THREE EXAMPLES OF THE EARTHQUAKE INDUCED COLLAPSE SIMULATION FOR HIGH-RISE BUILDINGS

Lu, Xinzheng
Lu, Xiao
Ye, Lieping

(Citation)
神戸大学都市安全研究センター研究報告,16:139-146

(Issue Date)
2012-03

(Resource Type)
departmental bulletin paper

(Version)
Version of Record

(JaLCDOI)
https://doi.org/10.24546/81011383

(URL)
https://hdl.handle.net/20.500.14094/81011383

神戸大学都市安全研究センター
研究報告，第16号，平成24年３月

THREE EXAMPLES OF THE EARTHQUAKE INDUCED COLLAPSE SIMULATION FOR HIGH-RISE BUILDINGS

Xinzheng LU [1)]
Xiao LU [2)]
Lieping YE [3)]

Abstract: Structural collapse resistance capacity is an important part of seismic design. And numerical simulation has been proved as one of the most powerful tools for collapse simulation. In this paper, potential collapse processes of three actual high-rise buildings subjected to strong earthquakes were simulated by finite element (FE) method. These analysis results indicate that the proposed FE method is capable of simulating the collapse process of actual high-rise buildings, understanding the mechanism of the collapse and identifying the corresponding potentially weak components that may induce collapse. And these study outcomes will be beneficial to aid further development of optimal design philosophy.

Key words: Finite element method, collapse simulation, high-rise building

1. INTRODUCTION

Collapse prevention has always been a key topic in earthquake engineering research and this research issue has become increasingly significant in recent years due to frequent occurrence of strong earthquakes all over the world.

In order to effectively prevent earthquake induced structural collapse, the collapse process and the failure modes of structures should be properly predicted. Large-scale shaking table tests have been used in an attempt to understand the fundamental mechanism and behavior of earthquake induced structural collapse (Huang 2006; Wu *et al*, 2009; Yamada *et al*, 2008; van de Lindt *et al*, 2010). However such tests are very expensive and even the largest shaking table in the world cannot simulate the collapse of full-scale high-rise buildings. As an alternative, numerical simulation has been widely accepted as an important technique to study earthquake induced structural collapse, by which both structural collapse modes and entire collapse processes can be clearly identified and replicated.

Many numerical methods such as Discrete Element Models (DEM) (Azevedo *et al*, 2006; Lemos *et al*, 2007) and Applied Element Method (AEM) (Sasani *et al*, 2008; Asprone *et al*, 2010) have been proposed to simulate collapse. In this paper, the Finite Element Method (FEM) is proposed to simulate the structural collapse. And three actual high-rise building are used to illustrate the capacity of the proposed FEM model for the structural collapse simulation subjected to strong earthquake. The three actual building include an 18-story frame-core-tube high-rise building, a 20-story frame-core-tube high-rise building and Shanghai Tower with a total height of 632m.

In the FE models, fiber-beam element and multi-layer shell element are adopted to simulate the frame beams/columns and the shear walls respectively. And the efficiency and accuracy is verified by many literatures (Li *et al*, 2011; Lin *et al*, 2009; Miao *et al*, 2009). During the structural collapse, the whole structure changes from a continuum system into discrete parts through structural fracturing and element crushing. And the elemental deactivation technology is adopted to simulate the components failure when a specified elemental-failure criterion is reached. The details of failure criterion are described in Lu *et al*, (2011).

In general, the collapse subjected to strong earthquakes that have been considered in the design codes can be prevented via following the latest seismic design regulations. In practice, on the other hand, earthquakes are of complicated nature. As such, structures may experience extreme earthquakes that are much larger than those considered in the design regulations. Furthermore, for some research purposes such as collapse fragility analysis based on increment dynamic analysis (Vamvatsikos *et al*, 2002, 2010; Mander *et al*, 2007), very large earthquake ground motions are required to be used as input to obtain a full collapse fragility curve from 0% to 100% of collapse. In view of the above, this study takes into account extreme ground motions which are 5 to 10 times larger than those specified in the design code (GB-50011, 2010). Despite this assumption, the collapse simulation undertaken in this study aims to offer fundamental understanding of the ultimate structural behavior which will be beneficial for both scientific research and engineering application. And the following sections will discuss the structural collapse simulation with three actual high-rise buildings in details.

