STUDY ON PERFORMANCE-BASED SEISMIC VULNERABILITY OF REINFORCED CONCRETE FRAME STRUCTURES

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Abstract

With the rapid economic growth of China, there is a great development of urbanization. However, for the urban building group, due to the differences in the age of the structure, the adopted seismic zoning and code for seismic design of buildings, and the coexistence of different age buildings in Chinese cities, there is a significant difference about the seismic capacity among the buildings. Therefore, the problems that need to be solved currently include three:

(1) How to quantify the difference in seismic capacity of various building structures in different cities, which has different construction age, fortification standards, building system structure, architectural function, and number of building floors?

(2) What about the ability of collapse resistance for urban building in the face of rare earthquakes?

(3) How to quickly assess the overall earthquake damage of urban building group before and after an earthquake?

Focused on urban building group, this paper introduces the concept of "performance-based seismic assessment", conducts research on behavioral group seismic vulnerability analysis method for reinforced concrete frame structures, and construct a standard sample database of the seismic vulnerability curves that are suitable for China's national conditions. This paper does the following works:

(1) Considering the factors such as seismic fortification intensity, construction age and number of building floors, the criteria for seismic classification of RC frame structures in China has been established. According to US HAZUS classification method, there are four categories for the seismic resistance of Chinese buildings: High-Code, Moderate-Code, Low-Code and Pre-Code.

(2) Study the establishment of reasonable ground motion record selection and scaling methods and structural refinement modeling methods considering the influence of infill walls and slabs, and verify the rationality of the model compared with actual seismic damage of a four- story T-frame structure, which suffered from the 7.1-magnitude earthquake occurred in Yushu County.

(3) Considering the uncertainty of structural parameters and the uncertainty of ground motion and using MATLAB for Latin hypercube sampling, the seismic vulnerability curve of RC frame structure based on behavioral state is established by IDA analysis.

The research shows that, although there is a little error between the time history analysis result and the actual seismic damage, the error is not large, and considering the randomness of ground motion, the time history analysis result can be considered to have certain accuracy and reliability. And compared with basically intact buildings, the seismic vulnerability curve of buildings that are on the state of destruction are more gradual, and the transcendental probability of structural failure is getting smaller and smaller under certain peak ground acceleration (PGA) conditions.

This study can provide a reference and basis for all levels of government to comprehensively understand the earthquake disaster risk faced by urban buildings and an objectives-oriented decision of urban construction and transformation.

Keywords: earthquake damage prediction, reinforced concrete frame structure, IDA, seismic vulnerability

1. Introduction

With the rapid development of the economy, China will enter a period of accelerated urbanization. By 2020, the urbanization rate will increase from the current 40% to 57%, and the total urban population will reach 828 million. Of the 122 cities with a population of more than one million in China, 85% are located in seismic activity areas. The forthcoming new generation of China Earthquake Parameter Zoning Map shows that more than 75% of China's cities are facing serious threats from potential earthquake disasters. As a main body of urban engineering structure, the building group has significant “space-time” distribution characteristics: on the one hand, there are a large number of building structures built in different ages in the city, which are constructed according to seismic zoning maps and seismic design codes of different periods. On the other hand, there are obvious buildings with different floors, and the distribution of old urban areas is obvious. At the same time, new engineering structures such as high-rise buildings have emerged in recent years, and some seismic technologies and measures have not yet been tested by major earthquakes. In the event of a devastating earthquake, it will cause a large number of casualties and huge economic losses, and may cause serious secondary disasters, which will have a gigantic impact on the national economy and hinder the sustainable development of society. Therefore, how to quantify the seismic capacity difference between various building structures of different cities in different construction times, fortification standards, architecture, function, and number of layers, and how to effectively evaluate the resistance of urban buildings in the rare or rare earthquakes. The collapse ability, how to quickly assess the overall earthquake disasters of urban buildings before and after the earthquake, is the most concerned and need to answer questions about earthquake vulnerability research.

