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Research on Seismic Performance of Hectometer Reinforced Block Masonry High-rise Buildings

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Abstract

Combined with the construction of the first hectometer reinforced block masonry building in the world, this paper intends to investigate the seismic performance of reinforced block masonry high-rise buildings through a shaking table test and numerical simulation. The 10-story 1/4-scaled model of fully grouted reinforced block masonry shear wall structure was designed and tested under different ground motion intensities on a shaking table. The structural responses that have been extracted from the test include the model's dynamic property, acceleration response and displacement response. The dynamic characteristics and dynamic response of the model were analyzed for elastic, cracking and damage phases. It is demonstrated that the fully grouted reinforced masonry shear wall structures have good seismic performance and deformation capacity, and they can meet the requirement of seismic fortification intensity 6 and 7. Furhermore, the elastic response of the structure under frequent seismic actions and the elastoplastic response under infrequent seismic actions were calculated by the method of time-history. The results meet the requirements of 6 degree and 7 degree seismic fortification intensity, and prove constructing hectometer high-rise buildings by a reinforced concrete block masonry is feasible.

Keywords: High-rise building, Numerical simulation, Reinforced concrete block masonry structure, Seismic performance, Shaking table test.

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Introduction

With the rapid development of economy, China's construction market has thrived dramatically. The reinforced concrete block masonry shear wall (RBMW) structure, which has not only the characteristics of RC structures' high strength, good ductility and excellent dissipation, but also holds the merits of short construction period, low steel usage and project cost [1], meets the requirements of building an economical society advocated by Chinese government and has fairly good application prospects.

Nowadays, many progresses have been achieved in the research of the RBMW structures in material, structure component [2-6], low-rise and mid-rise buildings [7,8]. There is few experimental research and numerical analysis on the seismic behavior of high-rise and super high-rise RBMW structures [9,10]. Correspondingly, revealing the dynamic properties and work behavior characteristics of RBMW high-rise structure could have great theoretical significance and the engineering application value to develop this type of structure system and improve its applicable height. Based on the above considerations, a hectometer RBMW high-rise building was constructed in Harbin, the Heilongjiang Province, China, and related researches on seismic behavior of this demonstration project were carried out. This paper presents the results of an experimental study through the shaking table test and the finite element simulation research of the seismic performance of RBMW high-rise buildings, aimed at providing the experimental and theoretical basis for the construction of the hectometer RBMW structure, and also technical support to the development of the RBMW structural system in high-rise and super high-rise buildings.

Design of the Hectometer RBMW Structure

This reinforced block masonry high-rise shear wall building was constructed in Harbin, China, which has 28 stories, a building height of 98.2m, and a total construction area of 16187 square meters. The typical floor plan of the building is shown in Figure 1. It is the first RBMW structure with such an applicable height in China, and there is no related specification in codes, so it is of great importance to analyze its structural characteristic and performance, especially the seismic performance. The seismic fortification intensity is 6, the site class is III, and the area belongs to the first earthquake group.

Figure 1. *Plan View of the Structure's Typical Floor (Unit: mm)*

The geometric dimensions of the concrete hollow block widely used in China is 390mm×190mm×190mm, which means the thickness of the shear wall is 190mm. A concrete hollow block 290mm thick is designed and used for the construction of this hectometer high-rise building. The dimensions of the new block is 390mm×290mm×190mm, and the 290mm block has a 53% hole ratio, which is different from the 45% hole ratio of the ordinary 190mm block. The shear walls of the building are all constructed with MU20 block and Mb20 motar, and the shear walls of the 1-12 stories use 290mm thick block, and the 13-28 stories use 190mm thick block. The strength grade of the grouted concrete for the masonry shear walls is C40, and the concrete of the ring beam and floor slab is C30.

Shaking Table Experimental Study of RBMW High-rise Building

Introduction of the Shaking Table Test

Test Specimen

Considering the theory of similarity, purposes of the test and laboratory conditions, a 1/4-scaled 10 stories, a two-bay RBMW structure was designed and established, which has a similar structural characteristics with the hectometer structure, and can be used to investigate the failure mode and dynamic response of RBMW high-rise buildings. The floor height of the model is 0.7m, and the structural plan dimensions are 3.2m×2.0m. The views of the model structure were shown in Figures 2 and 3.

