Proc. of the 6th Intl. Symposium on Reliability Engineering and Risk Management (6ISRERM)
31 May – 1 June 2018, Singapore
Editor(s) Xudong Qian, Sze Dai Pang, Ghim Ping Raymond Ong, Kok-Kwang Phoon

SEISMIC COLLAPSE FRAGILITY ASSESSMENT OF REINFORCED CONCRETE FRAME STRUCTURES WITH CONSIDERATION OF MODELING UNCERTAINTIES USING EQUIVALENT SDOF SYSTEMS

TING-TING LIU, DA-GANG LU, and XIAO-HUI YU

School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
E-mail: liutingtinghit@163.com
E-mail: xiaohui.yu@hit.edu.cn *E-mail: ludagang@hit.edu.cn*

The conventional method for collapse fragility analysis requires a lot of computation time and resources. In this paper, the collapse fragility curves are obtained by performing incremental dynamic analysis on the nonlinear equivalent single degree of freedom (ESDOF) systems for reinforced concrete (RC) frame structures. A five-story three-span reinforced concrete frame structure is taken as a case study, which is substituted by ESDOF systems by pushover curve. The nonlinear ESDOF systems adopt the modified Ibarra-Krawinkler (I-K) hysteretic model in the platform OpenSees. In order to quantitatively evaluate the applicability and accuracy of the nonlinear ESDOF systems, 20 real ground motion records are selected as the inputs, compared with the results of seismic collapse fragility analysis of the original structure. To consider the effects of modeling uncertainties on collapse fragility, random pushover analysis considering modeling uncertainties are conducted on the nonlinear ESDOF systems. The results show that, the developed ESDOF systems can efficiently evaluate the collapse-resistant capacity of the prototype structure while maintaining the accuracy of the approximate model, the collapse margin ratios of the ESDOF systems agree quite well with the original structure. Moreover, the collapse margin ratios of the ESDOF systems considering modeling uncertainties are larger than that not considering modeling uncertainties.

Keywords: P ESDOF systems; modified I-K model; collapse fragility; collapse margin ratio; modeling uncertainty

1 Introduction

Many researchers analyzed and evaluated the seismic collapse capacity of the building structure based on incremental dynamic analysis (IDA) that increasing the values of ground motions intensity measures until the structure collapses. IDA is an effective method for seismic collapse fragility analysis, which has been widely application in the field of earthquake engineering. Seismic collapse fragility refers to the probability of collapse subjected to different earthquake intensity. Tang *et al*. (2011) used IDA method to compare collapse fragility capacities of 10 typical RC frames with seismic fortification categories B and C. Shi *et al*. (2011) studied the collapse fragility capacity of RC frame with different seismic fortification levels. However, the results of IDA depend on the randomness of ground motions, so that many researchers usually used a series of ground motion records to analyze the collapse fragility of the building structure.

From the view of uncertainty, it is not only to consider the randomness of ground motion records, but also to further consider the uncertainties of the structures themselves. The traditional method of collapse fragility requires a lot of computing time and resources, which will increase the difficulty to calculate and reduce the application of the engineering. Yu and Lu (2012) proposed the random IDA based on the first order second moment method that considering the structure uncertainty, they obtained the seismic collapse fragility curves of five-storey three-span reinforced concrete frame structure based on OpenSees. Ibarra and Krawinkler (2011) used the first order second moment method and Monte Carlo method to study the uncertainty of seismic collapse resistance capacity for SDOF systems.

In order to satisfy the balance of accuracy and efficiency, nonlinear dynamic analysis of SDOF systems have become a major tool of the performance-based seismic design (ATC-40 1996, FEMA 273 1997). Shi *et al*. (2012) established ESDOF systems to analyze the seismic collapse fragility based on IDA method, the constitute model can simulate hysteretic pinching and stiffness, strength deterioration. Shi *et al*. (2012) quantitatively evaluated the seismic collapse capacity of SDOF systems to obtain structural seismic collapse resistance spectrum that satisfy the three level seismic design code. Above all, this paper use 100 random pushover curves by Latin Hypercube Sampling to equivalent to the SDOF systems (Chopra 2001, Seifi *et al*. 2008), the modified I-K hysteretic model that represent stiffness and strength deterioration is used to get the response variables of ESDOF systems, then obtain the mean seismic collapse fragility curve.

