Acta Technica 62 No. 2A/2017, 365–374

Risk assessment of existing concrete frame structure in geological hazards area with high incidence

Jiawei Sun[1], Hainan Liu[1]

Abstract. To provide a quantitative measure of hazard performance evaluation, we carried out a probabilistic seismic risk analysis and proposed an economic performance evaluation index. The economic performance evaluation index is based on the performance of the hazard engineering. We also proposed the vulnerability index analysis based on risk and robustness analysis. We compared the seismic demand and seismic damage risk of the different index structures of the corresponding prototype structures. The results indicate that the reinforced concrete frame structure can meet the demand of "the great hazard will not make too great changes". The model we proposed has higher accuracy and computational efficiency

Key words. Risk assessment, concrete frame structure, geological hazards.

1. Introduction

At home and abroad, a lot of researches have been done on the study of hazard loss estimation, and the research object is mainly divided into two categories: the study of regional loss estimation and the estimation of single building loss. The so-called regional loss estimation is to take a large number of building loss estimation in a region as the research objects, to make the economic loss estimation. While single building loss estimation study is the accurate estimation of loss for a specific site on the concrete building. As to the research method, the hazard loss estimation can be divided into deterministic method and probabilistic method [1]. And both of them are based on the corresponding risk analysis. The difference is that the deterministic risk analysis is only to consider the given magnitude of given level in a specific site, while the probabilistic seismic hazard analysis is to consider the exceedance probability of all possible ground motion strengths.

Probabilistic seismic risk assessment is the basis of hazard risk decision and safety management. On the basis of the previous studies, this paper will first of all explore

[1]Shaanxi Institute of Geo-Environment Monitoring, Xi'an, 710000, China

the probabilistic seismic risk assessment index. The paper introduces the seismic risk evaluation indexes such as risk probability, risk loss, internal rate of return, net present value, dynamic investment recovery period, vulnerability index and risk based robustness index and so on hazard risk assessment indexes. On this basis, the risk assessment of concrete frame structure in geological hazards area with high incidence.

2. Probabilistic risk analysis of concrete frame structure

2.1. Probabilistic seismic risk analysis function

The probability λ_{LS} of exceeding a certain limit state failure of the structure each year can be calculated by the following formula:

$$\lambda_{\mathrm{LS}} = \int_X F_{\mathrm{R}}(x) \left| \mathrm{d}H(x) \right| . \tag{1}$$

In the above formula, $H(x)$ refers to the hazards risk function, indicating the probability that the hazards with a certain strength happened in the design site each year [2]. The hazards risk function $H(x)$ can be expressed by the maximum distribution function of extreme of II type:

$$H\left(x\right) = P\left[\mathrm{IM} \geq x\right] = 1 - \exp\left[-\left(\frac{x}{u}\right)^{-k}\right] . \tag{2}$$

In (2), u indicates the hazards scale parameter and k represents the shape parameter.

In the probability frame, $H(x)$ usually uses power exponent for the approximation, suggested as Log-linear relationship

$$\lambda_{\mathrm{IM}}(x) \approx \left(\frac{x}{u}\right)^{-k} \approx k_0 x^{-k} . \tag{3}$$

In (3), k_0 and k are the shape parameters, which can be obtained by DBE (Design Based Earthquake) and considering the earthquake motion strength fitting corresponding to the hazards MCE [3].

In 1994, Cornell substituted seismic vulnerability function

$$F_{\mathrm{R}}(x) = P\left[D \geq C \left| \mathrm{IM} = x\right.\right]$$

(IM refers to the intensity measure, $D \geq C$ indicates the structure reaches or exceeds a certain extreme state where D is the demand and C suggests the seismic capacity and $F_{\mathrm{R}}(x)$ is called seismic vulnerability function) into (1), and then he derived and obtained the analytical expression of probabilistic seismic risk

$$\lambda_{LS} = H(m_{\mathrm{R}}) \exp\left[\frac{1}{2} k^2 \beta_{\mathrm{R}}^2\right] . \tag{4}$$