Figure 2. *Plan View of the Test Model Structure (Unit: mm)*

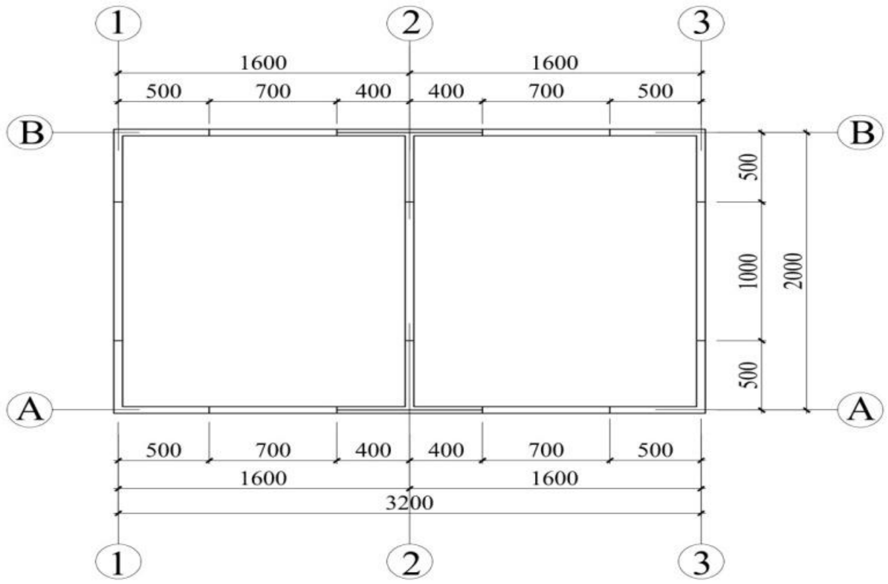


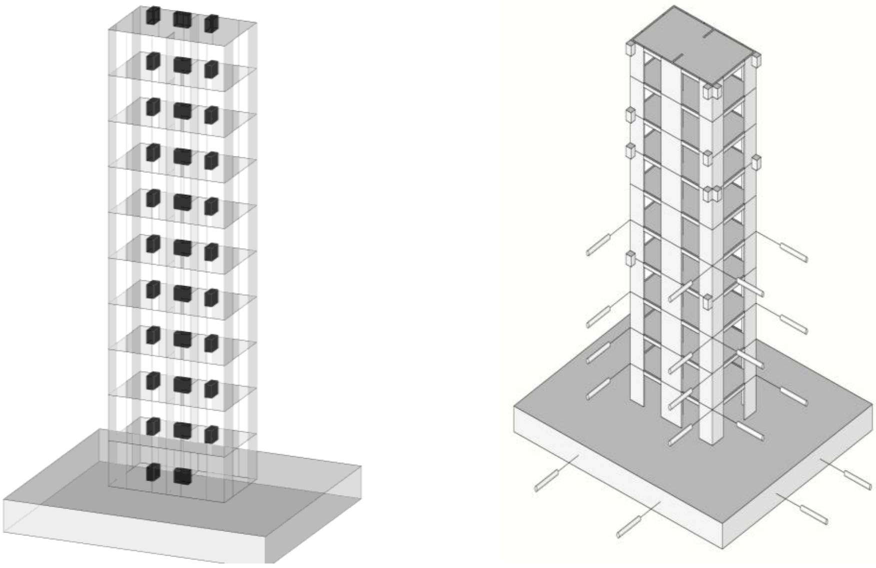
Figure 3. *The Model Structure for the Test*

Test Procedure and Measurements

According to the natural vibration period of the prototype structure, the classification of the construction site and the limit of the shaking table, three earthquake waves adopted as the input waves of the test, which were EI centro record, CA0295 record and TCU116 record. According to the value of peak ground acceleration (PGA), these seismic waves were loaded from small to large, which included two single direction (X&Y) inputs and bidirectional seismic wave inputs. Low amplitude white noise was loaded between the inputs of a different seismic wave to measure the dynamic property variation of the structure model.