2 Based Modified I-K Model on ESDOF Systems

2.1 *Modified I-K Model*

On the basis of the Ibarra and Krawinkler model, Lignos (2008) proposes modified I-K hysteretic model to improve some definitions and degradation rules of the original I-K model. The skeleton curve of the modified I-K model controls by the following parameters: elastic stiffness, yield strength, pre-capping stiffness and displacement, post-capping stiffness and displacement, ultimate displacement and residual strength. This paper does not consider the residual strength that is equal to zero. Peak-oriented hysteretic model in OpenSees is used to simulate the stiffness and strength degradation under cyclic loading and unloading. Ibarra *et al.* (2005) proposes the rate of cycle degradation, the degradation rule of the model is mainly controlled by the degradation parameter β, which is given by the following expression:

$$\beta_i^{+/-} = \left(\frac{E_i}{E_t - \sum_{j=1}^{i-1} E_j} \right)^c \cdot D^{+/-} \tag{1}$$

where $D^{+/-}$ represents the rate of positive and negative cycle degradation; E_i is the hysteretic energy dissipated in excursion *i*; $\sum E_j$ is the hysteretic energy dissipated in all previous excursions; $E_t = \gamma F_y \delta_y$ is the hysteretic energy dissipation capacity, where γ is a function of hysteretic energy dissipation capacity and it is calibrated from experimental results; *c* is the exponent defining the rate of deterioration of the evaluated hysteretic parameter.

2.2 *Main Procedures of Build ESDOF Systems*

The original structure subject to the Square Root of Sum of Squares (SRSS) load pattern, which is given by the following expression:

$$F_{ij} = \alpha_j \gamma_j \phi_{ij} w_i \tag{2}$$

where α_j is the earthquake affecting coefficient of the jth mode; γ_j is the vibrating mode participation factor of the jth mode; ϕ_{ij} is the jth modal vector of the ith story; w_i is the gravity load of the ith story.

The five-story three-span reinforced concrete frame structure is obtained the pushover curve by the first mode of lateral load pattern. On the basis of the energy law and the A-D format conversion, using the dynamic balance equation to get the equivalent mass, equivalent displacement, equivalent force and equivalent damping of the SDOF systems. Based on the OpenSees, the zero-length element is used to simulate the performance of components that parallel the modified I-K hysteretic model and damping material (Liu, 2012).

3 The Seismic Collapse Vulnerability Only Considering the Ground Motion Uncertainty

3.1 *Ground Motion Selection*

From the Pacific Earthquake Engineering Research center (PEER) strong motion database, we collected more than 20,000 ground motion records. Different magnitude M_w and distance R bins of 20 ground motion records are selected from the literature Yu and Lu (2013). Four $M_w - R$ bins of ground motion records are used to avoid the tendency of obvious results in this paper Yu and Lu (2013) as shown in Fig. 1. The response spectra of ground motions are shown in Fig. 2.