By using the seismic vulnerability function based on displacement, we can get the analytical expression of probabilistic seismic risk only considering the intrinsic uncertainty [4]

$$\lambda_{\mathrm{LS}} = H\left\{\left(\frac{m_C}{\exp\left(\beta_0\right)}\right)1/\beta_1\right\}\exp\left[\frac{1}{2}k^2\left(\frac{\beta\left|^2_{D|\mathrm{IM}}+\beta_C^2\right.}{\beta_1^2}\right)\right]. \tag{5}$$

In (5), if the capability uncertainty in the analytical expression of probabilistic seismic risk is not considered, then we can get:

$$\lambda_D = H\left\{\left(\frac{d}{\exp\left(\beta_0\right)}\right)^{1/\beta_1}\right\}\exp\left[\frac{1}{2}k^2\left(\frac{\beta_{D|\mathrm{IM}}^2}{\beta_1^2}\right)\right]. \tag{6}$$

In the frame of PBEE (Performance Based Earthquake Engineering), (5) and (6) can be understood as the different stages of uncertainty transmission [5]

$$\lambda_{\mathrm{LS}} = \int_{\mathrm{edp}}\int_{\mathrm{im}} G\left(\mathrm{dm}\left|\mathrm{edp}\right.\right)\left|\mathrm{d}G\left(\mathrm{edp}\left|\mathrm{im}\right.\right)\right\|\mathrm{d}\lambda\ \left(\mathrm{im}\right)\right|, \tag{7}$$

$$\lambda_D = \int_{\mathrm{im}} G\left(\mathrm{edp}\left|\mathrm{im}\right.\right)\left|\mathrm{d}\lambda\left(\mathrm{im}\right)\right|. \tag{8}$$

From (7), it can be seen that λ_{LS} considers the uncertainty of structure capability and it can be seen as the results of hazards risk transmission to structure damage layer, which is called "Probabilistic seismic damage risk". From (8), it is known that λ_D does not consider the uncertainty of structure capability, which is called "Probabilistic seismic demand risk" [6]. And the "Probabilistic seismic demand risk function" shown in (6) is also called "structural seismic hazard function". The seismic risk analysis of structures can be regarded as the extension of the seismic hazard from the site to the structure. If the seismic demand d is taken in a reasonable range, the seismic demand risk is expressed in the form of seismic demand risk curve. If we only pay attention to the seismic demand d^{LS} at a certain level, the seismic demand risk represents the average annual probability of the event $\left\{d > d^{\mathrm{LS}}\right\}$. However, the seismic damage risk characterizes the probability of earthquake damage that occurs in different states each year.

2.2. Probabilistic seismic demand risk analysis

Based on the index prototype structure DBE and MCE Sa (T1,5%) value designed, we can get the structural hazard function parameters, as shown in Table 1. According to the seismic code, the hazards intensity increases for 1 degree, and the hazards action increases twice. As a result, we obtain SaMCE/SaDBE = 2 [7].

The seismic demand risk curve of the prototype structure is obtained based on the above formulas. From the results, it is known that with the increase of the level of structural fortification, the risk of seismic demand has not weakened, but increased. According to the research in the previous parts, it shows that with the increase of the fortification level, seismic vulnerability of the structure under the same seismic fortification level gradually weakened [8]. That is to say, the improvement of structure fortification enhances the ability of earthquake resistant structure. However, the increase in fortification levels also increases the risk of structural seismic damage. Of course, if there is an earthquake risk in the same site, the structure with a stronger ability to resist ground motion should have a smaller seismic demand risk.

