Seismic Vulnerability Analysis of Post-earthquake Typical Existing RC Buildings in Wenchuan

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LISBOA 2012

SUMMARY:
This paper investigated the seismic vulnerability assessment towards the post-earthquake typical existing RC building in Wenchuan China. Based on the Cornell theory coupled with Wenchuan earthquake scene records, a hazard model considering the ground effects is built. As the premise of the indexes of four ultimate damage state defined by the field survey, a simplified vulnerability assessment method considering ground motion parameters is suggested, and then the vulnerability curves of typical existing RC buildings in Wenchuan were drawn to describe exceeding probability of the various damage states. Meanwhile, the annual exceeding probability of the different damage states is respectively derived, on the basis of model of ground seismic hazard and the calculated vulnerability curves. Summary the regulation of the seismic vulnerability with the natural period changing through contrasting results of three RC numerical models of various natural period simulated.

Keywords: Hazard model, Seismic vulnerability, Wenchuan earthquake, RC buildings

INTRODUCTION

On May 12, 2008 at exactly 14:28:01, a huge earthquake with a magnitude 8.0 on the Richter scale occurred in the Wenchuan area of the Sichuan Province in China, causing tens of thousands of casualties and hundreds of billions RMB[1]. According to the post-earthquake survey, the main structures of the destructive buildings are masonry building，reinforce concrete frame building and reinforced concrete-masonry mixed building，of which reinforce concrete frame building is quite large proportion. Meanwhile as the common structure of the Chinese urban buildings, it is of great significant to investigate its performance appearance under the intense earthquake. Consequently, the paper chose the typical existing RC buildings in Wenchun area as the objects of vulnerability analysis and investigated the probability of the various damage state though a simply analysis vulnerability assessment method considering ground motion parameters.

1. SEISMIC HAZARD MODEL

Seismic hazard analysis is required to give the probability that the sites will encounter a earthquake whose intensity is more than a given one in the future. It is also called exceeding probability. American scholar Cornell proposed probabilistic study methods, which consider different magnitude earthquakes in all the potential seismic source area have the impact on the given area over the region. The level of seismic hazard in the target areas within the given years can be assessed quantitatively through the parameters of ground motion intensity and their exceeding probability, which facilitates the conduct of seismic design. According to Cornell's theory, the seismic hazard probability model is certainly concerned with the magnitude, the epicenter distance and the ground motion attenuation law. In the theoretical framework of the United States Pacific Earthquake Engineering Research Center (PEER), when the exceeding probability is small, the seismic hazard probability model[2] of the design site can be expressed as follows:

$$v_{IM}(im) = P[im \geq x] = k_0 \cdot (im)^{-k} \tag{1.1}$$

Where, im is the earthquake intense parameter, k_0 and k are the shape parameters of the hazard curve. According to the standard design response spectrum in the Chinese ground motion parameter zoning map and the site characteristics of Wenchuan, it can be drawn that

$$k = 2.3753 \qquad\qquad k_0 = 0.0245 \tag{1.2}$$

The mathematical expression of the seismic hazard probability model is that:

$$v_{IM}(im) = 0.0245 \cdot (im)^{-2.3753} \tag{1.3}$$

In order to verify the rationality of the model, The annual exceeding probability of the ground motion calculated according to the assumptions of Cornell is compared with the one calculated by Equation(1.3). The result is shown in Fig1.1. The seismic hazard curves got from Equation (1-3) and the result calculated according to the assumptions of Cornell are plotted on the same graph, it is shown in Fig1.1. By seeking a logarithmic on both sides of Equation (1.4), it can be got:

$$\ln\left(v_{IM}(im)\right) = \ln 0.0245 - 2.3753 \ln(im) \tag{1.4}$$

It means that the relationship between the logarithm of the annual exceeding probability of ground motion and the logarithm of intensity indicators of the ground motion is linear. The seismic hazard curve of design sites can be drawn by using this linear expression as shown in Fig1.1.