The test measurements included the absolute acceleration response on each floor, the displacement response of selected stories and the strain of the reinforcement in masonry shear walls at the bottom floors. The arrangement of the accelerators and displacement meters were shown in Figure 4.

Figure 4. *The Arrangement of the Accelerator and Displacement Meter*



Test Results and Anaysis

Test Phenomenon and Failure Model Analysis

When the PGA of the table-board input motion was 35gal, 50gal and 125 gal, the structural vibration of the mode was very small, and no cracks appeared in the walls. When the PGA of the input seismic wave was 220gal, horizontal cracks appeared along two top and bottom mortar joints in the wall of the bottom floor in a short side direction (Y-axis), as shown in Figure 5(a). As the input seismic record had a PGA of 336gal, horizontal cracks were showing in the X-axis wall of the model's third floor, as can be seen in Figure 5(b). When the input earthquake wave had a PGA of 509gal, the walls of the 7th, 8th, 9th and 10th floor in both X and Y directions appeared horizontal cracks in the mortar joints, and the flexure cracks appeared in the reinforced concrete beam's end in Y-direction, as shown in Figure 5.

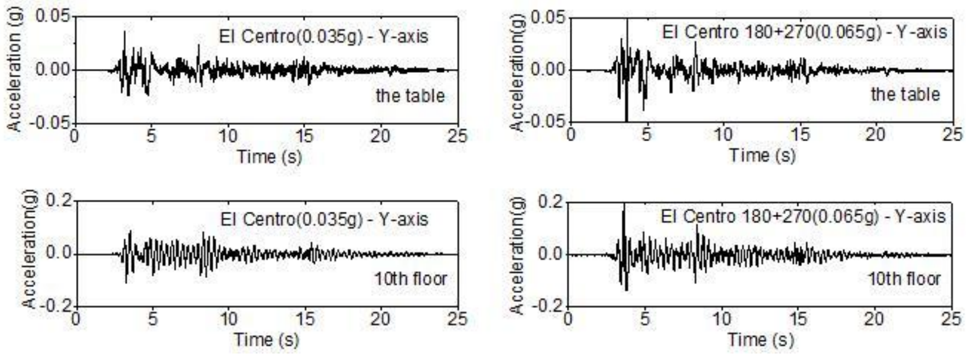
Figure 5. *The Arrangement of the Accelerator and Displacement Meter*

(a) PGA=220 gal (b) PGA=336 gal (c) PGA=509 gal

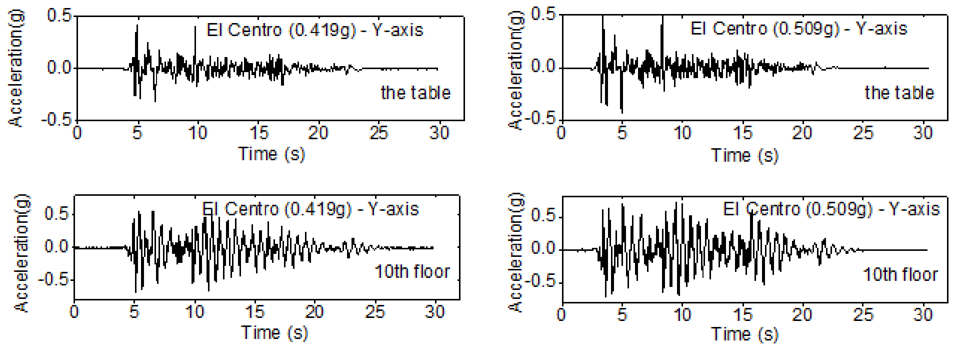
Corresponding to an 8-degree rarely occurred earthquake, the acceleration amplification factor of the 10^{th} floor to the table was 1.43. It was found that the acceleration amplification factor was reduced when the intensity of the input ground motion increased. The test indicated that the structure's lateral stiffness decreased, and its plastic deformation and damage caused by the input ground motion was gradually increased along with the enhancing of the input ground motion. Figure 6 shows the Acceleration time-history of the model structure.

