6th International Conference on Advances in Experimental Structural Engineering
11th International Workshop on Advanced Smart Materials and Smart Structures Technology
August 1-2, 2015, University of Illinois, Urbana-Champaign, United States

Multi-modal Shaking Table Testing for Inner-Skin Curtain Wall System of Shanghai Tower

Y.L. Wang[1], W.S. LU[2], K.M. Mosalam[3]

1 Ph. D. candidate, College of Civil Engineering, Tongji University, Shanghai, China.
E-mail: wangyangling00@gmail.com
2 Professor, College of Civil Engineering, Tongji University, Shanghai, China.
E-mail: wally@tongji.edu
3 Professor, Dept. of Civil and Environmental Engineering, University of California, Berkeley, United States.
E-mail: mosalam@berkeley.edu

ABSTRACT
Shanghai Tower has a unique exterior and interior "double-skin" curtain wall system with a tapering atrium in between, which makes the interior curtain wall system in enclosed spaces and designed not to be pressure-equalized. Therefore, the seismic performance is of great concern. Aiming at investigating its seismic performance, the seismic inputs to the system, including multi-dimensional accelerations and inter-story drifts, were determined from the analysis of a finite element model and shaking table test of the main structure. Subsequently, a shaking table test on the typical curtain wall unit mockup is conducted utilizing a designed multi-modal loading device. This device, together with shaking table, achieved the reproduction of three-dimensional dynamic acceleration time-history actions and step-by-step loading of horizontal and vertical in-plane drifts simultaneously. The test results indicate that the vertical drift influences the dynamic property and acceleration responses of the curtain wall systems.

KEYWORDS: *inner curtain wall system, multi-modal loading, seismic performance, shaking table test.*

1. INSTRUCTIONS

Shanghai Tower, as shown in Fig. 1.1, is the tallest high-rise building in China with the height of 632 m, which is located in the Lujiazui financial CBD in Shanghai. It adopts a unique exterior envelop design utilizing double skin curtain wall (CW) system [1] which rotates approximately one degree in each floor. The building is divided into nine zones with number of stories varying from twelve to fifteen. Each zone has a refuge floor and mechanical floor that functions as the supports for curtain wall systems. In each zone, an atrium is created by the interstitial space between the inner and outer curtain wall systems, Fig. 1.2, which operates as a gathering space and the center for activity within a particular zone.

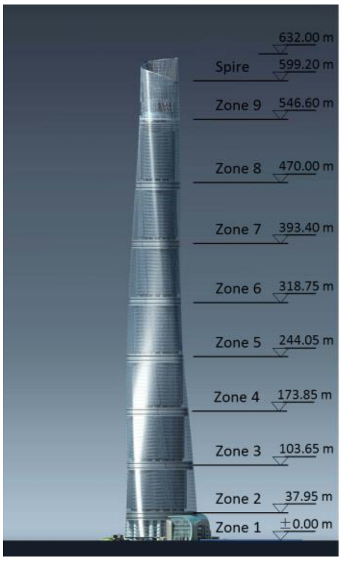


Figure 1.1 Overall view of Shanghai Tower

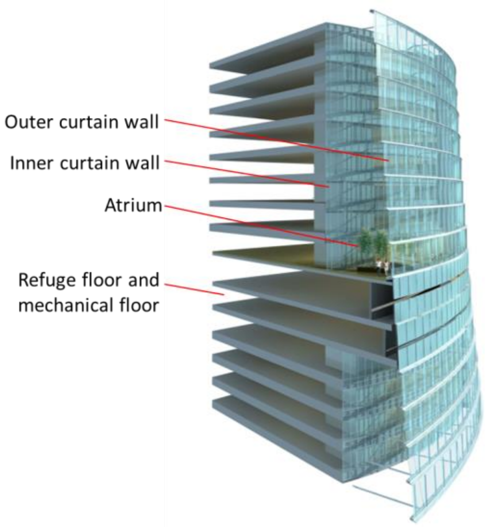


Figure 1.2 Section of one typcial zone

The inner curtain wall employs the zonal frame-supported unitized system with a four-sided structural sealant glazing (SSG) system where the top and bottom are fixed to the adjacent mechanical floors. In the unitized system, each floor is considered as a unit that connects to the corresponding glass panel by stainless steel hangers. The adjacent unit is assembled by horizontal stacked mullion and clips [2] shown in Fig. 1.3. The three dimensions used in this paper are defined: X direction is perpendicular to the glass panel as out of plane direction; Y and Z directions are parallel to the panel as in-plane directions, which refer to horizontal and vertical directions, respectively, as illustrated in Fig. 1.3.

