Ductility reduction factor analysis of RC frames considering influences of infilled walls

LI Yanjun1,*, LU Dagang2, WANG Zhenyu2
1School of Civil Engineering and Architecture, University of Jinan, Jinan 250022, China;
2School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
*Corresponding author’s e-mail: mmssott@163.com

Abstract. The value of ductility reduction factor is directly related to seismic design force. And then it has a vital impact on the safety and economy of structures. Influences of infilled walls as nonstructural members on ductility reduction factor is usual neglected in current codes. According to Chinese code for seismic design of buildings six typical RC frames with different height in seismic precautionary intensity of 8-degree and design basic acceleration of ground motion of 0.2g are designed. The rationality and accuracy of finite element models are verified by comparing simulation results with test results. Finite element models of RC frame with and without infilled walls are built on OpenSees software. The influence of infilled walls on ductility reduction factor of RC frames are developed by adaptive pushover analysis (APOA) and incremental dynamic analysis (IDA). Results show that influences of infilled walls on ductility reduction factor of RC frames is significant, but with increase of structural height influences gradually decline. Based on analysis results of this paper, the value of ductility reduction factor of RC frame without infilled walls is 2.5 and that of RC frame with infilled walls is 3.6. Analysis methods affect the value of ductility reduction factor significantly. Values of ductility reduction factor based on APOA is less than those based on IDA.

1. Introduction
Ductility reduction factor, also known as strength reduction factor, is an important part of seismic performance factors. At present, most of codes for seismic design of buildings are based on strength in the world. The minimum yield strength of a structure with predefined ductility coefficient is obtained by ductility reduction factor. The design seismic force can be obtained by modifying the minimum yield strength using overstrength factor. So, ductility reduction factor directly affects the magnitude of design seismic forces and develops relationships between bearing capacity and deformation capacity.

The structural ductility reduction factor ($R_\mu$) is the ratio of the maximum base shear of linearly elastic structures under design earthquake ground motions to the equivalent yield strength of real structures. Its expression is as follow:

$$R_\mu = \frac{V_e}{V_y}$$

Where,
- $V_e$ is the maximum base shear of linearly elastic structures under design earthquake ground motions.
- $V_y$ is the equivalent yield strength of real structures.

Existing researches of $R_\mu$ can be divided into two categories. One is for single degree of freedom system and the other one is for multi degree of freedom system. Many researchers studied ductility reduction factor of various multi degree of freedom systems such as frame structure and shear wall.
structure using laboratory tests, field tests and finite element simulation [1-11], but comprehensive studies of influences of infilled walls on ductility reduction factor of RC frame are rarely reported. By comparing results of bare RC frame with those of RC frame with infilled walls the intent of this paper is to develop values and rules of ductility reduction factor of RC frame considering influences of infilled walls by APOA and IDA.

2. Analysis of ductility reduction factor

2.1 Analysis of ductility reduction factor based on APOA

The traditional pushover analysis develops relationship between structural load and deformation under uniform load mode, inverted triangle load mode, quadratic parabola load mode and so on. Two problems arise. Resulted load-deformation curves depends on the choice of initial load modes. And analysis results can not reflect changes of structural dynamic characteristics caused by nonlinearity. APOA improves the traditional pushover analysis. It can consider influences of higher-order modes and structural period changes caused by stiffness degradation on load-deformation curves. So APOA is developed with OpenSees platform and used to develop relationship between structural load and deformation in this paper. Analytical processes of ductility reduction factor are as follows:

1. Develop relationship between structural load and deformation in form of base shear ($V_b$) and top displacement ($\Delta$) by APOA.
2. The equal energy theory is adopted to fit original $V_b$-$\Delta$ curve into bilinear curve. According to bilinear curve calculate initial stiffness of structure ($k_0$), equivalent yield strength of structure ($V_y$) and yield displacement of structure ($\Delta_y$).
3. Carry out APOA of elastic system with initial stiffness of structure ($k_0$). Solve top displacement ($\Delta_e$) corresponding to the maximum inter-story drift ratio of 2%
4. According to the formula $R_\mu=\frac{V_e}{V_y}=\frac{k_0\Delta_e}{V_y}$ calculate $R_\mu$.

2.2 Analysis of ductility reduction factor based on IDA

IDA can be seen as dynamic pushover analysis. And it can represent structural practical dynamic performance under different intensity ground motions. The analysis of ductility reduction factor combines dynamic time history analysis and IDA. Analytical processes of ductility reduction factor are as follows:

1. Develop dynamic capacity curve of structure in form of base shear ($V_b$) and top displacement ($\Delta$) by IDA, and solve base shear ($V_b$), top displacement ($\Delta_{\text{max}}$) and spectral acceleration ($S_{a0.02}$) with the maximum inter-story drift ratio of 2% by iterative analysis.
2. Solve base shear ($V_b$) and top displacement ($\Delta_e$) using linear time history analysis of structures subjected to ground motion records with spectral acceleration of $S_{a0.02}$.
3. According to the formula $R_\mu=\frac{V_e}{V_y}$ calculate $R_\mu$.

