismic vulnerability are analyzed, which proves that, compound stochastic indeed has little effect on seismic vulnerability. The results show that compound stochastic seismic vulnerability curve reflects the actual situation.

Based on method of MC and results of seismic vulnerability analysis for large long span cable-stayed bridge, seismic risk analysis evaluation for bridges is performed, which has taken difference of site type, randomness of time, space and intensity into consideration. Seismic risk situation within any years for bridge structure is measured by using the experience of situation description for bridge risk evaluation.

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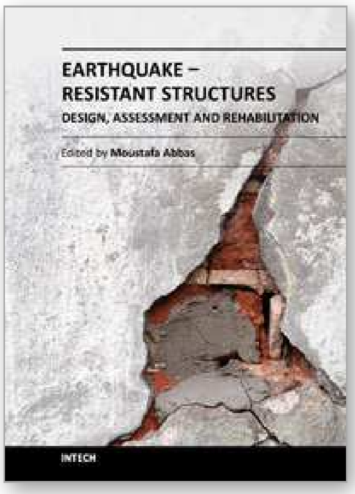

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How to reference

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