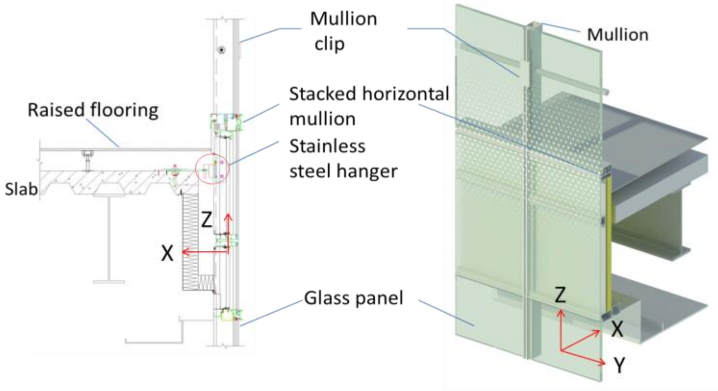


Figure 1.3 Section detail of inner curtain wall system

The above characteristics make it essential to confirm the seismic performance of the inner curtain wall system and its connection to the main structure. To minimize glass damage induced by earthquake actions, International Building Code (ICC 2009) [3], which adopts ASCE7-10 (ASCE 2010) [4], requires the curtain walls to accommodate the seismic relative displacements requirements determined as design building story drifts. ASCE7-10 seismic provisions reference the American Architectural Manufacturer’s Association (AAMA 2009) [5-6] test procedure for determining the glass fallout resistance from CW mock-ups. Experimental [8-10] and analytical [11-12] studies were conducted to investigate the deformation performance of CW and develop a general prediction model for glass cracking during seismic induced drift. However, published studies related to the use of finite element analysis to predict the performance of CW systems under earthquake are scarce, due to the complex components and configuration of the CW systems.

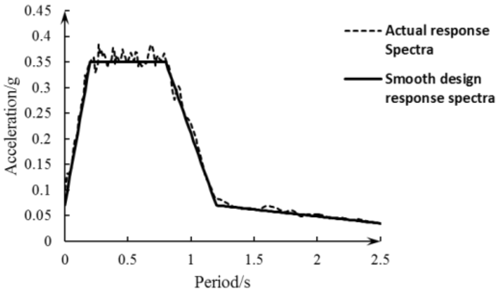
Different from conducting dynamic racking tests to investigate the drift capacity of a curtain wall system associated with glass fallout, a shaking table test is performed in this paper with the mock-up of the typical curtain wall units and the connection to the main building to evaluate the seismic performance. The seismic inputs of the inner curtain wall system including three-dimensional acceleration and in-plane drift were obtained first. Subsequently, the shaking table test using a designed multi-modal loading device was conducted. Finally, the seismic performance of the curtain wall system is estimated by analyzing the results of full-scale tests on the behavior of the glass, framing and connections.

2. SEISMIC INPUTS

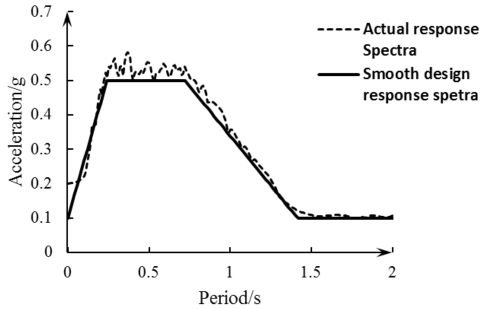
The curtain wall system receives multi-dimensional earthquake actions, including floor acceleration time history and inter-story displacements, from attached floors of the main structure instead of ground seismic motions [13]. In order to obtain the seismic actions of Shanghai Tower, the finite element model using SAP 2000 software and the shaking table test of the main structure were conducted. Taking Shanghai Type IV soft soil into consideration, four seismic ground motions were chosen as inputs: (a) MEX 006-008 recorded form the Mexico city earthquake of September 19, 1985; (b) US 1213-1215 records from Borrego Mountain earthquake of April 9, 1968; (c) S79010-12 artificial accelerogram; and (d) SHW3 artificial accelerogram specified for the particular soil conditions of Shanghai (Shanghai Code for Seismic Design of Buildings, DGJ08-2003). All inputs are applied in three orthogonal directions except the Shanghai artificial accelerogram, which is one-dimensional input.