Table 1.1 Calculated result compared of exceeding probability

Exceeding probability	The Conell calculated results	The paper calculated results
$v_{sa}(63.2\%, 50y)$	0.02	0.024500
$v_{sa}(10\%, 50y)$	0.002105	0.002100
$v_{sa}(2\%, 50y)$	0.000404	0.000405

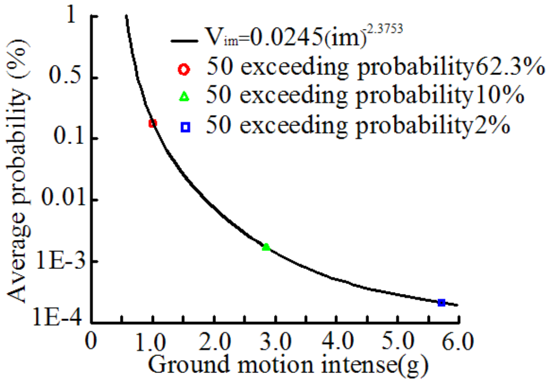


Figure 1.1. Seismic hazard curve

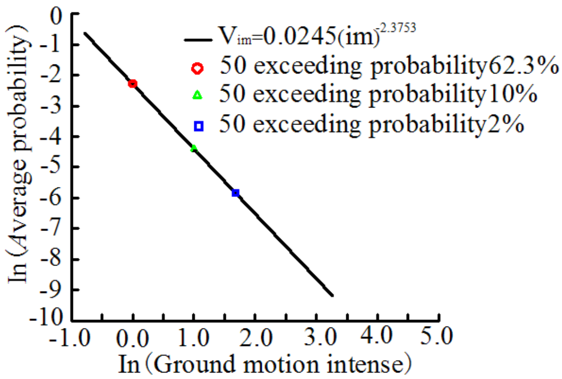


Figure 1.2. Linearized seismic hazard curve

From the comparison of ground motion annual exceeding probability calculation results (shown in Table1.1), it is concluded that the calculation results according to the seismic hazard analysis model used in the paper is very close to or even larger than that according to the assumptions of Cornell. It can be shown more clearly in Figure 1.1 and Figure 1.2. It shows that the seismic hazard analysis model mentioned in this paper is reasonable and the site seismic risk curve drawn according to the formula can reflect the hazard information of design sites well. But the hazard is estimated conservatively.

2. THE SAMPLES GENERATED IN WENCHUAN

2.1. Typical existing reinforced concrete frame constructions in Wenchuan

The building is located in Dujiangyan and designed as fortification intensity 7 degrees. The intensity of the earthquake happened in Wenchuan is 8 to 9 degrees, which is equivalent to the earthquake encountering the design earthquake or exceeding the design earthquake. However, the building did not collapse. It meets the goal "constructions do not fall" in the current seismic code. After the earthquake, the plastic hinge damages were found in the End-column of the first floor framework columns. It cannot achieve the yielding mechanism called "strong column and weak beam" expected as the seismic code in China. There are more destructed buildings close or similar to this building in the earthquake disaster area and the collection data are complete. Therefore, this paper takes the typical building structure as a reference and sets up model 1 and model 3 respectively. Specific data are summarized in Table 2.1.

Table 2.1. Parameters of the framework model

Model	Column section $mm \times mm$	Beam section $mm \times mm$	Column steel $/ mm^2$	Beam steel $/ mm^2$	Storey mm	Span mm	period s
Model 1	400×500	250×720	1608	804	2800×3	7800+2800+7800	0.567
Model 2	400×500	400×500	2036	1527	2800×6	7800+2800+7800	0.972
Model 3	400×500	400×500	2036	1527	2800×8	7800+2800+7800	1.531

2.2. Samples generated

To study the probability seismic vulnerability performance of the typical existing reinforced concrete frame constructions in Wenchuan, 100 structure samples are set up respectively using Model 1, Model 2 and Model 3 as prototype. The samples consider the randomness of the structural material properties. Random variables involve such as concrete axial compressive strength f_c , steel yield strength f_y and elasticity modulus E . They are all assumed to be in accordance with the lognormal distribution. Meanwhile, 95 seismic waves are synthesized as the outer load input of the structure using the three main earthquakes recorded by the national strong earthquake station and data from the two local fixed stations. And 100 random samples of structures and ground motions are formatted by the method of Latin cube sampling, which are used in the seismic vulnerability study.