Figure 6. *Acceleration Time-history of the Model Structure*

a) PGA=0.035g in Y-axis b) PGA=0.065g in X&Y-axis



c) PGA=0.4g in Y-axis d) PGA=0.5g in Y-axis

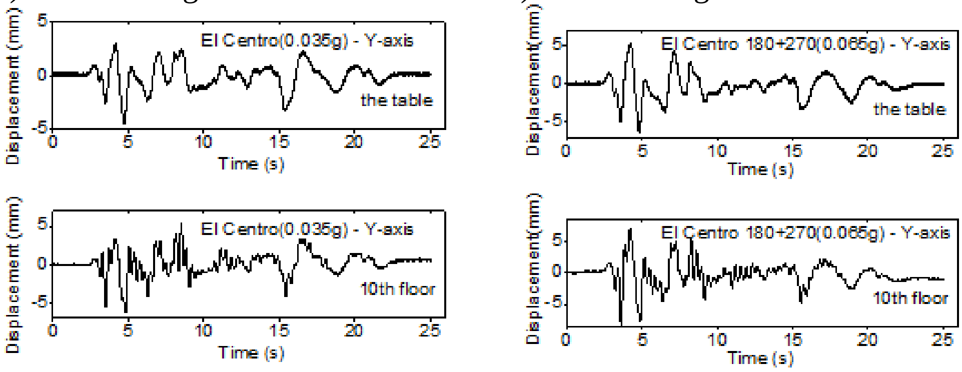


Displacement Response

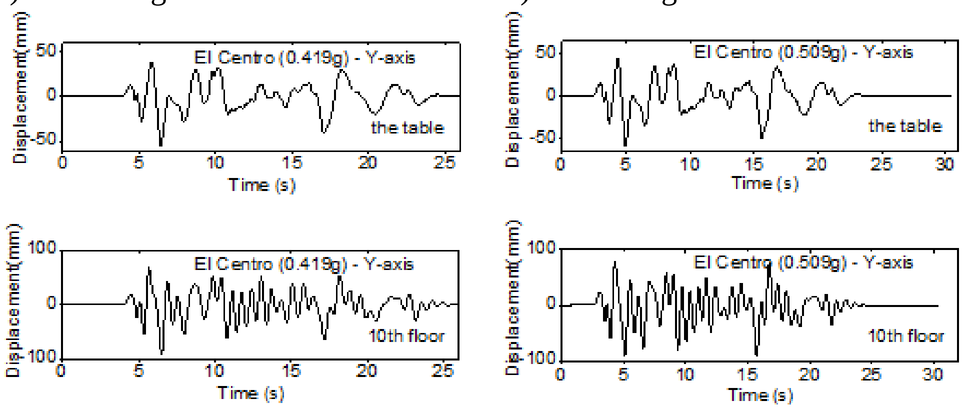
For the same reason mentioned above, this paper only presented the displacement responses of the model's top and bottom floor in Y direction under the input of EI Centro seismic waves, as shown in Figure 7. As can be seen from the test results, the maximum absolute displacement of the table-board and the 10th floor were 4.53mm and 6.59mm under the effect of minor earthquake (PGA=0.035g). Notice that the difference was small which meant that the structure was still in an elastic state. When the PGA of the input seismic wave was 0.5g, corresponding to the major earthquake, the maximum absolute displacement of the table-board and the 10th floor were 60.25mm and 93.10mm. The difference between them was quite large. One reason for the difference was the rigid slope displacement caused by the horizontal crack, and the other was that part of the shear wall was in a plastic state, and had a significant plastic deformation, leading to the increase of the top floor's drift.

Figure 7. *Displacement Time-history of the Model Structure*

a) PGA=0.035g in Y-axis b) PGA=0.065g in X&Y-axis



c) PGA=0.4g in Y-axis d) PGA=0.5g in Y-axis



Numerical Simulation Study of RBMW High-rise Building

Elastic Analysis of the Structure under Frequently Earthquake Action

Period and Vibration Mode of the Structure

Model periods of the hectometer high-rise building calculated by Satwe, Etabs and Abaqus were shown in Table 1. In Abaqus, the shell element in which concrete and steel can be set in different layers was adopted to simulate the reinforced masonry shear wall of the structure.