2.1. Acceleration action

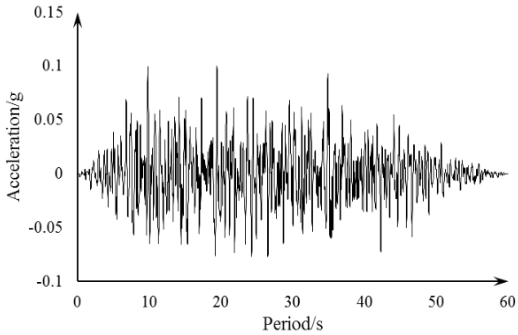
The three-dimensional acceleration responses at the connection point were extracted from the finite element analysis and shaking table test results of the main structure, which were used for acceleration spectra analysis [14]. Due to the symmetrical plan configuration of the main structure, only one horizontal acceleration response was analyzed. The horizontal and vertical smooth design response spectra were developed to be compatible with the synthetic accelerograms. Fig. 2.1 shows the smooth design spectra, the accelerograms and the actual response spectra of the synthetic accelerograms in X, Y and Z directions. These accelerograms were used as the inputs for the shaking table tests and the amplitudes were controlled by the envelope value from the seismic actions of the main structure, which are listed in Table 2.1.



a-1) response spectra

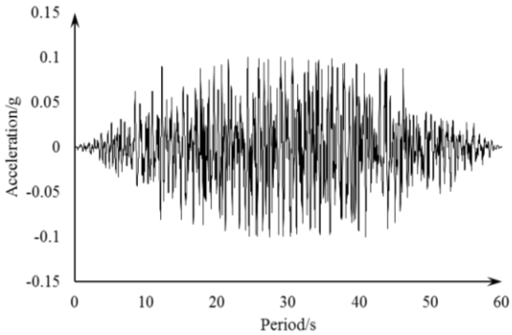


b-1) response spectra



a-2) synthetic accelerogram

a) X and Y direction



b-2) synthetic accelerogram

b) Z direction

Figure 2.1 Acceleration spectra and synthetic accelerograms in horizontal and vertical directions

2.2. In-plane drift action

The displacement actions transferred to the CW system are the inter-story drift of the main structure, including in-plane relative displacements which are parallel to the panel of the curtain wall (Y and Z directions) and the out-of-plane displacement (X direction) which is perpendicular to the panel. Only the in-plane displacement actions are discussed, because the in-plane stiffness of the CW is much larger than the out-of-plane one, i.e. larger in-plane forces are expected than those in the out-of-plane under the same drift ratio. Due to the limitations of the test setup, the static step-by-step loading method was applied in this shaking table test to realize the loading of in-plane relative drift actions on the CW specimen. The envelope value of the in-plane drifts are listed in Table 2.1.

Table 2.1 Envelope values of earthquake actions

Intensity 7				
		Frequent	Basic	Rare
Acceleration [g]	Horizontal (X & Y)	0.18	0.49	1.03
	Vertical (Z)	0.15	0.42	0.91
In-plane horizontal drift (Y) [mm] (drift ratio)		9.0 (1/500)	16.6 (1/272)	56.3 (1/80)
In-plane vertical drift (Z) [mm]		-	-	+17/-21

Note: "+" in vertical drift refer to the relative displacement of pulling the upper mullion away from the lower mullion;
"-" in vertical drift refer to the relative displacement of pushing the upper mullion away from the lower mullion.