2. COLLAPSE SIMULATION OF AN 18-STORY FRAME-CORE-TUBE BUILDING

This actual high-rise building has 18 stories above the ground and a 4-story basement with a total height of 74.8m and its standard plane view are shown in Figures 1. The core-tube is made up of four sub-tubes connected by coupling beams. The thickness of the shear wall changes from 500 mm (at the bottom story) to 350 mm (at the top story). More details of this structure are described in Lu *et al*. (2009). The three dimensional FE model is presented in Figure 2a. The columns and beams are simulated by the fiber-beam element model, and the RC shear wall and coupling beams are simulated using the multi-layer shell model.

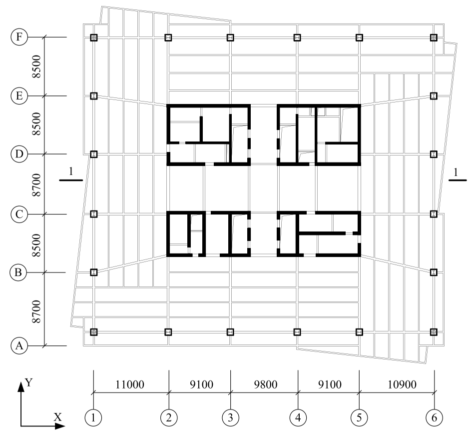


Figure 1 Standard plane layout of the 18-storybuilding (Unit: mm)

The fundamental period of this structure T_1=1.55s and El-Centro EW Ground Motion (PEER NGA Database, 2006) which is scaled to PGA=1500 cm/s^2 is used as an earthquake input to the structure along the X-axis. Figure 2 clearly displays the collapse process of this high-rise building. The ground story is identified to be the weakest part of the building due to its much larger height than the other stories. This leads to yielding of the columns (buckling) and shear wall (crushing) in this story (Figures 2b, c). With an increase in time, collision occurs between the basement and the upper stories (Figure 2d) which in turn results in a total collapse of the ground floor and subsequently the whole building.

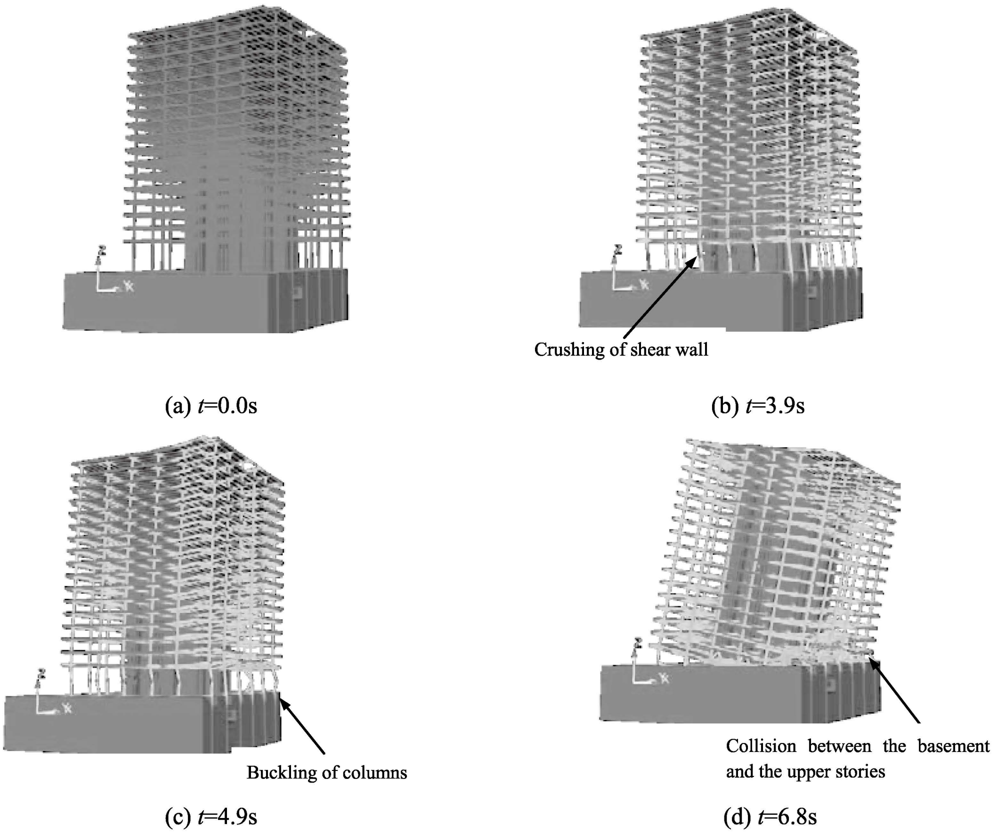


Figure 2 Collapse process of the 18-story frame-core-tube building (Ground motion: El-Centro EW, 1940, PGA=1500 cm/s^2)