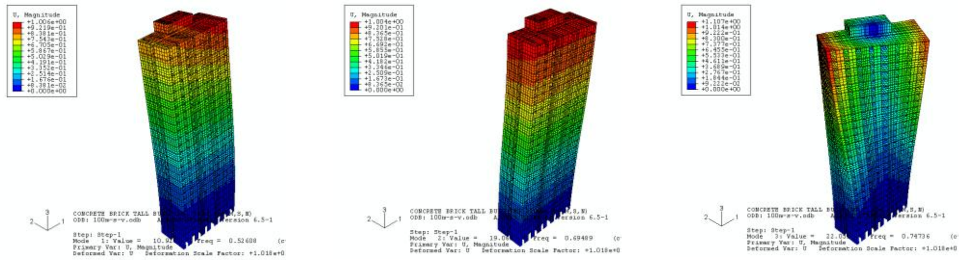
The 1^{st} to 6^{th} mode shapes calculated by Abaqus were shown in Figure 8. It's clear that the 1^{st} and the 2^{nd} mode shapes were translational modes, but the 3^{rd} mode shape was a torsion vibration mode. The ratio between the model periods of the first torsional mode T3 and the first horizontal model T1 was 0.6(1.147/1.925=0.6), less than the specified value 0.9 for the high-rise building in Chinses building code.

Table 1. *Comparison of Model Periods Calculated by Different Software*

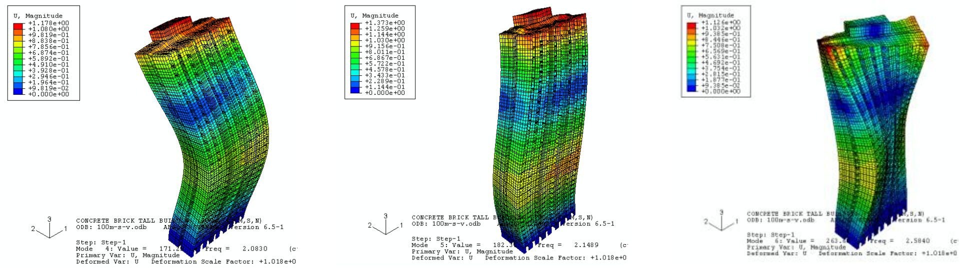
Vibration Model	Satwe	Etabs	Satwe/Etabs	Abaqus	Satwe/Abaqus
1	1.925	1.931	99.7%	1.901	101.3%
2	1.376	1.228	112.0%	1.439	95.6%
3	1.147	1.065	107.7%	1.338	85.1%
4	0.451	0.450	100.1%	0.480	94.0%
5	0.409	0.381	107.4%	0.465	88.0%
6	0.343	0.326	105.4%	0.387	89.0%

Figure 8. *The 1st ~ 6th Vibration Model Shapes of the Structure*

(a) the 1st model shape (b) the 2nd model shape (c) the 3rd model shape



(d) the 4th model shape (e) the 5th model shape (f) the 6th model shape



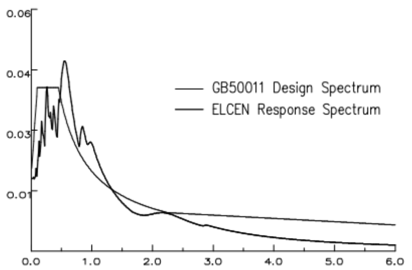
Elastic Time-history Analysis of the Structure

The earthquake waves used to analyze the seismic performance of the structure were EIcentro record, Lwd_del record, Pel_180 record and an artificial wave composed according to seismic design response spectrums for site class III, which was specified in Code for seismic design of buildings (GB50011-2010). The response spectra of the four selected earthquake waves were shown in Figure 9.