Table 1. The distribution of the dynamic comfort

Structures	Sa_{DBE}/g	Sa_{MCE}/g	k_0
F3-1	0.07	0.13	3.29×10^{-6}
F3-2	0.17	0.33	2.90×10^{-5}
F3-3	0.17	0.33	2.90×10^{-5}
F3-4	0.32	0.64	1.41×10^{-4}
F3-5	0.43	0.86	2.81×10^{-4}
F3-6	0.70	1.40	9.00×10^{-4}
F5-1	0.05	0.10	1.62×10^{-6}
F5-2	0.11	0.21	1.03×10^{-5}
F5-3	0.15	0.31	2.45×10^{-5}
F5-4	0.22	0.44	5.74×10^{-5}
F5-5	0.29	0.59	1.14×10^{-4}
F5-6	0.52	1.03	4.38×10^{-4}
F8-1	0.04	0.08	8.97×10^{-7}
F8-2	0.08	0.16	5.04×10^{-6}
F8-3	0.11	0.23	1.20×10^{-5}
F8-4	0.15	0.30	2.29×10^{-5}
F8-5	0.24	0.48	6.99×10^{-5}
F8-6	0.32	0.64	1.38×10^{-4}
F10-1	0.03	0.07	6.07×10^{-7}
F10-2	0.07	0.13	3.31×10^{-6}
F10-3	0.10	0.19	7.89×10^{-6}
F10-4	0.12	0.25	1.47×10^{-5}
F10-5	0.20	0.40	4.63×10^{-5}

3. Assessment of concrete frame structure risk

3.1. Assessment of concrete frame structure risk

Taking into account the uncertainty of structural capacity, the results of seismic damage risk analysis considering the intrinsic uncertainty of the prototype structure are obtained according to the formula, as shown in the following table.

Table 2. Probabilistic seismic damage risk values for index architype buildings considering intrinsic uncertainty

Structures	SD(10^{-2})	MD(10^{-3})	ED(10^{-4})
F3-1	1.46	0.27	0.56
F3-2	7.05	0.46	5.55
F3-3	7.05	1.29	5.55
F3-4	1.64	1.37	10.51
F3-5	1.15	2.30	18.51
F3-6	15.50	0.18	49.32
F5-1	0.32	0.53	1.23
F5-2	1.41	1.87	0.62
F5-3	1.16	2.26	1.08
F5-4	1.55	1.31	1.43
F5-5	1.17	0.75	1.69
F5-6	0.49	1.87	3.83
F8-1	0.60	0.16	0.16
F8-2	3.01	0.84	2.72
F8-3	3.02	1.72	1.78
F8-4	2.32	1.53	5.11
F8-5	1.77	2.68	3.08
F8-6	0.93	0.76	7.14
F10-1	0.43	0.27	0.64
F10-2	1.90	1.14	2.86
F10-3	4.24	2.71	6.03
F10-4	6.28	3.58	1.01
F10-5	2.93	4.21	1.45

Taking the structure F5-2 as an example, the structural seismic demand risk curve is compared with the structural damage risk, as shown in the Fig. 1. As can be seen from the graph, the value of the seismic damage falls above the seismic demand risk curve [9]. In order to make a further comparison, this paper compares the seismic demand and seismic damage risk of the different index structures of the corresponding prototype structures. And the comparison results suggest that the risk of hazard demand is less than the risk of earthquake damage due to the uncertainty of capacity.

3.2. Probabilistic seismic risk analysis in the service life of structures

It should be pointed out that the probabilistic seismic risk involved in this paper is expressed in the form of annual average exceedance probability [10]. In the existing anti-seismic standards, it is not clear that the limit of annual average exceedance probability has been used as the criterion for evaluating the seismic risk of structures.

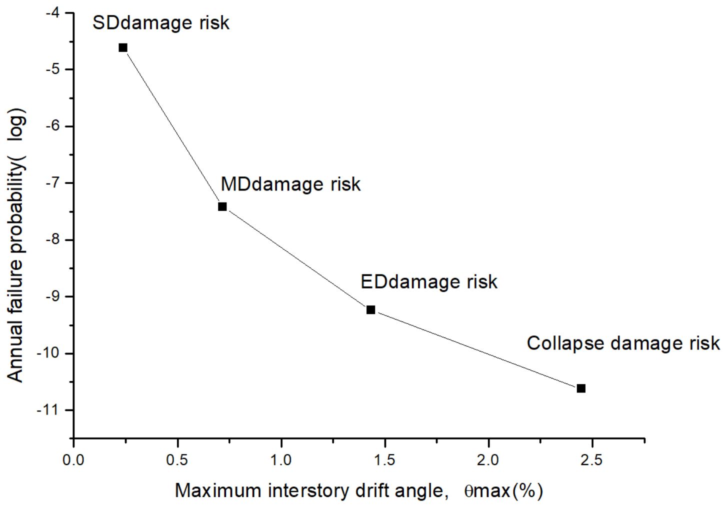

Fig. 1. Comparisons of the seismic demand risk curve and the seismic damage risk values for building F5-2