In previous work by the authors [1-4], and built on the seismic design concept based on behavior, this paper proposes and establishes a multi-factor seismic classification criterion for reinforced concrete frame structures in China. The numerical simulation of typical structures is established considering factors such as floor stiffness, infill wall stiffness and structural material uncertainty. The model, and selected 40 pieces of incremental dynamic analysis, finally obtained the performance-based seismic vulnerability curve of the reinforced concrete frame structure.

2. Performance-based seismic vulnerability assessment method

The so-called behavioral vulnerability assessment method [5, 6] for buildings based on the behavior is to refer to the structural performance level classification criteria, determine the structural seismic performance level classification, and consider the structure, material and ground motion uncertainty to establish the structural seismic vulnerability curve.

Considering the evolution of seismic design codes in different periods in China, according to different factors such as seismic fortification intensity, basic acceleration and construction age, the US HAZUS classification method [7] is used to classify the seismic resistance of Chinese buildings into four categories: High-Code, Moderate-Code, Low-Code, and Pre-Code; meanwhile these buildings can also be subdivided into three categories according to the number of layers: High-Rise (8+), Mid-Rise (4-7), and Low-Rise (1-3). Finally, China's RC framework structure is divided into 12 categories (see the Table 1 below).

Table 1– China RC frame structure seismic design waterproof classification

Seismic intensity	**Construction age**			
	≥2001	**1990-2001**	**1979-1989**	**≤1978**
IX(0.40g)	High-Code	High-Code	Moderate-Code	Pre-Code
VIII(0.30g)	Moderate-Code	Moderate-Code	Moderate-Code	Pre-Code
VIII(0.20g)	Moderate-Code	Moderate-Code	Low-Code	Pre-Code
VII(0.15g)	Low-Code	Low-Code	Low-Code	Pre-Code
VII(0.10g)	Low-Code	Low-Code	Pre-Code	Pre-Code
VI(0.05g)	Pre-Code	Pre-Code	Pre-Code	Pre-Code

3. Seismic vulnerability analysis technology of reinforced concrete frame structure

In the process of incremental dynamic analysis of reinforced concrete frame structures, the effects of infill wall effect and floor stiffness on the seismic performance of reinforced concrete frame structures must be considered.

3.1 Floor stiffness considerations

For cast-in-place floor coverings and integral monolithic floor coverings, the influence of the slab as a flange on the stiffness and bearing capacity of the beam should be considered [8]. In this paper, according to the specifications, the thickness of each floor of the beam is 6 times as the effective flange of the beam section. The beam section forms and the finite element division considering the rigidity of the slab are shown in Fig. 1.

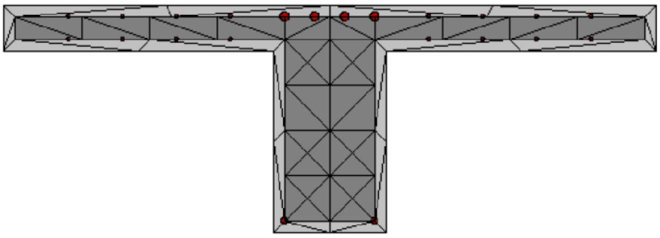
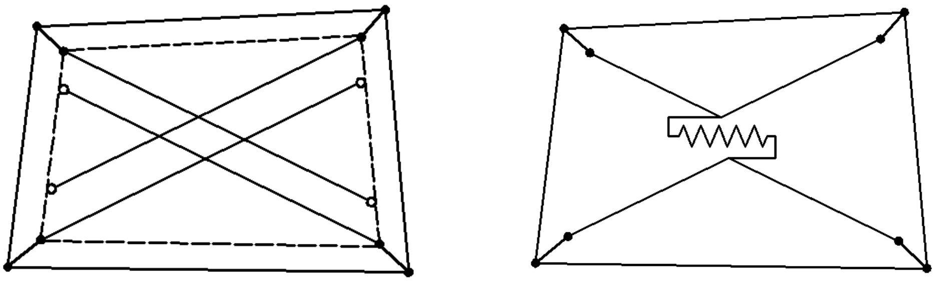