3. SEISMIC VULNERABILITY MODEL

3.1. Probabilistic seismic capacity analysis

Probabilistic seismic capacity analysis is to determine the probability of statistical characteristics of the structure to achieve a set level of damage state threshold values, Specifically, A variety of factors of the structure of space, non-elastic properties, materials effectiveness, damping changes have led to the randomness of the structure itself, And thus led to threshold values of the limit state of breach with the randomness, Then we need to analyze disaster information and experimental data statistically to determine the probability of statistical characteristics of the structure in each level of injury status through the probability density function of the seismic capacity of the structure to describe the damage state and the seismic capacity. Literature get through the model parameters of the structures of the overall seismic capacity $K-S$ test, pointed out that the structure based on the nonlinear-static analysis of the model parameters of the bilinear overall resistance obey the logarithmic normal distribution well. Therefore, this study is based on the above conclusions, and proposed the lognormal distribution of the seismic capacity of structure, With the finite element software OpenSEES, through the nonlinear static analysis of three sets of samples generated in text 2, in the analysis process, we selected yield displacement and the maximum story drift angle to measure the seismic capacity level indicators, used the two polylines energy equivalent method suggested by FEMA273 to determine the yield displacement of the structure and thus obtain the maximum drift angle of the vertex. In this study, the probability function C of the structural seismic capacity can be shown by the following formula:

$$C=\ln\left(\hat{C},\beta_C\right) \tag{3.1}$$

Where is $\hat{C}$ is the median of seismic capacity, β_c is the logarithmic standard deviation. Through the maximum displacement angle of the structure vertex calculated by statistical analysis, the probability functions of the overall structure seismic capacity were obtained. The specific data is shown in Table 3.1.

Table 3.1. Statistics of the maximum drift angle of the vertex

Number	Median $\hat{C}$	Logarithmic standard deviation β_C
Model 1	0.01417	0.09701
Model 2	0.01042	0.13527
Model 3	0.01071	0.04637

3.2. Probabilistic Seismic Demand Analysis

Probabilistic Seismic Demand Analysis refers to analysis on the response of structure in the random motions. Through establishing damage indicator function curves of ground motion intensity indicators and limits of structural response to, It can clearly reflect Structural response changes with the ground motion intensity changing, In order to assess the seismic performance of building structures in ground motion of different strength grades. Introduction by literature[3], Engineering seismic demand parameters ($\widehat{EDP}$) and ground motion parameters comply with the exponential relationship:

$$\widehat{EDP}=a\left(im\right)^b \tag{3.2}$$

In this study, Ground motion seismic demand parameters (D) and ground motion intensity indicators (I) meet the above formula.

$$D=a\left(I\right)^b \tag{3.3}$$

Taking logarithmic at the same time on both sides in above formula:

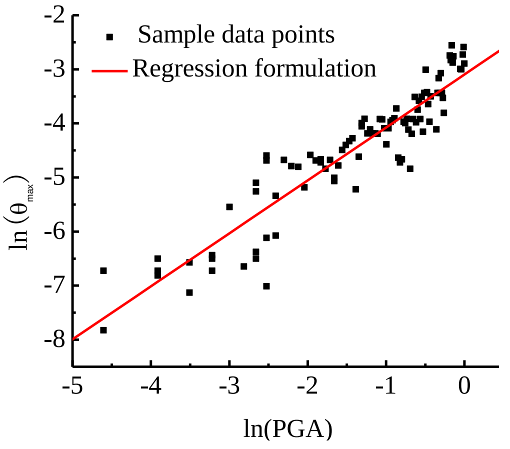
$$\ln D=\ln(a)+b\cdot\ln\left(I\right)=A+B\cdot\ln\left(I\right) \tag{3.4}$$