3. COLLAPSE SIMULATION OF 20-STORY FRAME-CORE TUBE BUILDING

This structure is a 79.47 m tall, 20-story office with a 4-story skirt building. The finite element model is shown in Figure 3. The lateral-force-resisting system of the building consists of reinforced concrete external frame and core-tube. The cross-sectional dimensions of the columns from bottom to top of the building are 800 mm×800 mm, 700 mm×700 mm, 600mm×600mm. The beam sections are 350mm×650mm in the X-direction and 350mm×600mm in the Y-direction. The thickness of the core-tube is 350mm. And the more details of the structural geometries are described in Lu *et al*, (2009).

Illustrated in Figure 3 is the collapse process of this building subjected to El-Centro EW Ground Motion (PEER NGA Database, 2006) which is scaled to PGA=4000 cm/s^2. The shear wall at the 16th story has its concrete strength changed from C40 to C30 and the column section changes from 700mm×700mm to 600mm×600mm. This results in a sudden change in stiffness which in turn yields stress concentration. In consequence, at t=4.5s, the shear wall at this story is crushed as demonstrated in Figure 3b. With propagation of the failed structural elements including buckled columns (Figure 3c), the stories above the 16th story comes down and impacts on the lower stories (Figure 3d), thereby leading to a progressive collapse of the whole building.

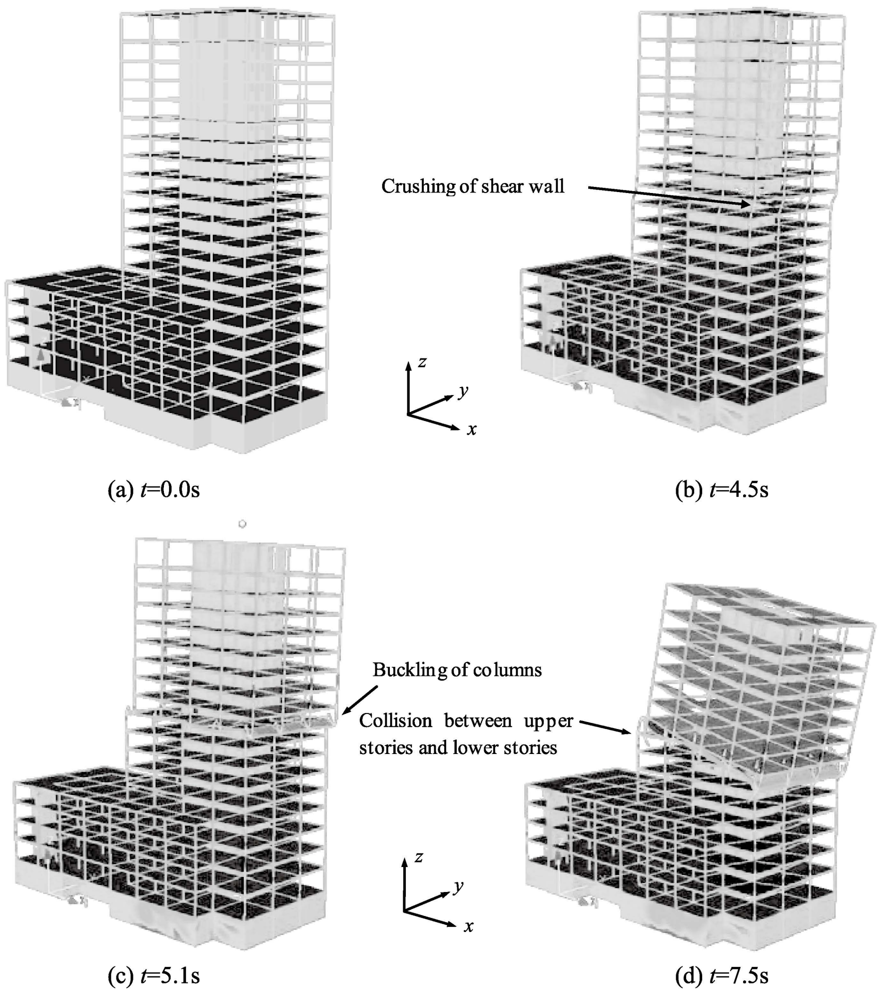


Figure 3 Collapse process of the 20-story frame-core tube building (Ground motion: El-Centro, EW, 1940, PGA=4000 cm/s^2)