Fig.1– RC beam modeling scheme considering floor effect

3.2 Consideration of the stiffness of the infill wall

According to previous work by the authors [9], the seismic damage indicates that the stiffness of the infill wall is closely related to the seismic performance and seismic performance of the structure. In this paper, when building a numerical simulation model, the wall element model is used to consider the stiffness of the infill wall. The wall element model is a four-node unit that simulates the nonlinear response of the infill wall in the frame structure. Each of the infill walls is composed of six supporting units, two opposite diagonal sides are respectively supported by two parallel struts, and the third struts bear the shearing force from top to bottom of the filling wall. It only works when the diagonal is under pressure. It can be seen whether it is enabled or not depending on the deformation of the infill wall. The axially loaded compression bar adopts the masonry support hysteresis model, and the shear bar adopts the bilinear hysteresis model. The schematic diagram of the wall element model is shown in Fig.2.



a) Truss model

b) Shearing model

Fig.2 – Infill wall plane unit

3.3 Model instance verification

At 7:49 on April 14, 2010, a 7.1-magnitude earthquake occurred in Yushu County, Yushu Tibetan Autonomous Prefecture, Qinghai Province. After the earthquake, the Yushu State Traffic Police Team office building suffered moderate damage. The building is a four-story T-frame structure (as shown in Fig.3); the filling material is clay brick; the seismic fortification intensity is seven degrees, the first group. The basic seismic acceleration of the design is 0.15g.

a) Overall appearance of the structure

b) Loose wall under the beam

c) Wall damage

Fig.3 – Typical earthquake damage in the Yushu Prefecture Traffic Police Team office building

The structure was finite element modeled using Seismostruct software. The established finite element model is shown in Fig.4.

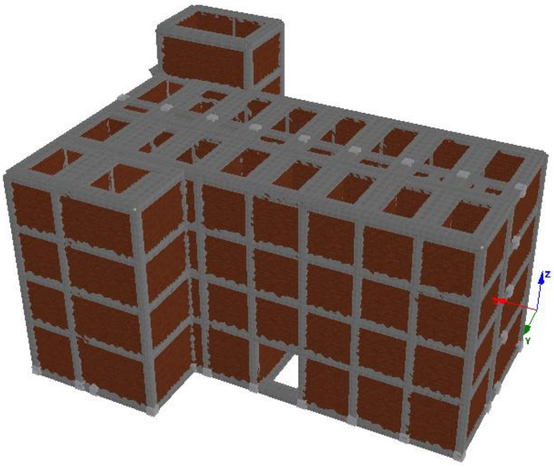


Fig.4 – The finite element model of the verifying example structure

The time history analysis of the ground motion record obtained from the Izmit station of the 1999 Turkey Kocaeli 7.2 earthquake with a PGA of 0.4g was selected. During the time history analysis, the ground motion time history of the two components is inputted horizontally. The maximum inter-layer displacement angle of the structure is 1/163.

Based on the existing achievements and regulations, and referring to the actual method of the earthquake site, the damage compensation of the structure is measured according to the maximum interlayer lateral movement angle. The measurement criteria are shown in Table 2.

Table 2 – Classification criteria for seismic damage of reinforced concrete frame structures

Basically intact	**Minor damage**	**Medium damage**	**Serious damage**	**Destruction**
$\theta_{\max} \leq \frac{1}{550}$	$\frac{1}{550} < \theta_{\max} \leq \frac{1}{300}$	$\frac{1}{300} < \theta_{\max} \leq \frac{1}{150}$	$\frac{1}{150} < \theta_{\max} \leq \frac{1}{50}$	$\frac{1}{50} < \theta_{\max}$

According to Table 2, it can be judged that the structure has moderate damage when the PGA is 0.4g, and the actual damage level is slightly moderately moderate. Although there is a certain error between the time history analysis result and the actual seismic damage result, the error is not large, and considering the randomness of ground motion, the time history analysis result can be considered to have certain accuracy and reliability.