Where, A and B are obtained by regression analysis through the structure under the earthquake response data.
The probability function of structural response can be described by the form the following formula:

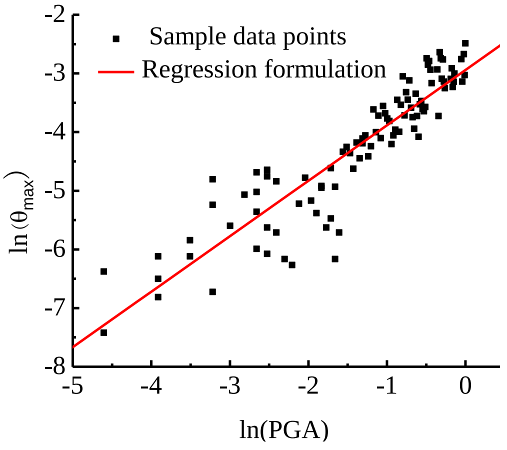
$$D=\ln\left(\hat{D},\beta_D\right) \tag{3.5}$$

Where, $\hat{D}$ is median of structural response values, β_d is standard deviation of structural response values.

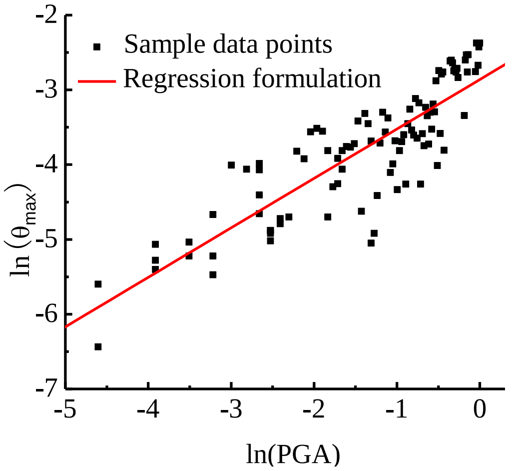
With the finite element software OpenSEES, through the dynamic history analysis the three sets of samples generated above, the response characteristics of the samples of the various structures under seismic action can be counted, And then the results of each ground motion-the response of the structural sample are plotted in Figure 3.1. Among them, the abscissa is the logarithmic of the maximum ground acceleration, the ordinate is the logarithmic of the maximum displacement angle between the layer. According to the form of formula (3.4) , As the logarithm of   is the independent variable, As the logarithm of the maximum displacement angle between the layer is the dependent variable linear regression, through regression analysis, we can obtain the structural response formula of model 1, model 2 and model 3 can be presented as follows:



(a) Model 1.



(b) Model 2.



(c) Model 3.

Figure3.1 Regression analysis of responding value

$$\ln\left(\theta_{\max}\right) = 0.97978 \ln(PGA) - 2.73352 \tag{3.6}$$

Linear correlation coefficient is 0.92903.

$$\ln\left(\theta_{\max}\right) = 0.94529 \ln(PGA) - 2.23989 \tag{3.7}$$

Linear correlation coefficient is 0.91127.

$$\ln\left(\theta_{\max}\right) = 0.66177 \ln(PGA) - 2.06171 \tag{3.8}$$

Linear correlation coefficient is 0.85885.

3.3. Damage state defined

The paper, based on the post-earthquake resource, presented the advised damage state about the RC frame building in Wenchuan referring to four performance levels of performance design method, as Figure 3.2 is shown.