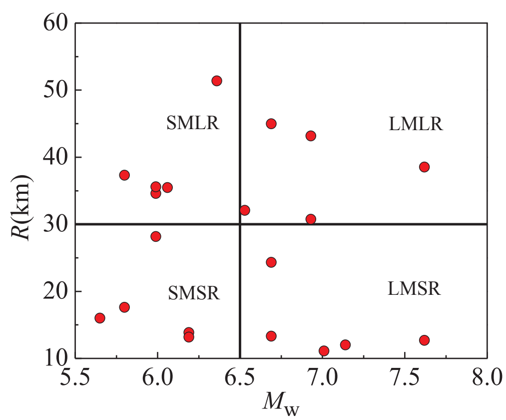

Figure 1. Selected ground motions in Mw-R bins

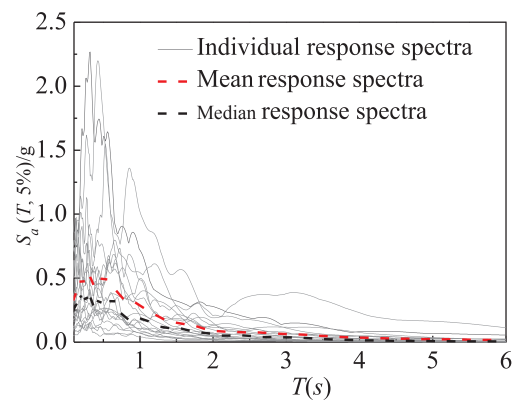

Figure 2. Response spectra of the ground motions

3.2 *The Build of Nonlinear ESDOF Systems*

A five-story three-span reinforced concrete frame structure is selected in the literature Yu and Lu (2013). Based on the OpenSees platform to get the pushover curve considering the P-Δ effect, and Fig. 3 shows the pushover curve of original structure that is linearized by the law of energy. The skeleton curve parameters of ESDOF systems are obtained by the dynamic equation and A-D format conversion, and the skeleton curve of ESDOF systems shown in Fig. 4. It can be seen that the parameter of ESDOF systems is smaller than the original structure. The elastic stiffness, harden stiffness and the ultimate deformation capacity of the ESDOF systems can evaluate from the skeleton curve (Liu, 2012).

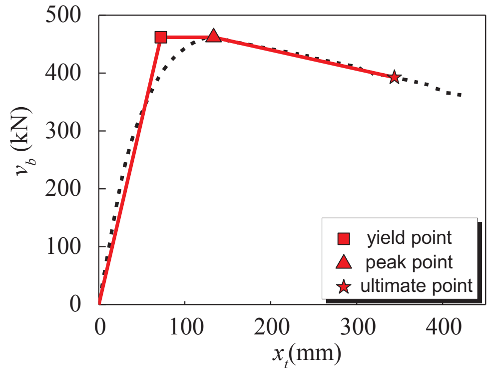

Figure 3. Pushover curve of the original structure with P-Δ

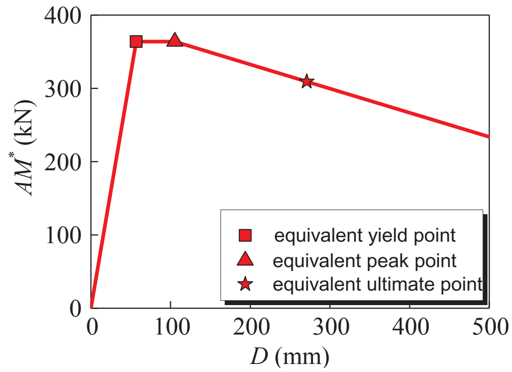

Figure 4. Skeleton curve of ESDOF systems

3.3 *Collapse Vulnerability Analysis of the ESDOF Systems*

The simulation of structural collapse based on collapse vulnerability is more and more widely, which can quantitatively represent seismic collapse resistant capacity (Lu *et al*., 2011). Collapse resistant capacity of structure under earthquake plays an important role in seismic design (Ye *et al*., 2008). The vulnerability analysis assessing structural collapse that reaches a critical threshold state of ground motion intensity measure (Shi *et al*., 2012). Ye *et al.* thinks collapse margin ratio can evaluate seismic collapse resistant capacity, and the ATC-63 considers collapse margin ratio can be used to compare the seismic collapse resistant capacity of structures under different fortification level (Tang *et al*., 2010)

$S_a(T, 5\%)$ is the spectral acceleration of structural period while the damping ratio is 5%. Then according to the principle of Hunt & Fill, IDA is nonlinear dynamic analysis through scaling the normalization ground motion acceleration. The IDA curve can be obtained by approximate and search the intensity measure due to the collapse of the structure (Vamvatsikos and Cornell, 2010), it is shown in Fig. 5. The curve of IDA use S_a as the vertical coordinates and the damage index DM as the horizontal coordinates, and the expression of DM is as follows below:

$$\mathrm{DM}=\frac{|D_{\max}|}{D_y} \tag{3}$$

where $|D_{\max}|$ represents maximum displacement of ESDOF systems through nonlinear dynamic analysis under a given ground motion intensity measure. D_y is the yield displacement of ESDOF systems.