4. Incremental dynamic analysis

This paper selects a typical RC frame structure for finite element modeling and vulnerability analysis. The basic information of the selected structure is as follows:

The structure is 50.4 meters long and 16.5 meters wide. The total number of layers is six layers, the total height is 21.72m, the height of each layer is 6m, and the outdoor elevation is -0.45m. The building area is 5000m2, the seismic fortification intensity is 7 degrees, and the basic seismic acceleration is designed to be 0.15g. The structural floor plan and the finite element model renderings are shown in Fig.5 and Fig.6, respectively.

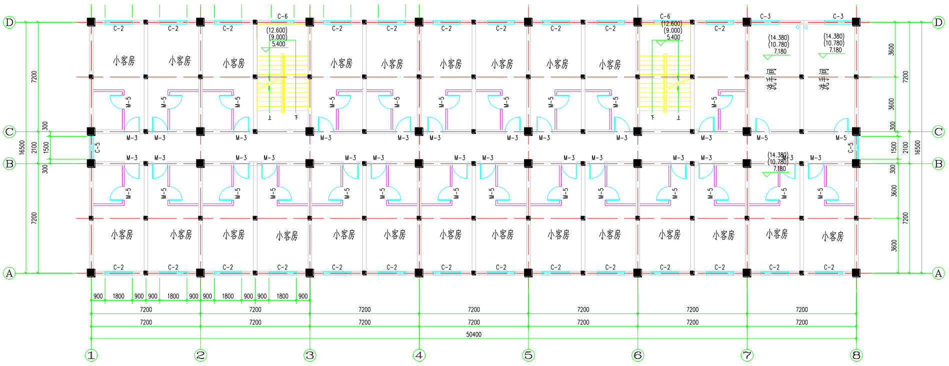


Fig.5 – Structure layout

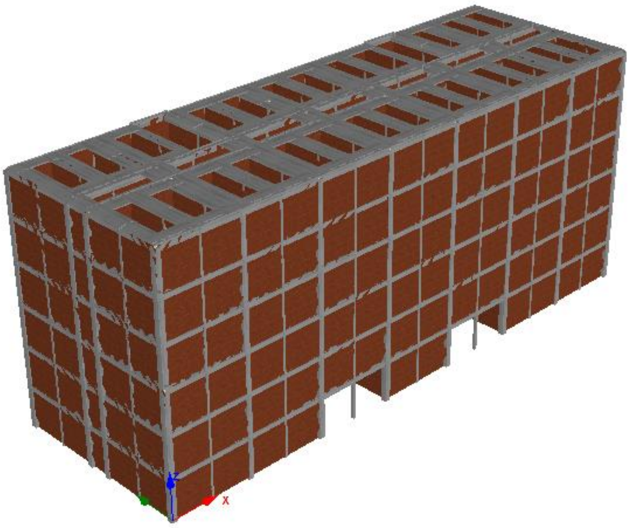


Fig.6 – Perspective view of the finite element model

Considering the uncertainty of structural materials, this paper selects column concrete (C30), beam concrete (C25) and stressed steel bar (HRB335) as variables, and uses Latin hypercube sampling method to determine the combination of six structural materials. Assume that the three independent variables follow a normal distribution. The intensity averages and standard deviations corresponding to the three independent variables are listed in Table 3.