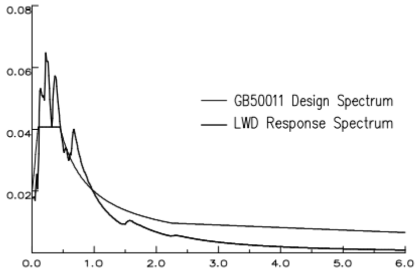
The story drifts of the structure calculated by the elastic time-history analysis through Abaqus were shown in Table 2. The maximum story drift was 1/3385 under Pel_180 earthquake wave in Y-axis, which was less than the limit value 1/1000 in the code. The result analyzed by the response spectrum method was also given in the table, and it was very close to the average value of the time-history analysis results.

Figure 9. *Response Spectra of Earthquake Waves*

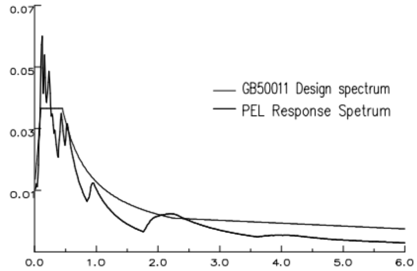
(a) EIcentro Wave



(b) Lwd_del Wave



(c) Pel_180 Wave



(d) Simulated Earthquake Wave

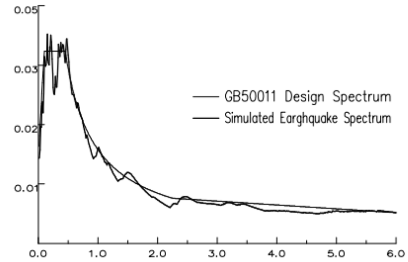


Table 2. *Story Drifts of the Structure under Earthquake Action*

Earthquake record	Story dirft in X-axis	Relative ratio	Story dirft in Y-axis	Relative ratio
Response spectrum analysis	1/6222	1.00	1/3929	1.00
EIcentro	1/6908	0.90	1/3493	1.12
Lwd_Del	1/7480	0.83	1/5012	0.78
Pel_180	1/8765	0.71	1/3385	1.16
Simulated wave	1/5561	1.12	1/3806	1.03

Elastic-plastic Time-history Analysis under Rarely Earthquake Action

Constitutive Relations of Materials

The constitutive relation of grouted concrete block masonry used in the numerical simulation was proposed by the Tang Daixin research group of Harbin Institute of Technology according to the results of the experiment, which adopt a parabolic curve and straight line to express the ascend segment and descent segment respectively:

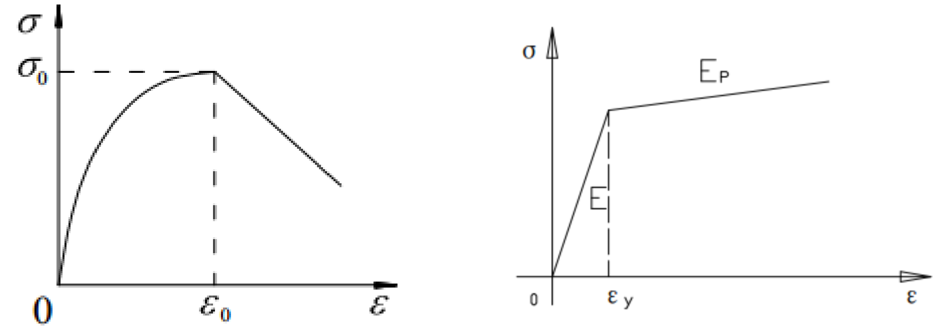
$$\frac{\sigma}{\sigma_c} = 2\left(\frac{\varepsilon}{\varepsilon_c}\right) - \left(\frac{\varepsilon}{\varepsilon_c}\right)^2 \qquad \varepsilon < \varepsilon_c$$

$$\frac{\sigma}{\sigma_c} = -0.19\left(\frac{\varepsilon}{\varepsilon_c}\right) + 1.19 \qquad \varepsilon_c < \varepsilon < 4\varepsilon_c$$

Where, σ is the stress of masonry, ε is the strain of masonry, σ_c is the uniaxial peak stress of masonry, ε_c is the peak strain of masonry.

The reinforcing steel bar was simulated by a bilinear kinematic hardening model in the finite element analysis. The constitutive relations of grouted masonry and the rebar were shown in Figure 10.