Table 3.2. The damage state defined of RC buildings in Wenchuan

Damage state	Performance level	Description	Degree of difficulty in restoration
No damage	Normal use	No damage in both the bearing and the non-load bearing component, in the elastic working stage	No need to repair
Slight damage	Temporary use	The slight cracks appeared in the bearing and the non-load bearing component appears, the intensity and stiffness have degradation slightly, but approximately to be in the elastic working stage	Easier to repair, local repair
Moderate damage	Life safety	The broad and deep cracks appeared the non-load bearing component appears, expand cracks appeared in the bearing component appears, column root appears plastic hinge, into the elastic-plastic work stage	It could repair, but need to do repair evaluation
Extent damage	Close to collapse	The non-load bearing component starts to collapse, transfixion cracks appeared in the bearing component, large area of spalling appears in beam-column protection layer and the longitudinal and stirrup reinforcement bared	Uneasy to repair suggest dismantle
Complete damage	Collapse	bearing capacity lost, structure collapses	Unable to repair , force to dismantle

Based on the division of the damage state in HAZUS risk assessment, and the level of the damage state, combined with China's code for seismic design of buildings, in this paper, the buildings in Wenchuan are divided into the new buildings and the original old ones, referring to the limit year (2001) when our country's building codes update. The limit value of damage index in every damage level is given, as be shown in the table 3.3.

Table 3.3. The suggested damage limited value of the RC buildings in Wenchuan

The damage level	Buildings before 2001		Buildings after 2001	
	Inter-story drift	overall deformation	Inter-story drift	overall deformation
Slight damage state	0.25	Δ_y / H	0.40	$2\Delta_y / H$
Moderate damage state	0.40	$3\Delta_y / H$	1.00	$4\Delta_y / H$
Extent damage state	0.80	$8\Delta_y / H$	1.80	$10\Delta_y / H$
Complete damage state	2.50	$> 8\Delta_y / H$	4.00	$> 10\Delta_y / H$

3.4. Seismic vulnerability curve

The probability of seismic demand exceeding capacity can be indicated

$$P_f = P(C / D \le 1) \tag{3.9}$$

It is assumption D and C obey logarithmic normal distribution, then failure probability P_f can be shown by the following formulation[4].

$$P_f = \Phi\left[\frac{-\ln\left(\hat{C}/\hat{D}\right)}{\sqrt{\beta_c^{\,2} + \beta_d^{\,2}}}\right] \tag{3.10}$$

Where, $\hat{C}$ is the median of seismic capacity, β_c is the logarithmic standard deviation. $\Phi(x)$ is the normal distribution formulation, namely

$$\Phi(x) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{x} \exp\left(-\frac{t^2}{2}\right)dt \tag{3.11}$$

The value can be calculated by the standard normal distribution table, and the failure probability can be derived by bring the various PGA to the formulation(3-10). The curve can be drawn as the Figure.3.2.