The critical collapse state of IDA curve is the intensity measure corresponding to the minimum value of the 20% of initial slope and ultimate displacement (Zareian and Krawinkler 2007, FEMA 2009). Collapse fragility analysis is the probability of structure collapse under given ground motion intensity measure. According to the intensity measure of red solid point as shown in Fig. 5, ranking the intensity measure to evaluate how many ground motion N_{collapse} due to the collapse of structure under given the intensity measure, the probability of collapse is N_{collapse} divide by 20. It can be seen from Fig. 6 that the intensity measure and the probability of collapse corresponding the collapse point, then based on the lognormal distribution to fit the curve of collapse fragility. This paper compares the seismic collapse fragility analysis of ESDOF systems with the original structure as shown in Fig. 6, and the collapse fragility curve of the original structure see the literature (Yu and Lu, 2012) The results indicate that the original structure is somewhat safer than the ESDOF systems. The collapse margin ratio (CMR) is a probability indicator to assess the seismic collapse resistant capacity considering the ground motion uncertainty, and the CMR of ESDOF systems is 7.54, which is expressed by:

$$\mathrm{CMR}=\frac{S_{\mathrm{a}}(T,5\%)_{50\%}}{S_{\mathrm{a}}(T,5\%)_{\mathrm{MCE}}}=\frac{S_{\mathrm{a}}(T,5\%)_{50\%}}{\alpha(T)_{\mathrm{MCE}}\,g} \tag{4}$$

where $S_{\mathrm{a}}(T,5\%)_{50\%}$ is the spectral acceleration corresponding to the probability of collapse is 50%, $S_{\mathrm{a}}(T,5\%)_{\mathrm{MCE}}$ is the spectral acceleration of the rare earthquake, $\alpha(T)_{\mathrm{MCE}}$ is the earthquake influence coefficient of the rare earthquake.

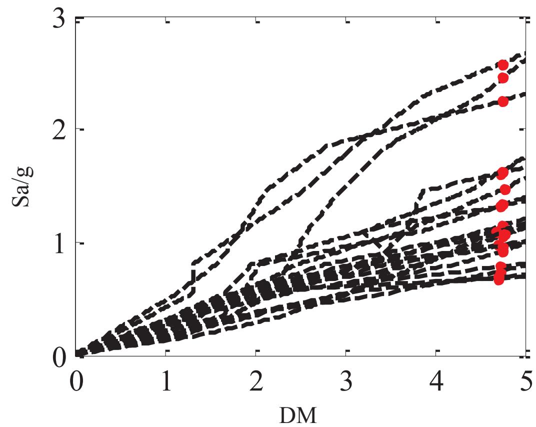

Figure 5. IDA curve for ESDOF systems

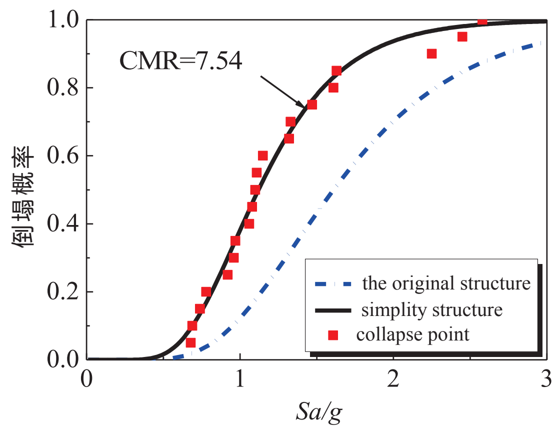

Figure 6. Collapse fragility curve for ESDOF systems

4 The Seismic Collapse Vulnerability Considering the Structural Uncertainty

4.1 *Random Pushover Analysis*

From the respect of uncertainty, it not only consider the ground motion uncertainty but also consider structural uncertainty. The ground motion uncertainty factors are the focal mechanism, site effect and intensity measure et al. A suite of ground motions are selected to consider the ground motion uncertainty. The distribution of structural uncertainty parameters can be seen from the literature (Yu and Lu, 2012). 100 random pushover curves are obtained by considering the structural uncertainty and using Latin Hypercube Sampling, the curves considering P-Δ effect are shown in Fig. 7. It can be seen that the parameters of the structural uncertainty have some effect until the structure enter the yield phase.