4. COLLAPSE SIMULATION OF SHANGHAI TOWER

Shanghai Tower, located in Lujiazui, Shanghai, is a multi-functional office building (as shown in Figure 4). The total height of the main tower is 632 m, and the structural height is 580 m. This building contains 124 stories. A hybrid lateral-force-resisting system referred to as "mega-column/core-tube/outrigger" was adopted for the main tower.

The main part of the core-tube is a 30 m by 30 m square RC tube. (Mao *et al*, 2010; Ding *et al*, 2010).The mega-column system consists of 12 shaped-steel reinforced concrete columns with a maximum cross-sectional dimension of 5,300 mm×3,700 mm (Ding *et al*, 2010). 8 mega-columns extend from the bottom to the top of the building. The remaining 4 columns are located at each corner and only extend from the ground floor to Zone 5. The outrigger system, located at the mechanical stories, consists of circle trusses and outriggers with a total height of 9.9 m. All of the components of the outriggers are composed of H-shaped steel beams. The more details of structural properties are available in Lu *et al*, (2011a)

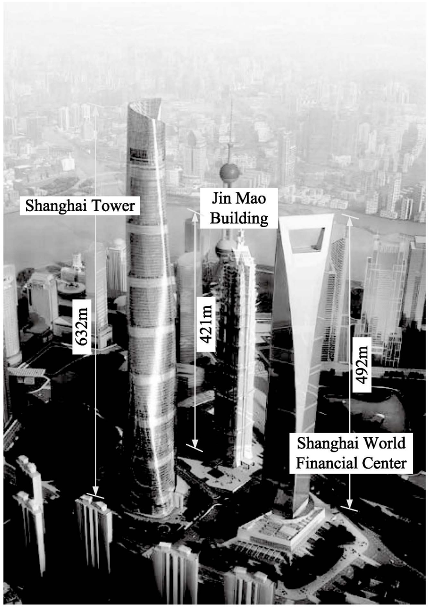


Figure 4 The location of Shanghai Tower
(From: www.eastday.com)

The external frames and outriggers are modeled with traditional fiber beam element and the shear walls of core-tube are simulated by multi-layer shell elements (Lu *et al*, 2011a). Meanwhile, few experimental data regarding the mega-columns can be found in the literature, so a multi-layer shell element-based simplified model was proposed for the mega-columns and the parameters of the simplified model were determined based on the detailed FE model of mega-columns with solid elements (Lu *et al*, 2011b). The elemental deactivation technology is adopted to simulate the components failure of structure during the collapse process. The more details of these numerical models and failure criteria can be seen in Lu *et al*, (2011a) and the whole FE model of Shanghai Tower is shown in Figure 5.

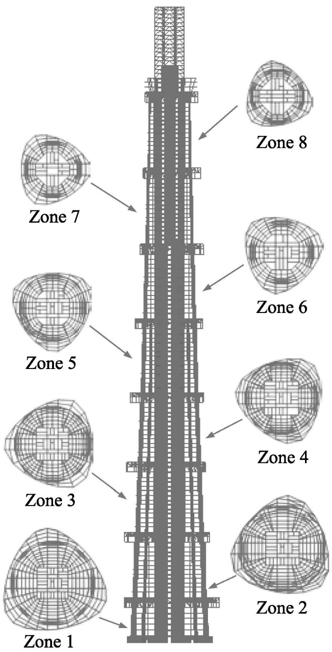


Figure 5 The whole FE model of Shanghai Tower

The fundamental period of Shanghai Tower is 9.83 s, which is far beyond the range of 6 s specified in the design response spectrum in the Chinese Code for the Seismic Design of Buildings (GB50011, 2010). Like the analysis above, the El-Centro EW ground motion was chosen as a typical example of ground motion input. The peak ground acceleration (PGA) is scaled to 1960 cm/s^2, and then used as input for the FE model in the X direction. The final collapse mode is shown in Figure 6.