Figure 10. *Constitutive Relations of Materials*
(a) Grouted masonry (b) Rebar



Period and Vibration Mode of the Structure

Under the nonlinear dynamic procedure, the designed seismic forces, their distribution over the height of the structure, the corresponding internal forces and system displacements were determined through the inelastic time-history dynamic analysis. The RBMW high-rise building was calculated by PKPM/EPDA and Abaqus, whose story displacements and story drifts under different seismic waves were shown in Figures 11 and 12.

Figure 11. *Elastic-plastic Time-history Analysis Results by EPDA*
(a) Story Displacement (b) Story Drift

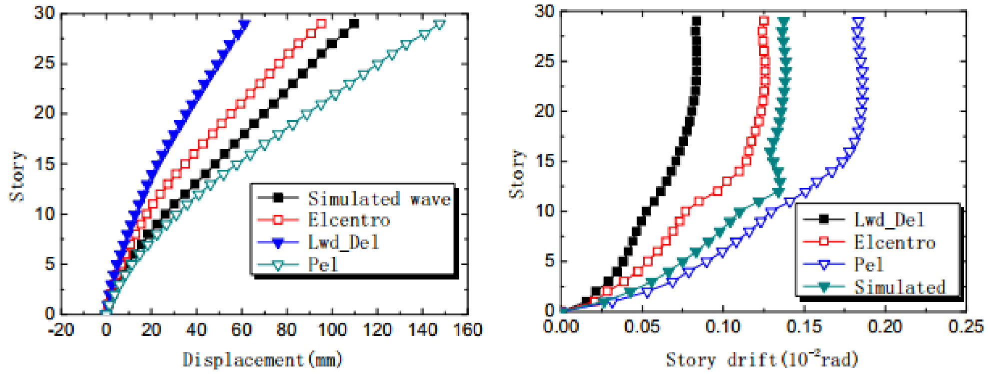
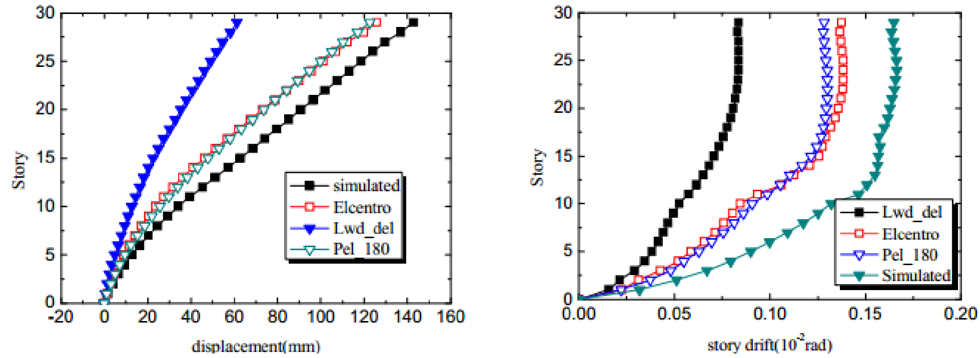


Figure 12. *Elastic-plastic Time-history Analysis Results by Abaqus*
(a) Story Displacement (b) Story Drift



Story drifts of the structure in the Y-axis (the minor axis) under earthquake action for fortification intensity 6 were given in Table 3. As we can see, the maximum value is 1/538 in EPDA and 1/666 in Abaqus, and both of them are less than 1/120, the limit of the code.

Table 3. *Story Drifts of the Structure in Fortification Intensity 6*

Earthquake record	EPDA	Abaqus	Limit of code
EIcentro	1/794	1/769	
Lwd_Del	1/1197	1/1397	
Pel_180	1/538	1/767	1/120
Simulated wave	1/721	1/666	
Average value	1/748	1/829	

Story drifts of the structure in the Y-axis (the minor axis) under earthquake action for fortification intensity 7 were given in Table 4. As we can see, the maximum value is 1/204 in EPDA and 1/326 in Abaqus, and both of them are less than 1/120, the limit of the code.