Table 3 – Structural material strength average and coefficient of variation

Material category	**C30**	**C25**	**HRB335**
Average intensity（MPa）	369.0000	26.1100	389.9000
Standard deviation（MPa）	4.0068	6554.0000	27.2930

Based on the data in Table 3, using MATLAB for Latin hypercube sampling, six sets of material parameter combinations can be obtained, as shown in Table 4.

Table 4 – Combination of 6 material parameters determined by Latin hypercube sampling

Serial number	**C30（MPa）**	**C25（MPa）**	**HRB335（MPa）**
1	24.70434	31.07912	389.81260
2	31.55825	29.40316	426.34570
3	37.56357	22.58129	395.53710
4	37.82391	25.55974	374.97190
5	32.53590	20.50097	415.48910
6	34.50757	27.04655	337.03600

According to the magnitude, fault distance, focal depth, site category and other indicators, according to the selection method based on the design response spectrum, 40 ground motion records were selected from the PEER/NGA strong earthquake record database for IDA analysis. Based on the combination of 6 sets of material parameters, inputting 40 ground motions, 240 analysis conditions can be obtained. In the IDA analysis, the structural reaction of the structure under the conditions of PGA of 0.05g, 0.1g, 0.2g, 0.4g, 0.6g, 0.8g, and 1.0g was obtained, and a total of 1680 sets of data sample was obtained.

According to the data obtained by IDA analysis, the empirical formula for fitting the relationship between interlayer displacement angle and PGA is as follows:

$$Ln(\theta_{\max}) = -3.879 + 1.123 \times Ln(PGA) \tag{1}$$

The R-square coefficient of the formula (1) is 0.7139>0.7, which satisfies the requirement. The fitted formula and data samples are plotted in Fig.7.

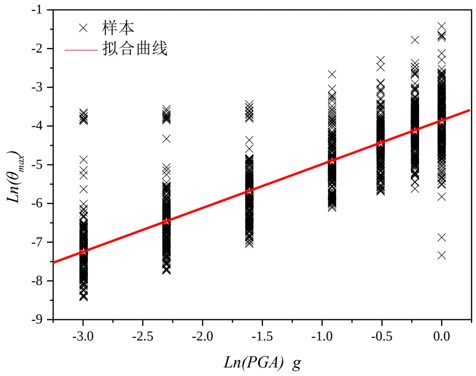


Fig.7 – Relationship between data samples and fitting formulas

In order to determine the value of Y corresponding to different damage levels, first determine the PGA value corresponding to the 50% of the number of samples in each IDA analysis result. After the PGA is determined, the Y corresponding to each failure level state can be obtained according to the formula (2).

$$Y = 0.0207 \times (PGA)^{1.123} \tag{2}$$

The statistically obtained PGA and the calculated Y are listed in Table 5.

Table 5 – The number of PGA and Y corresponding to 50% quintiles of each damage level sample number

	Basically intact	**Minor damage**	**Medium damage**	**Serious damage**	**Destruction**
PGA(g)	0.050000000	0.140229885	0.284269663	0.593209877	0.746808511
Y	0.000716001	0.002279672	0.005040919	0.011515515	0.014913664

Take $\sqrt{\beta_Y^2+\beta_{EDP}^2}=0.5$ and calculate the overshoot probability corresponding to different damage levels at different PGA levels. The seismic vulnerability curve of the reinforced concrete frame structure based on the behavior determined in this paper is shown in Fig. 8.