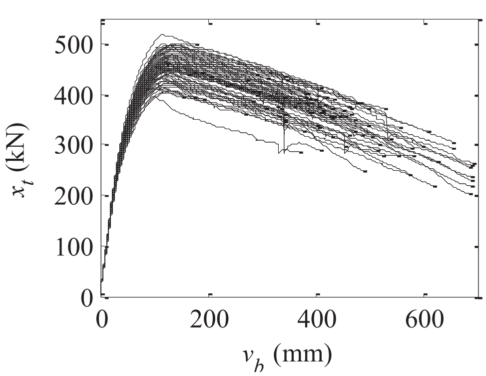

Figure 7. 100 random pushover curves of the original structure with P-Δ

4.2 *Collapse Vulnerability Analysis of the ESDOF Systems with Consideration Structural Uncertainty*

The sampling of random pushover curves considering structural uncertainty are equivalent to 100 ESODF systems by the law of energy, and the skeleton curves of 100 ESDOF systems are shown in Fig. 8. It can be seen that the discreteness of equivalent yield point is smaller than equivalent peak point, and the equivalent ultimate point with consideration the randomness of structures have some strongly effect. The results show that the randomness of the ESDOF systems before entering the yield phase is significantly less than after that.

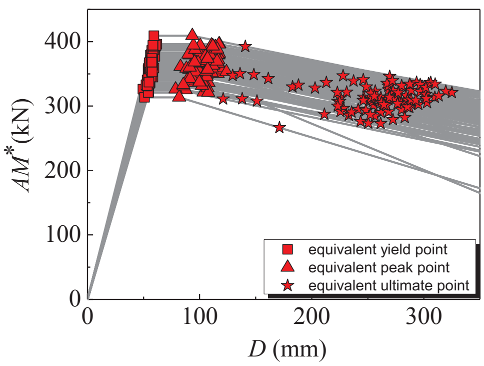

Figure 8. Skeleton curve of 100 random ESDOF systems

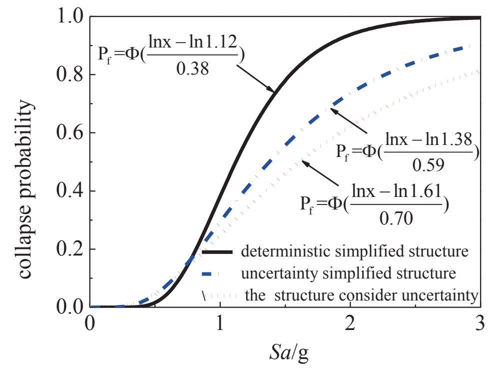

Figure 9. Collapse fragility curves with structural uncertainty

The collapse vulnerability analysis of the original structure considering the structural uncertainty has low computational efficiency. In order to reduce the computational cost, the collapse vulnerability with consideration the uncertainty is obtained by the mean collapse vulnerability of 100 random ESDOF systems, as shown in Fig. 9. The results show that considering the structural uncertainty makes the median of collapse fragility curve of the ESDOF systems from 1.12 up to 1.38, logarithmic standard deviation from 0.38 up to 0.59, therefore the structural uncertainty can't be ignored on collapse vulnerability. On the basic of consider structural uncertainty, the collapse fragility curve of ESDOF systems agree quite well with the original structure, therefore the ESDOF systems can efficiently evaluate the seismic collapse resistant capacity of the original structure.

5 Conclusions

This paper compare the collapse vulnerability of the original structure with the ESDOF systems, it can be seen only considering the ground motion uncertainty the original structure is somewhat safer than the ESDOF systems. On the basic of consider the ground motion uncertainty, considering the structural uncertainty makes the median of collapse fragility curves of the ESDOF systems from 1.12 up to 1.38, logarithmic standard deviation from 0.38 up to 0.59, therefore the structural uncertainty can't be ignored on collapse vulnerability. When considering the ground motion uncertainty and structural uncertainty, the collapse fragility curves of ESDOF systems agree quite well with the original structure, which make the median from 1.38 up to 1.61, logarithmic standard deviation from 0.59 up to 0.70, indicating that the ESDOF systems can accurately assess seismic collapse resistant capacity of the original structure.

Acknowledgments

The financial support received from the National Science Foundation of China (Grant Nos. 51378162, 51408155, 51678209) is gratefully appreciated.

References

ATC-40, Seismic Evaluation and Retrofit of Concrete Buildings, *California, US: Applied Technology Council*, 1996.