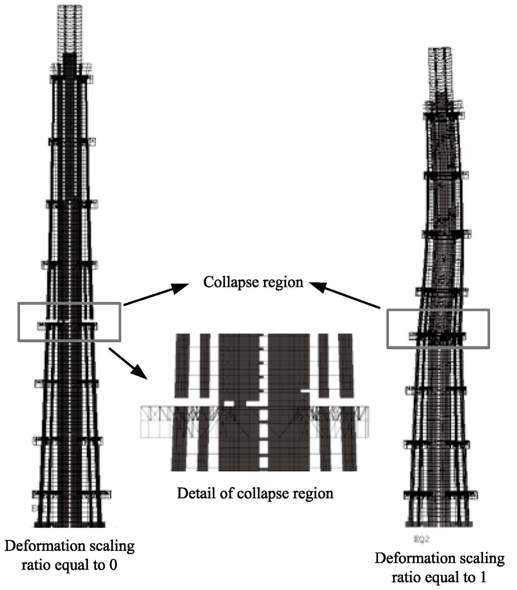
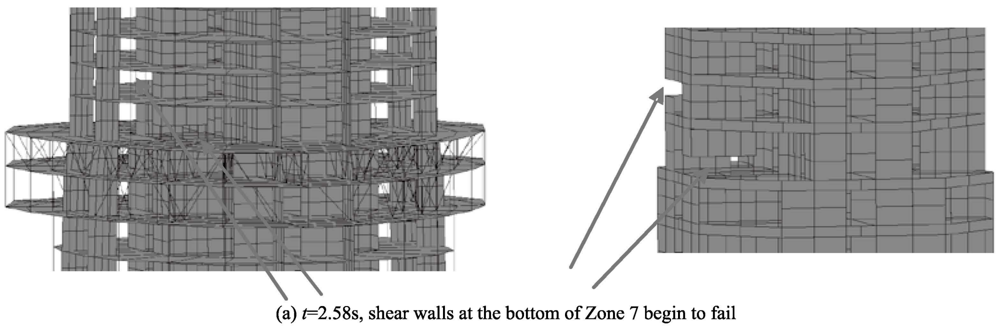
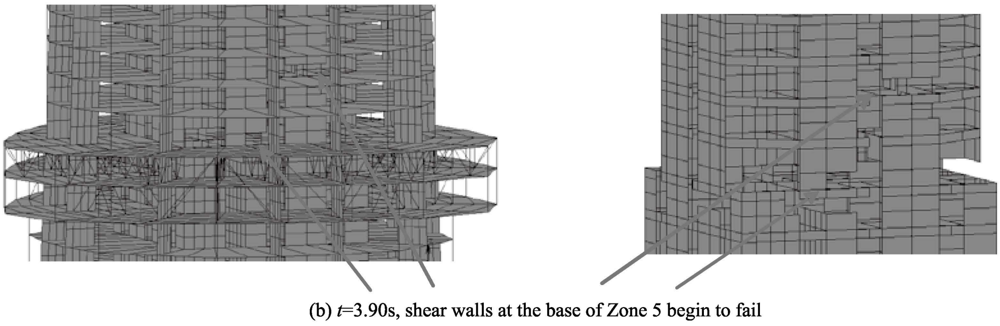


Figure 6　Collapse mode subjected to El-Centro EW (PGA=1960 cm/s^2)