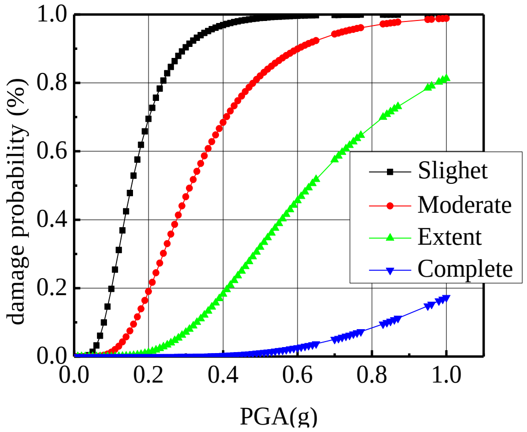


Figure 3.2. Model 1 seismic vulnerability curve

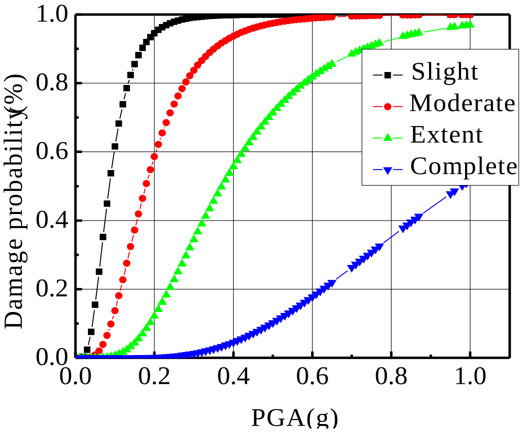


Figure 3.3. Model 2 seismic vulnerability curve

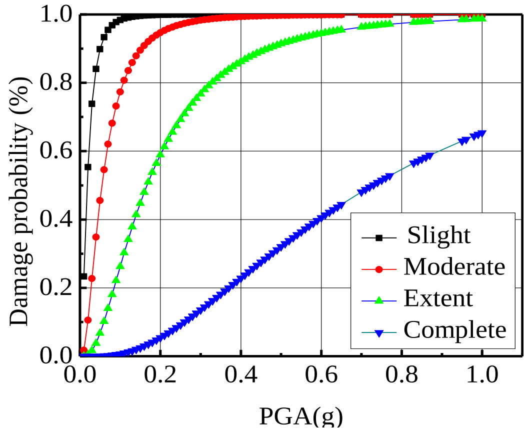


Figure 3.4. Model 3 seismic vulnerability curve

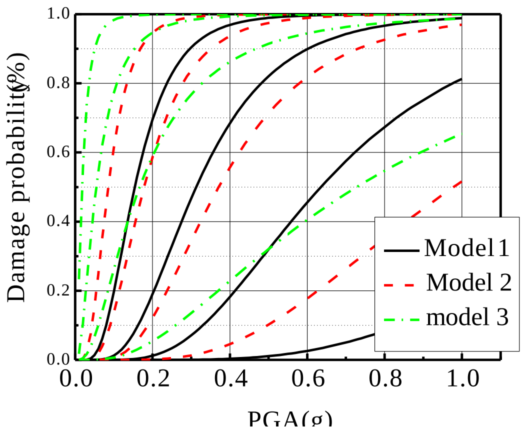


Figure 3.5. Seismic vulnerability compared

Make the curves of all models draw into the same coordinate system as is shown Figure 3.5, Figure 3.3, Figure 3.4 and Figure 3.5. By comparison, the overall tendency of vulnerability curves is that the failure probability increases with the enhancement of natural period every damage state. The specific performance is presented that model 3 failure probability is 15.03% larger than mode 2 and model 2 failure probability is 11.25% larger than model 1 in the slight damage state. model 3 failure probability is 19.77% larger than mode 2 and model 2 failure probability is 16.27% larger than model 1 in the moderate damage state. model 3 failure probability is 21.63% larger than mode 2 and model 2 failure probability is 20.08% larger than model 1 in the extent damage state. model 3 failure probability is 11.76% larger than mode 2 and model 2 failure probability is 8.13% larger than model 1 in the complete damage state. It is found that the failure probability increases with the enhancement of natural period in the first three damage state, however, it indicated breaking down in the complete state, which is relevant with too large deformation.
It is discovered that the correlation of the system maximum respond decreases with the enhancement of natural period, when PGA is as the input index of earthquake intensity. The specific performance is presented that the model 1 natural period 0.5671 is the relevant respond correlation 0.92903. The model 2 natural period 0.9726 is the relevant respond correlation 0.91127. The model 3 natural period 1.5313 is the relevant respond correlation 0.85885. Namely, the correlation of the system maximum respond for long period structure is better than the short period one.

4. THE AVERAGE ANNUAL EXCEEDANCE PROBABILITY.

In a certain period, the probability of the structure response value beyond a certain limit can be calculated by formulation (4.1).

$$P_{LS} = \sum_{x} P\left[L_S / I = x\right] P\left[I = x\right] \tag{4.1}$$

Where $P\left[LS / I = x\right]$ is the failure probability, namely the seismic vulnerability, .And $P\left[I = x\right]$ shows that the probability, when the earthquake intensity I reached x, which can be calculated by the seismic risk analysis.
Both of the Seismic intensity and damage state is successive[5]. So the formulation (4.1) can be transformed to,

$$P_{LS} = \int_0^{\infty} F_R(x) dG_I(x) \tag{4.2}$$

Where, $F_R(x) = P\left(L_S / I = x\right)$, $G_I(x) = P\left[I \geq x\right]$ present the exceeding probability when the seismic intensity beyond or equal x .