Table 4. *Story Drifts of the Structure in Fortification Intensity 7*

Earthquake record	EPDA	Abaqus	Limit of code
EIcentro	1/294	1/566	
Lwd_Del	1/348	1/687	
Pel_180	1/258	1/334	1/120
Simulated wave	1/204	1/326	
Average value	1/265	1/429	

Conclusions

To research the seismic performance of the high-rise RBMW buildings especially the hectometer buildings, a shaking table test and a related numerical simulation analysis by finite element software were conducted. The following observations and conclusions were made:

(1) The RBMW structures have a good deformation capacity and ductility as well as great seismic performance. The shaking table test proved that the structure was basically in the elastic state under the effect of a 7-degree frequently occurred earthquake, and serious and irreparable damage did not appear in a 8-degree rarely occurred earthquake. As the intensity of the ground motion improved, the floor's acceleration amplification factor decreased, indicating that the damage of the structure increased.

(2) The numerical simulation showed that in the region of seismic intensity 6, the maximum story drift of the hectometer building by time-history analysis method was 1/3385 in elastic analysis, and 1/666 in elastic-plastic analysis; In region of intensity 7, the maximum story drift of the hectometer building was 1/326 in elastic-plastic analysis. The results satisfied the criterion request.

(3)Through the results of the shaking table test and numerical simulation, it is concluded that the RBMW structure system is feasible in the high-rise even hectometer buildings in earthquake zone.

References

[1] SUN, X. J., ZHANG, H., LU, D. G., and WANG, F. L. 2012.Study on Seismic Performance of Reinforced Concrete Masonry High-rise Building. *A, Applied Mechanics and Materials*, Vols. 166-169, pp. 2164-2170. DOI=10.4028/ www.scientific.net/AMM.166-169.2164

[2] Zhai, X. M., and Stewart, M. G. 2010. Structural reliability analysis of reinforced grouted concrete block masonry walls in compression. *Engineering Structures*, 2010(32):106-114. DOI= 10.1016/j.engstruct.2009.08.020.

[3] Voon, K. C. and Ingham, J. M. 2006. Experimental in-plane shear strength investigation of reinforced concrete masonry walls. *J. Journal of Structural Engineering.* 132(3): 400-408. DOI= http://bit.ly/2lvjCuE.

[4] Voon, K. C. and Ingham, J. M. 2007. Design expression for the in-plane shear strength of reinforced concrete masonry. *Journal of Structural Engineering.* 133(5): 706-713. DOI= http://bit.ly/2mwoipd.

[5] Shedid, M. T., Drysdale, R. G., and El-Dakhakhni, W. 2008. Behavior of Fully Grouted Reinforced Concrete Masonry Shear Walls Failing in Flexure: Experimental Results. *J. Struct. Eng.*, 1754-1767. DOI=10.1061/(ASCE)0733-9445(2008)134:11(1754).

[6] Shedid, M. T., El-Dakhakhni, W. and Drysdale, R. G. 2009. Behavior of fully grouted reinforced concrete masonry shear walls failing in flexure: Analysis. Engineering Structures. 31(9): 2032-2044. DOI=10.1016/j.engstruct.2009.03.006.

[7] Stavridis, A., Ahmadi, F., Mavros, M., Shing, P., Klingner, R., and McLean, D. 2016. Shake-table tests of a full-scale three-story reinforced masonry shear wall structure. *J. Struct. Eng.*, 04016074. DOI=10.1061/(ASCE)ST.1943-541X.0001527.

[8] Seible, F., Priestley, M., Kingsley, G., and Kürkchübasche, A. 1994. Seismic response of full-scale five-story reinforced-masonry building. *J. Struct. Eng.*, 925-946. DOI= http://bit.ly/2mNZIfi.

[9] Chopra, A. K. and Goel, R. K. 2002. A modal pushover analysis procedure for estimating seismic demands for buildings. *Earthquake Engineering & Structural Dynamics*, 561-582. DOI= http://dx.doi.org/10.1002/eqe.144.

[10] Seible, F., Hegemier, G., Igarashi, A., and Kingsley, G. 1994. Simulated seismic-load tests on full-scale five-story masonry building. *J. Struct. Eng.*, 903-924. DOI=http://bit.ly/2lvjCuE.