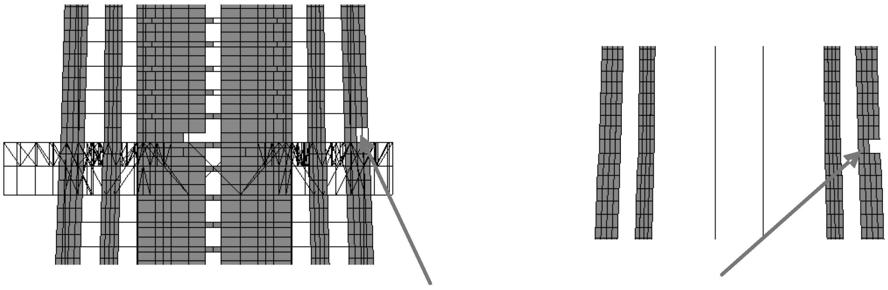
The details of the collapse process are clearly shown in Figure 7. First, when t=2.58 s, some coupling beams in the core-tube begin to fail, and the flange wall of the core-tube at the bottom of Zone 7 is crushed. The reason for this crushing is that the layout of the openings in the core-tube changes between Zones 6 and 7, resulting in a sudden change of stiffness and stress concentration. After that, when t=3.90 s, the shear wall at the bottom of Zone 5 begins to fail because the cross section of the core-tube changes from Zone 4 to Zone 5 as shown in Figure 7b. When t=5.88 s, more than 50% of the shear walls at the bottom of Zone 5 fail, and the internal forces are redistributed to other components. The vertical and horizontal loads in the mega-columns increase gradually and reach their load capacities. The mega-columns then begin to fail. Finally, when t=6.18 s, the core-tube and mega-columns in Zone 5 are completely destroyed, and the collapse begins to propagate to the entire structure.



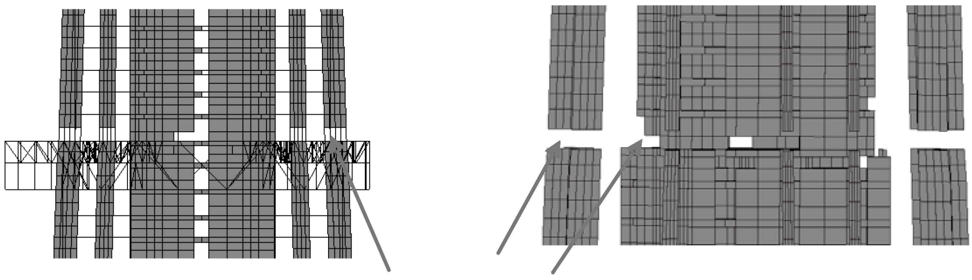
(a) t=2.58s, shear walls at the bottom of Zone 7 begin to fail



(b) t=3.90s, shear walls at the base of Zone 5 begin to fail



(c) t=5.88s, mega-columns at Zone 5 begin to fail



(d) t=6.18s, more than 50% shear walls and all mega- columns destroyed at Zone 5
the whole structure begins to collapse

Figure 7 Collapse process of Shanghai Tower (Ground motion: El-Centro, EW, 1940, PGA=1960 cm/s^2)

Obviously, when subjected to El-Centro ground motion in the X direction, Shanghai Tower is mainly damaged in Zones 5, 6 and 7. Finally, collapse occurs in Zone 5, and the entire structure breaks into two parts. It can be clearly seen that Zone 5 is a potentially weak part, where structural collapse can be initiated. Therefore, more attention should be paid to this area during the design.

5. CONCLUSIONS

The use of a Finite Element Method to simulate structural collapse subjected to strong earthquakes has been illustrated using three actual high-rise buildings. For a given strong ground motion, the potential collapse modes and corresponding weak parts can be predicted which gives a better understanding of the collapse mechanism of building structures and promotes collapse analysis in real engineering application. Although these simulations presented above are very encouraging, further research is needed to verify the specified elemental failure criteria and the accuracy of this method.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (Grant No. 90815025, 51178249), National Key Technologies R&D Program (Grant No. 2009BAJ28B01) and “Program for New Century Excellent Talents in University”(Grant No. NCET-10-0528).

REFERENCES

Asprone, D., Nanni, A., Salem, H., *et al.* Applied element method analysis of porous GFRP barrier subjected to blast. Advances in Structural Engineering, Vol.13, No.1, pp.152-170, 2010.

Azevedo, N.M., Lemos, J.V.. Hybrid discrete element/finite element method for fracture analysis. Computer Methods in Applied Mechanics and Engineering, Vol.195, No.33-36, pp.4579-4593, 2006.

Ding, J.M., Wu, H.L., Zhao, X.. Seismic performance analysis and evaluation of Shanghai Tower under Maximum Considered Earthquake (in Chinese). Journal of Civil, Architectural & Environmental Engineering, Vol.32, No.Sup.2, pp.231-233, 2010.

Huang, Q.H.. Study on spatial collapse response of reinforced concrete frame structures. P.h.D. Thesis, University of Tongji, Shanghai, China, 2006.