There are three levels of fortification requirements for structural design in the anti-seismic standards of China: "the small hazard is not serious, the moderate hazard can be repaired, and the great hazard will not make too great changes", in which the occurrence probability of small, moderate, and great hazards within 50 years is 63.2 %, 10 % and 2 % in turn [11]. Because our specification does not consider the influence of structural uncertainty, from the viewpoint of probability, the three level design can be understood as: "the probability for structure to have a slight damage within 50 years does not exceed 63.2 %, the occurrence probability of moderate damage does not exceed 10 %, and the probability of collapse is not more than 2 %" [12]. Based on the above understandings, this paper extends the analysis results of seismic damage risk to 50 years to assess the probability of hazard risk. The failure probability of structure in different damage levels within 50 years can be calculated according to the Poisson hypothesis, shown as follows

$$P_{\mathrm{DM}} = 1 - (1 - \lambda_{\mathrm{DM}})^{50} \,. \tag{9}$$

In the period of usage within 50 years, the probability of the damage of the prototype structure is larger, and the probability of failure of most structures is greater than 63.2 %, which is inconsistent with the requirements of "the small hazard is not serious". With the increase of the structure fortification intensity, the risk of structural damage is not reduced, but increased [13]. This shows that improving the structure fortification and increasing its resistance level is to reach the "balance" at the expense of hazard risk". The probability of the intermediate failure of many index prototype structures is greater than 10 %. While the damage only with F3-6 structure is more than 2 % [14]. Therefore, reinforced concrete frame structure designed according to the standard meets the requirements of "the great hazard does not make too great changes", which is certain.

3.3. Results

This chapter is based on the analysis of seismic vulnerability function, using the probabilistic risk relationship in the classical form of power function. We derive the analytic function of probabilistic seismic risk, which includes: only considering the intrinsic uncertainty probabilistic seismic demand risk function and the probability of hazard damage risk function. By comparing the seismic demand and seismic damage risk of different limit states, it can be seen that the risk of seismic demand is less than the risk of earthquake damage since the capacity uncertainty is not considered [15].

The goal of probabilistic risk analysis is to evaluate the seismic safety of structures. To achieve this goal, this paper expanded the probability characterized as annual exceeding probability seismic risk as the failure probability with the use period of structures, and assessed the seismic safety of the reinforced concrete frame structure designed according to the evaluation standard in our country. The results show that the structure to improve the fortification and increase the resistance level is a "balance" reached at the expense of seismic risk. At the end of this chapter, according to the results of seismic vulnerability of population structure obtained, we further analyze the seismic risk of concrete frame structure. And it is found that: the reinforced concrete frame structure designed according to the code of our country cannot meet the requirement "the small hazard is not serious, and the moderate hazard can be repaired", but it can meet the demand of "the great hazard will not make too great changes".

4. Conclusion

In this paper, a new generation of performance based earthquake engineering risk framework is taken as the research background, the open hazard engineering simulation software as the research platform, and the reinforced concrete frame structure with large volume as the research object. The paper intends to assess the safety and potential risk of concrete structures designed aaccording to the current specification, with seismic analytic function vulnerability and risk function and efficient simulation technique as the research tools. The main conclusions are as follows:

In the aspect of uncertainty analysis methods, the proposed method has higher accuracy and computational efficiency. The sensitivity parameters presented in this paper can be used to describe the effect of the change of random variables in the standard normal space on the function response.

In the aspect of probabilistic seismic demand analysis, the seismic intensity evaluation system proposed in this paper can be used to evaluate the statistical characteristics of ground motion from a probabilistic point of view.