Chopra, A.K., *Dynamic of Structures-theory and Applications to Earthquake Engineering*, Upper Saddle River, NJ: Prentice Hall, 2001.

FEMA 273, NEHRP Guidelines for the Seismic Rehabilitation of Buildings, *Washington, D.C., US: Federal Emergency Management Agency*, 1997.

Federal Emergency Management Agency, Quantification of Building Seismic Performance Factors, FEMAP695, Washington DC: Federal Emergency Management Agency, 2009.

Ibarra L., Krawinkler H., Variance of Collapse Capacity of SDOF Systems under Earthquake Excitations, *Earthquake Engineering & Structural Dynamics*, 40(12): 1299-1314, 2011.

Ibarra L. F., Medina R. A., Krawinkler H., Hysteretic Models that Incorporate Strength and Stiffness Deterioration, *Earthquake Engineering and Structural Dynamics*, 34(12): 1489-1511, 2005.

Lignos D., *Sidesway Collapse of Deteriorating Structural Systems under Seismic Excitations*, ProQuest Digital Dissertations & Theses, 2008.

Liu T. T., *Seismic Collapse Resistant Capacity Analysis of RC Frame Structures Based on Nonlinear Equivalent SDOF Systems*, Harbin: Harbin Institute of Technology, 2012. (in Chinese)

Lu X. Z., Shi W., Zhang W. K., et al., Influence of Three-dimensional Ground Motion Input on IDA-based Collapse Fragility Analysis, *Earthquake Resistant Engineering and Retrofitting*, 33(6): 1-7, 2011. (in Chinese)

Shi W., Ye L. P., Lu X. Z., et al., Study on the Collapse-resistant Capacity of RC Frames with Different Seismic Fortification Levels, *Engineering Mechanics*, 28(3): 41-48, 2011. (in Chinese)

Shi W., Lu X. Z., Ye L. P., et al., Single-degree-of-freedom Hysteretic Model for Collapse Analysis of Building Structures. *Engineering Mechanics*, 29(10): 5-12, 2012. (in Chinese)

Shi W., Lu X. Z., Ye L. P., Study of Collapse Resistant Capacity Spectrum, *Journal of Building Structures*, 33(10): 1-7, 2012. (in Chinese)

Seifi M., Noorzaei J., Jaafar M. S., Nonlinear Static Pushover Analysis in Earthquake Engineering: State of Development, *International Conference on Construction and Building Technology*, 2008.

Shi W., Lu X. Z., Ye L. P., Study on Uniform Collapse Risk Evaluation Method for Building Structures under Earthquake, *Journal of Building Structures*, 33(6): 1-7, 2012. (in Chinese)

Tang D. Y., Lu X. Z., Ye L. P., et al., Influence of Axial Compression Ratio to the Seismic Collapse Resistance of RC Frame Structures, *Earthquake Resistant Engineering and Retrofitting*, 32(5): 26-35, 2010. (in Chinese)

Tang B. X., Ye L. P., Lu X. Z., Comparison of Collapse-resistant Capacities of RC Frames with Seismic Fortification Categories B and C, *Journal of Building Structures*, 32(10): 30-38, 2011. (in Chinese)

Vamvatsikos D., Cornell C. A., Incremental Dynamic Analysis, *Earthquake Engineering and Structure Dynamics*, 31(3): 491-514, 2002.

Ye L. P., Qu Z., Lu X. Z., et al., Collapse Prevention of Building Structures: A Lesson from the Wenchuan Earthquake, *Journal of Building Structures*, 29(4): 42-50, 2008. (in Chinese)

Yu X. H., Lu D. G., Seismic Collapse Fragility Analysis Considering Structural Uncertainties, *Journal of Building Structures*, 33(10): 8-14, 2012. (in Chinese)

Yu X. H., Lu D. G., Application Study of Probabilistic Seismic Risk Assessment Based on Analytical Functions of Seismic Fragility, *Journal of Building Structures*, 34(10): 49-56, 2013. (in Chinese)

Zareian F., Krawinkler H., Asessment of Probability of Collapse and Design for Collapse Safety, *Earthquake Engineering and Structural Dynamics*, 36(13): 1901-1914, 2007.