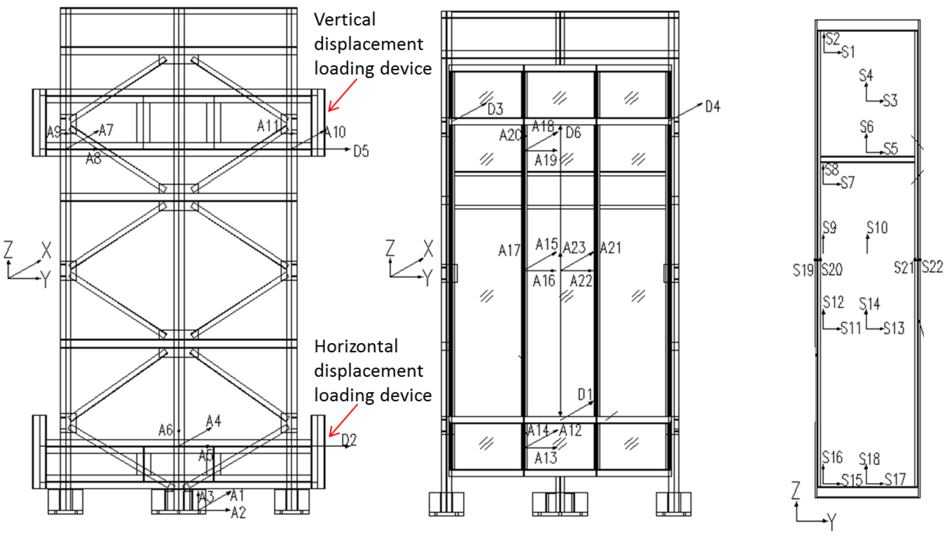
3. SHAKING TABLE TEST

The typical curtain wall units were installed on the test frame using the actual connections to the main structure as in the on-site construction. The shaking table test reproducing the envelope value of the in-plane horizontal and vertical drifts and three-dimensional acceleration time history, obtained as aforementioned, were conducted with the multi-modal loading apparatus. Subsequently, the seismic performance of the inner curtain wall system was evaluated by investigating the test results acquired from the arranged sensor system.

3.1. Test mock-up

The CW units between adjacent floors, containing the glass panels, non-thermally broken aluminum extrusion members and connections, together with the horizontal and vertical adjacent units, were selected as the test mockup, as illustrated in Fig. 3.1, due to its repeating arrangement on the unitized CW system. The selected unit is located on the second zone, whose size is 1050 mm wide by 4500 mm tall. The glazing panel adopts 25 mm insulated unit (6 mm heat-strengthened + 0.89 mm SGP +6 mm heat-strengthened +12 mm air space +8 mm fully tempered).

Figure 3.1 Multi-modal testing apparatus and test setup



Note: A, D and S refer to accelerometer, displacement transducer and strain gauge, respectively.

Figure 3.2 Deployment of sensor system

The sensor system used in the testing contained acceleration sensors, displacement transducers and strain gauges: as shown in Fig. 3.2. In order to measure the acceleration response of the mockup specimen, twenty-three accelerometers were arranged on the glass panel, mullion and hanging position on the main structure for the curtain wall. Six displacement transducers were installed in the specimen and displacement loading devices to observe the displacement response of key components. Twenty-two strain gauges were set up on glass panels and mullions to monitor the change of strain and accordingly compute the stress. The detailed instrumentation configuration information is presented in [15].

3.2. Multi-modal loading

The test apparatus (shown in Fig. 3.1) encompassed main framework, horizontal and vertical displacement loading device, which together with the shaking table, subjected the specimen to three-dimensional dynamic acceleration time history actions and step-by-step loading of horizontal and vertical inter-story drifts simultaneously. The amplitude of these acceleration and drift input were controlled by the envelope values in Table 2.1.

3.3. Evaluation of the seismic performance

The natural frequencies and damping ratios of the tested glass panels are obtained from white-noise scan tests. Table 3.1 lists the natural frequencies and damping ratios at the end of each occurrence phase in the X and Z directions. When vertical drift loads pulled glass units apart, the natural frequency of panels decrease slightly, while the damping ratio ascends slowly in both X and Z directions. When subjected to the pushing vertical drift, the natural frequency in X direction decreases and the situation is opposite in Z direction, while the damping ratio decrease slightly in both directions. The change of natural frequency and damping ratio in glass panel indicates the influence of vertical drift on the dynamic property of the CW system, which needs to be further investigated.