Lemos, J.V.. Discrete element modeling of masonry structures. International Journal of Architectural Heritage, Vol.1, No.2, pp.190 – 213, 2007.

Li, Y., Lu, X.Z., Guan, H., *et al*. An improved tie force method for progressive collapse resistance design of reinforced concrete frame structures. Engineering Structures, Vol33, No. 10, pp.2931-2942, 2011.

Lin, X.C., Lu, X.Z., Miao, Z.W., *et al*. Finite element analysis and engineering application of rc core-tube structures based on the multi-layer shell elements (in Chinese). China Civil Engineering Journal. Vol.42, No.3, pp.51-56, 2009.

Lu, X., Lu, X.Z., Zhang, W.K., *et al*. Collapse simulation of a super high-rise building subjected to extremely strong earthquakes. Science China Technological Sciences, Vol.54, No.10, pp.2549-2560, 2011a.

Lu, X.Z., Ye, L.P., Miao, Z.W., (2009), *Elasto-plastic analysis of building against earthquake*, Beijing, China, China Architecture and Building Press.

Lu, X.Z., Zhang, W.K., Lu, X., *et al*. Elasto-Plastic mechanical behavior of detailed finite element model and simplified model of mega-columns (In Chinese). Journal of Shengyang Jianzhu University (Natural Science), Vol.27, No.3, pp.409-417, 2011b.

Mander, J.B., Dhakal, R.P., Mashiko, N., Solberg, K.M.. Incremental dynamic analysis applied to seismic financial risk assessment of bridges. Engineering Structures, Vol.29, No.10, pp.2662-2672, 2007.

Mao, Y.J., Lu, X.L., Lu, W.S., *et al*. Study on seismic behavior of Shanghai Tower with shaking table test (in Chinese). Journal of Civil Architectural & Environmental Engineering, Vol.32, No.Sup.2, pp.534- 536 +549, 2010.

Men, J., Lu, X.Z., Song, E.X., *et al*. Application of layered model in analysis of shear wall structures (in Chinese). Protective Engineering, Vol.28, No.3, pp.9-13, 2006.

Miao, Z.W., Wu, Y.H., Ma, Q.L., *et al*. Seismic performance evaluation using nonlinear time history analysis with three-dimensional structural model for a hybrid frame-core tube structure (in Chinese). Journal of Building Structures. Vol.30, No.4, pp.119-129, 2009.

Ministry of Construction of the People's Republic of China. Code for seismic design of buildings, Code No. GB-50011, Beijing: China Architecture and Buildings Press, 2010.

Pacific Earthquake Engineering Research Center, PEER NGA Database, University of California, Berkeley, California, 2006.

Sasani, M.. Response of a reinforced concrete infilled-frame structure to removal of two adjacent columns. Engineering Structures, Vol.30, No.9, pp.2478-2491, 2008.

Vamvatsikos, D., Cornell, C.A.. Incremental dynamic analysis. Earthquake Engineering and Structural Dynamics, Vol.31, No.3, pp.491-514, 2002.

Vamvatsikos D, Fragiadakis M.. Incremental dynamic analysis for estimating seismic performance sensitivity and uncertainty. Earthquake Engineering and Structural Dynamics, Vol.39, No.2, pp.141-163, 2010.

van de Lindt, J.W., Pei, S,L., Pryor, S.E., *et al*. Experimental seismic response of a full-scale six-story light-frame wood building. Journal of Structural Engineering-ASCE, Vol.136, No.10, pp.1262-1272, 2010.

Wu, C.L., Kuo, W.W., Yang, Y.S., *et al*. Collapse of a nonductile concrete frame: Shaking table tests. Earthquake Engineering and Structural Dynamics, Vol.38, No.2, pp.205-224, 2009.

Yamada, S., Suita, K., Tada, M., *et al*. Collapse experiment on 4-story steel moment frame: part 1. Proceedings of 14th World Conference on Earthquake Engineering, Beijing, China, 2008, October,12-17.

Authors: 1) Xinzheng LU, Associate Professor, Department of Civil Engineering, Tsinghua University, Beijing, China; Visiting Associate Professor, Research Center for Urban Safety and Security, Kobe University, Japan; 2) Xiao LU, Ph.D Student, Department of Civil Engineering, Tsinghua University, Beijing, China; 3) Lieping YE, Professor, Department of Civil Engineering, Tsinghua University, Beijing, China.