3. Ductility reduction factor analysis of RC frames with and without infilled walls

3.1 Design and analysis of structural models

Height of buildings influences seismic performance of structures obviously. According to Chinese current seismic code, representative RC frames with and without infilled walls with different height are designed. And their seismic precautionary intensity is 8-degree. Their design basic acceleration of ground motion is 0.2g. The number of stories of structures is 3, 5 and 10 respectively with same plane layout, and infilled walls is full layout. The 5-story RC frame with infilled walls is shown in Figure 1. Detailed design data of structures are in References 12.

Finite element models are built with OpenSees software. And the rationality and accuracy of modeling methods are verified by comparing simulation results with test results [12]. The finite element model of the 5-story RC frame with infilled walls is shown in Figure 2.
3.2 Analysis of ductility reduction factor

Ductility reduction factors of RC frame with and without infilled walls based on APOA are shown in Figure 3. It can be concluded that with increase of height of RC frames ductility reduction factors of both RC bare frame and RC frame with infilled walls decrease. Ductility reduction factors of RC bare frames decrease by 44%, and ductility reduction factors of RC frames with infilled walls decrease by 66%. For structural models with the same height ductility reduction factor of RC frame with infilled walls is more than that of bare RC frame. For 3-story structure model, ductility reduction factors increase by 107.6% because of infilled walls. But for 10-story structure model, ductility reduction factors increase by 25.3% because of infilled walls. That means with increase of height of RC frames influences of infilled walls on ductility reduction factors gradually decline.

Ductility reduction factors of RC frame with and without infilled walls based on IDA are shown in Figure 4. It can be concluded that with increase of height of RC frames ductility reduction factors of both RC bare frame and RC frame with infilled walls decrease. For structural models with the same height ductility reduction factor of RC frame with infilled walls is more than that of RC bare frame. But different from results of APOA with increase of height of RC frames influences of infilled walls on ductility reduction factors little change.

It can be concluded from Figure 3 and Figure 4 that results of APOA are consistent with those of IDA, and with the increase of height of structures, ductility reduction factors gradually decline. According to the minimum principle the value of ductility reduction factor of RC frame without infilled walls is 2.5 and that of RC frame with infilled walls is 3.6.

4 Conclusion

Ductility reduction factors of six RC frames with and without infilled walls using APOA and IDA are studied. And The following is a summary of conclusions through contrastive analysis:

(1) Infilled walls increase ductility reduction factors of RC frames significantly. the value of ductility reduction factor of RC frame without infilled walls is 2.5 and that of RC frame with infilled walls is 3.6.
With increase of structural height influences of infilled walls on ductility reduction factors gradually decline.

(2) Analysis methods have important influences on ductility reduction factor analysis. Compared with IDA, ductility reduction factor analysis using APOA is more conservative. Compared with RC bare frames, because of roles of infilled walls ductility reduction factor analysis of RC frames with infilled walls is more sensitive to analytical methods.

Acknowledgments
The work described in this paper was fully supported by grants from University of Jinan Scientific Research Foundation (Project No. XBS1450 and XKY1909) and the National Natural Science Foundation of China (Project No. 51608229).

References
[1] Zerbin M., Aprile A., Spacone E. (2020) New formulation of ductility reduction factor of RC frame-wall dual systems for design under earthquake loadings. Soil Dynamics and Earthquake Engineering, 138:279-382.

[2] Javad V.A., Mojtaba A., Behnoud G. (2016) Ductility reduction factor for zipper-braced frames. European Journal of Environmental and Civil Engineering, 22:1-23.

[3] Moghaddam H., Mohammadi R.K. (2001) Ductility reduction factor of MDOF shear-building structures. Journal of Earthquake Engineering, 5:425-440.

[4] Zerbin M., Aprile A., Beyer K. (2019) Ductility reduction factor formulations for seismic design of RC wall and frame structures. Engineering Structures, 178:102-115.

[5] Lam N., Wilson J., Hutchinson G. (1998) The ductility reduction factor in the seismic design of buildings. Earthquake Engineering & Structural Dynamics, 27:749-769.

[6] Cai J., Zhou J., Fang X. (2006) Seismic Ductility Reduction Factors for Multi-Degree-of-Freedom Systems. Advances in Structural Engineering, 9:591-601.

[7] Cai J., Bu G., Zhou J. (2016) Modification of Ductility Reduction Factor for Strength Eccentric Structures Subjected to Pulse-Like Ground Motions. Journal of Earthquake Engineering, 20:12-38.

[8] Halabian A. M., Kabiri S., Amir M. (2011) Effect of foundation flexibility on ductility reduction factors for R/C stack-like structures. Earthquake Engineering and Engineering Vibration, 10:277-292.

[9] Asghari A., Gandomi A. H. (2016) Ductility reduction factor and collapse mechanism evaluation of a new steel knee braced frame. Structure & Infrastructure Engineering, 12:239-255.

[10] Reyes-Salazar A., Bojórquez, E., Velazquez-Dimas J. I. (2015) Ductility reduction factors for steel buildings considering different structural representations. Bulletin of Earthquake Engineering, 13:1749-1771.

[11] Ganjavi B., Hao H. (2012) Effect of structural characteristics distribution on strength demand and ductility reduction factor of MDOF systems considering soil-structure interaction. Earthquake Engineering and Engineering Vibration, 11:205-220.

[12] Li Y.J., Lu D.G., Wang Z.Y. (2017) Overstrength factor of RC frame with infilled walls based on adaptive POA and IDA. Engineering Mechanics, 34: 197-201.