Table 3.1 Natural frequencies and damping ratios in X and Z directions

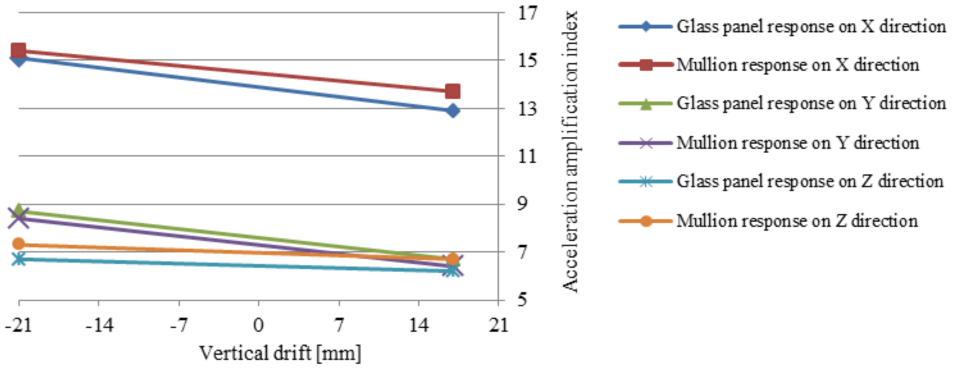
Horizontal drift [mm] (drift ratio)		9 (1/500)		56.3 (1/80)		9 (1/500)		56.3 (1/80)	
Vertical drift [mm]		+17		+17		-21		-21	
		f (Hz)	ξ	f (Hz)	ξ	f (Hz)	ξ	f (Hz)	ξ
X	Initial	7.6	0.020	7.3	0.029	9.1	0.024	9.2	0.036
	Intensity 7	7.3	0.039	7.1	0.046	8.5	0.019	8.1	0.030
Z	Initial	17.4	0.040	17.4	0.030	17.5	0.031	16.8	0.036
	Intensity 7	17.3	0.059	17.3	0.038	17.9	0.028	18.1	0.027

Note: f and ξ refer to the natural frequency and the damping ratio of the glass panel, respectively.
"+" in vertical drift refer to the relative displacement of pulling the upper mullion away from the lower mullion;
"-" in vertical drift refer to the relative displacement of pushing the upper mullion away from the lower mullion.

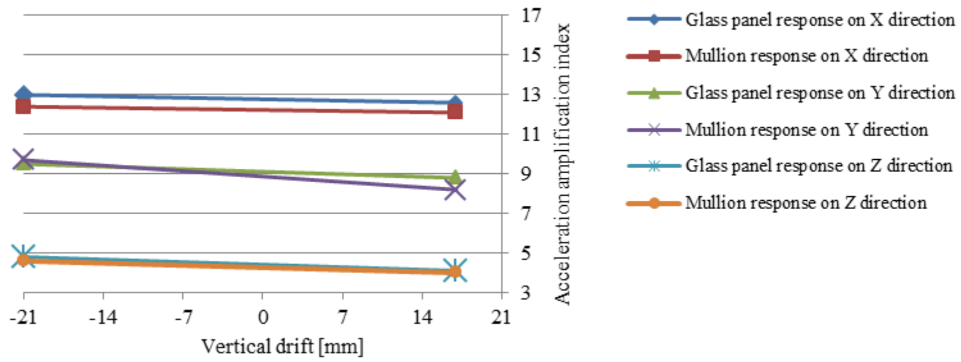
The peak value of acceleration and the corresponding amplification index (AAI, actual acceleration response value normalized by the ground acceleration value) on the center of the glass panel, the middle position of mullion and the hanged position on the main structure are listed in Table 3.2. According to the results, the seismic responses of glass unit are amplified and the maximum AAI on glass panel is 15.1 which is much larger than the code provision value of 5.0 according to Chinese current standards [16-17]. The peak horizontal inter-story drift ratio is 1/69 (65 mm in terms of the inter-story drift) which is larger than the code provision value of 1/80.

Figure 3.3 shows the influence of vertical drift to the acceleration response of glass panel and mullion under frequent and rare intensity 7. From the chart, the acceleration response of the glass unit (glass panel and mullion) increased when subjected to pushing vertical drift under frequent and rare intensity 7. The increase is clear in the X and Y directions.