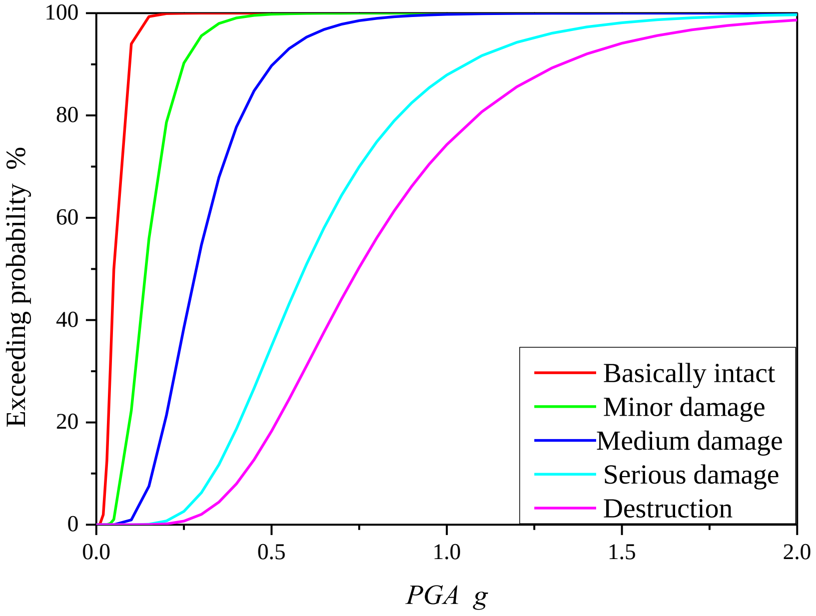


Fig.8 – Vulnerability curve of reinforced concrete frame structure

According to Fig.8, as the structure progresses from a substantially intact state to a collapsed state, the structural vulnerability curve gradually becomes gentle, and the failure probability becomes smaller and smaller.

5. Conclusion

When PGA=0.056g (corresponding to the small earthquake level), the probability of the structure reaching the basic intact state, minor damage state, medium damage state, severe damage state and collapsed state respectively are 59.94%, 1.95%, 0.01%, 0% and 0%. Basically, it is possible to achieve a waterproof standard that is not bad for small earthquakes.

When PGA=0.15g (corresponding to the mid-shock level), the probability of the structure reaching the basic intact state, minor damage state, medium damage state, severe damage state and collapsed state respectively are 99.31%, 55.90%, 7.51%, 0.1%, and 0.015%. It can realize the waterproof standard that the medium earthquake is not bad or the medium shock can be repaired.

When PGA=0.316g (corresponding to the magnitude of the large earthquake), the probability of the structure reaching the basic intact state, minor damage state, medium damage state, severe damage state and collapsed state respectively are 99.998%, 96.58%, 59.29%, 7.82% and 2.65%. It can realize the waterproof standard of the big earthquake.

6. Acknowledgments

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7. References

[1] Schotanus M, Franchin P, Lupoi A, Pinto P (2004): Seismic fragility analysis of 3D structures. Structural Safety, 26:421-441.

[2] Borzi B, Pinho R, Crowley H (2008): Simplified pushover-based vulnerability analysis for large-scale assessment of RC buildings. Engineering Structures, 30:804-820.

[3] Ji J, Elnashai AS, Kuchma DA (2007): An analytical framework for seismic fragility analysis of RC high-rise buildings. Engineering Structures, 29:3197-3209.

[4] Kirçil MS, Polat Z (2006): Fragility analysis of mid-rise R/C frame buildings. Engineering Structures, 28:1335-1345.

[5] Kwon O, Elnashai A (2006): The effect of material and ground motion uncertainty on the seismic vulnerability curves of RC structure. Engineering Structures, 28:289-303.

[6] Rossetto T, Elnashai A (2005): A new analytical procedure for the derivation of displacement-based vulnerability curves for populations of RC structures. Engineering Structures, 27:397-409.

[7] FEMA (2003): Earthquake Model HAZUS-MH MR1 Technical Manual. developed by the Department of Homeland Security Washington, DC.

[8] Camata G, Spacone E, Zarnic R (2007): Experimental and nonlinear finite element studies of RC beams strengthened with FRP plates. Composites Part B: Engineering, 38:277-288.

[9] Dolšek M, Fajfar P (2005): Simplified non‐linear seismic analysis of infilled reinforced concrete frames. Earthquake Engineering & Structural Dynamics, 34:49-66.