In the aspect of seismic risk assessment, the risk of hazard demand is less than the risk of hazard damage because of the uncertainty of capacity. The structure increases the resistance ability by improving the fortification is under the premise of losing hazard risk. From the perspective of hazard risk, the reinforced concrete frame structure designed according to the standards in China cannot strictly meet the design requirement of "the small hazard is not serious, and the moderate hazard can be repaired", but can fully meet the demand of "the great hazard will not make too great changes".

References

[1] R. Zeibak-Shini, R. Sacks, L. Ma, S. Filin: *Towards generation of as-damaged BIM models using laser-scanning and as-built BIM: First estimate of as-damaged locations of reinforced concrete frame members in masonry infill structures.* Advanced Engineering Informatics *30* (2016), No. 3, 312–326.

[2] S. W. Park, S. W. Choi, Y. Kim, B. K. Oh, H. S. Park: *Optimal retrofit design of reinforced concrete frame with infill wall using fiber reinforced plastic materials.* WASET, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering *10* (2016), No. 5, 572–576.

[3] N. Ganesan, P. V. Indira, S. R. Prasad: *Structural behaviour of steel fibre reinforced concrete wall panels in two-way in-plane action.* Indian Concrete Journal *84* (2010), No. 10, 21–28.

[4] A. Kadid, A. Boumrkik: *Pushover analysis of reinforced concrete frame structures.* Asian Journal of Civil Engineering (Building and Housing) (2008), No. 9, 75–83.

[5] G. A. Anwar, J. Anwar, P. D. Versaillot: *Effect of CFRP retrofitting on seismic vulnerability of reinforced concrete frame structures in Pakistan.* American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS) *26* (2016), No. 1, 145–158.

[6] P. Yan, B. Sun: *Earthquake damage of self-built reinforced concrete frame structures in M_S 8.1 Nepal earthquake.* IOP Conference Series: Earth and Environmental Science, International Conference on Energy Materials and Environment Engineering, 10–12 March 2017, Bangkok, Thailand, IOP Publishing *61* (2017), paper 012093.

[7] D. J. Kakaletsis, C. G. Karayannis: *Experimental investigation of infilled reinforced concrete frames with openings.* ACI Structural Journal *106* (2009), No. 2, 132–141.

[8] M. N. Bugeja, J. M. Bracci, W. P. Moore Jr.: *Seismic behavior of composite RCS frame systems.* Journal of Structural Engineering *126* (2000), No. 4, 429–436.

[9] Z. Lan, Y. Tian, L. Fang, S. Liang, X. Wang: *An experimental study on seismic responses of multifunctional vibration-absorption reinforced concrete megaframe structures.* Earthquake Engineering and Structural Dynamics *33* (2004), No. 1, 1–14.

[10] L. Zhang, H. Zhao, T. Wang, Q. Chen: *Parametric analysis on collapse-resistance performance of reinforced-concrete frame with specially shaped columns under loss of a corner column.* Open Construction and Building Technology Journal *10*, (2016), No. 1, 466–480.

[11] L. Wang, X. Wei, N. N. Feng, Q. Gao: *Research on seismic performance of reinforced concrete frame with unequal span under low cyclic reversed loading.* Open Civil Engineering Journal *10* (2016), No. 1, 373–383.

[12] V. Kilar, S. Petrovčič, D. Koren, S. Šilih: *Cost viability of a base isolation system for the seismic protection of a steel high-rack structure.* International Journal of Steel Structures *13* (2013), No. 2, 253–263.

[13] V. T. Dzyubenko, L. V. Zvorygin: *Characteristics of rock pressure manifestations on reinforced-concrete tubular shields.* Soviet Mining *5* (1969), No. 5, 583–586.

[14] J. W. Hwang, B. K. Oh, Y. Kim, H. S. Park: *CO2 emission and cost optimization of reinforced concrete frame designed by performance based design approach.* WASET, International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering *10* (2016), No. 3, 336–341.

[15] Z. Lu, X. Chen, X. Lu, Z. Yang: *Shaking table test and numerical simulation of an RC frame-core tube structure for earthquake-induced collapse*. Earthquake Engineering and Structural Dynamics *45* (2016), No. 9, 1537–1556.

Received July 12, 2017