The damage after each designed input motion is as follows: a) under frequent intensity 7, the specimens were undamaged, the relative displacement and deformation did not appear and the connections remained intact; b) under basic intensity 7, slight deformation on adjacent units were observed; c) under rare intensity 7, the increased relative deformation between adjacent units reached a maximum value of 45 mm, the maximum value of relative movement of the hanging clip was 5 mm and some abrasion on hanging strip were detected without significant damage observed on the glass panels, support system and the connections of the specimens. Fig. 3.4 shows the damage observed during the rare intensity 7.



a) Frequent intensity 7



b) Rare intensity 7

Figure 3.3 Acceleration responses of glass panel and mullion under different vertical drifts

Table 3.2 Acceleration responses of the glass panels

		Intensity 7					
		Frequent	Basic	Rare	Frequent	Basic	Rare
Horizontal drift [mm] (drift ratio)		9	16.5	56.3	9	16.5	56.3
		(1/500)	(1/272)	(1/80)	(1/500)	(1/272)	(1/80)
Vertical drift [mm]		17	17	17	-21	-21	-21
		Acceleration [g] (AAI)					
X	Glass panel	0.46	1.24	2.83	0.54	1.18	2.93
		12.9	12.2	12.6	15.1	11.6	13
	Mullion	0.49	1.18	2.72	0.55	1.26	2.79
		13.7	11.6	12.1	15.4	12.4	12.4
	Hanged position	0.38	0.69	1.71	0.35	0.72	1.65
		10.6	6.8	7.6	9.8	7.0	7.4
Y	Glass panel	0.24	0.7	1.97	0.31	0.65	2.14
		6.7	6.9	8.8	8.7	6.4	9.5
	Mullion	0.23	0.7	1.84	0.3	0.66	2.17
		6.4	6.9	8.2	8.4	6.5	9.7
	Hanged position	0.23	0.78	2.07	0.3	0.78	1.91
		6.4	7.6	9.2	8.4	7.6	8.5
Z	Glass panel	0.22	0.35	0.92	0.24	0.38	1.07
		6.2	3.4	4.1	6.7	3.7	4.8
	Mullion	0.24	0.35	0.92	0.26	0.39	1.06
		6.7	3.4	4.1	7.3	3.8	4.7
	Hanged position	0.12	0.19	0.65	0.11	0.18	0.65
		3.4	1.9	2.9	3.1	1.8	2.9

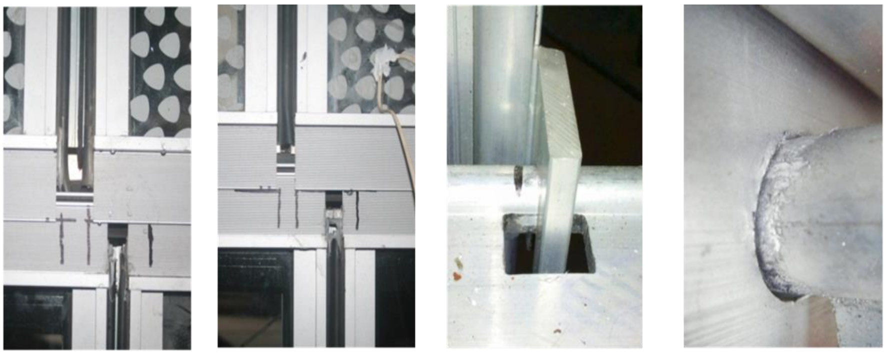


Figure 3.4 Relative deformation and scratch observed during the rare intensity 7

4. CONCLUSIONS

The in-between atrium in any of the zones in the Shanghai Tower significantly affects the requirement of seismic performance of inner curtain wall system of Shanghai Tower. Therefore, a typical full-scale mockup installed by practical construction method was tested on the shaking table utilizing multi-modal loading frame. The following conclusions can be drawn from the shaking table test results:

(1) The seismic inputs for inner curtain wall system are determined from the attached floor actions including three-dimensional accelerations and inter-story drifts.
(2) The peak value of acceleration amplification and inter-story drift ratio of glass unit are 15.4 and 1/69, respectively. They satisfy the design provision value according to the Chinese current standards.
(3) When subjected to different vertical drift, the natural frequency and damping ratio in glass panel change which indicates the influence of vertical drift on the dynamic property of the curtain wall system. It is shown that when subjected to pushing vertical drift, the three-dimensional acceleration responses of glass panel and mullion increased.
(4) After the loading with the rare intensity 7, relative deformation between adjacent glass units and the hangers increased. The maximum values are 45 mm and 5 mm, respectively. No glass fracture, excessive and permanent deformation of glazing frame and loss of attachment were observed.
(5) The mockup test results indicate that the curtain wall unit is able to withstand frequent, basic and rare intensity 7 earthquakes without severe damage.
(6) Different curtain wall systems may have certain limitations to comply with uniform acceleration amplification factor (e.g. 5.0) prescribed in current Chinese standards as seismic performance evaluation index, considering the effect of the dynamic properties of the main structure and the curtain wall system and the installation position of the curtain wall. Further study on setting reasonable seismic performance evaluation index and the influence of vertical drift for different curtain wall systems should be considered.