The formulation (4.2) can be transformed to,

$$P_{LS} = \int_0^{\infty} F_R(x) \frac{dG_I(x)}{dx} dx \tag{4.3}$$

That is the classical probability of interference integrals in structure reliability theory, the image can be shown by Figure 4.1. Annual average probability beyond the damage of the state level can be calculated by the formulation, which is shown the Table 4.1. It can be seen from the Table 4.1, the same structure's annual average exceeding probability towards same structure decreased with damage accumulation, and annual average exceeding probability of the different structure's increased with the natural period enhanced. It's consistent with the analysis results of structure seismic vulnerability analysis.

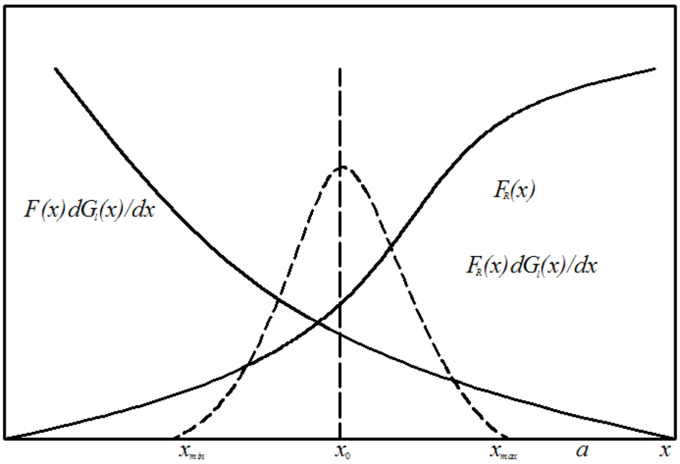


Figure 4.1. Interference probability of seismic vulnerability risk

Table 4.1. Annual average probability beyond the damage of the state level

Num.	Slight damage state	Moderate damage state	Extent damage state	Complete damage state
Model 1	0.0945	0.0532	0.0203	0.0014
Model 2	0.1429	0.0850	0.0433	0.0073
Model 3	0.3098	0.1896	0.0939	0.0212
Model 3	0.3098	0.1896	0.0939	0.0212

CONCLUSION

The conclusion drawn by the seismic vulnerability analysis on the post-earthquake typical existing RC buildings as follows:

The hazard model considering ground effects, based on Cornell theory, is so reasonable that can respond relation between the ground motion parameter and exceeding probability, and present a little conservative.

It can be an effective seismic vulnerability assessment means that the vulnerability analysis method consisted of Latin Hypercube Sampling, and probability seismic capability based on Push-over, probability demand analysis based on dynamic history analysis and statistical regression analysis. The relevant vulnerability curves can clear reflect the seismic resistance performance of the post-earthquake typical existing RC buildings in Wenchuan, which can provide an excellent application prospect.

The table made on the basis of HAZUS and the post-earthquake survey resources can reflect the building damage apparence and seismic characteristic, meanwhile can be effective assessment standard towards the existing buildings in Wenchuan .

The failure probability can increases with the enhancement of natural period in the first three damage state, however, it indicated breaking down in the complete damage state, it might to be relevant with too large deformation. And The average annual probability of exceedance is identical with the failure probability.

ACKNOWLEDGEMENT

This project is sponsored by National Natural Science Foundation of China (Grant No. 50978218, 51108376), Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20106120110003), Science and Technology Co-ordinator Innovation Project of Shann'xi Province in China (Grant No. 2011KTCQ03-05) and Office Educational of Shann'xi Province in China (Grant No. 2010JK633).

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