ACKNOWLEDGEMENT
The authors are grateful for the support from Shanghai Tower Construction and Development Co., Ltd., Beijing Jangho Curtain Wall Co., Ltd. and State Key Laboratory of Disaster Reduction in Civil Engineering in Tongji University.

REFERENCES

1. Zeljic A. S. (2010). Shanghai Tower Façade Design Process. *International Conference of Building Envelope Systems*. Vancouver, Canada.
2. Gensler and Architectural Design & Research Institute of Tongji University (2009). Shanghai Tower Exterior Curtain Wall Visual and Performance Mock-up Drawing.
3. ICC. (2009). *International building code*, Washington, DC.
4. ASCE. (2010). Minimum Design Loads for Buildings and Other Structures. *ASCE 7-05,* Reston, VA.
5. AAMA. (2009a). Recommended Static Testing Method for Evaluating Curtain Wall and Storefront Systems

Subjected to Seismic and Wind Induced Inter-story Drift, *AAMA 501.4-09*, Des Plaines, IL.

6. AAMA. (2009b). Recommended Dynamic Test Method for Determining the Seismic Drift Causing Glass Fallout from a Wall System. *AAMA 501.6-09*, Des Plaines, IL.
7. Memari, A., Behr, R., and Kremer, P. (2003). Seismic Behavior of Curtain Walls Containing Insulating Glass Units. *Journal of Architectural Engineering.* **9:2**, 70–85.
8. Memari, A., Fisher, S., Krumenacker, C., Broker, K., and Modrich, R. (2011). Seismic Evaluation of the Four-Sided Structural Sealant Glazing Curtain Wall System for Cathedral Hill Hospital Project. *Architectural Engineering Conference 2011*. Oakland, California, United States.
9. Eva C. and Hutchinson T.C. (2011). Experimental evaluation of the in-plane seismic behavior of storefront window systems, *Earthquake Spectra*. **27:4**, 997-1021.
10. O'Brien W.C., Memari A.M., Kremer P.A. and Behr R.A. (2012). Fragility Curves for Architectural Glass in Stick-Built Glazing Systems, *Earthquake Spectra*. **28:2**, 639-665.
11. Memari, A., Shirazi, A., Kremer, P., and Behr, R. (2011). Development of Finite-Element Modeling Approach for Lateral Load Analysis of Dry-Glazed Curtain Walls. *Journal of Architectural Engineering*. **17:2**, 24–33.
12. Memari, A., Chen, X., Kremer, P., and Behr, R. (2012). Prediction of Seismic Failure of Silicone Sealant in Two-Sided Structural Sealant Glazing Systems. *Journal of Architectural Engineering.* **18:1**, 16–26.
13. Wang Y. L., Lu W. S. and Cao W. Q. (2014). Seismic Action Mechanism and Multi-Modal Reproducing Method of Architectural Curtain Wall. J*ournal of Tongji University (Natural Science).* **11**, 1639–1646. (in Chinese)
14. Huang B.F., Liu D. and Li S.C. (2012). Analysis of Floor Seismic Action of Outer Glass Curtain Wall of Shanghai Tower, Technique Report. (in Chinese)
15. Li S.C., Liu D. and Huang B.F. (2012). Shaking Table Test of Inner Class Curtain Wall of Shanghai Tower, Technique Report. (in Chinese)
16. The Ministry of Construction of the People's Republic of China (2003). Technical code of glass curtain wall engineering. *JGJ 102-2003*, Beijing, China.(in Chinese)
17. General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (2001). Shaking table test method of earthquake resistant performance for building curtain wall. *GB/T 18575-2001*, Beijing, China. (in Chinese)