Collapse simulation of unreinforced masonry walls

C.H. Cuadra
Akita Prefectural University,Japan

W. Fujisawa
Shiki Kobo Construction Co., Japan

T. Saito
Building Research Institute, Japan

SUMMARY:
Majority of non-engineered houses in developing countries are constructed by unreinforced masonry. This type of structure is known quite vulnerable to earthquake and must be constructed properly to resist earthquake loads both in-plane and out-of-plane of masonry walls. In many masonry design codes, the effective height of the walls is calculated according to the thickness of the wall and recommended to be around 20 times the thickness of the wall. Then if the length of the wall is taken as twice the height of the wall or less than this value, it is considered that no verification is required for out of plane behavior. This assumption doesn't have enough theoretical background. Therefore the objective of the present study is to analyze the out of plane behavior of the masonry walls with different wall-length to wall-height ratios. Firstly, the characteristics of the collapse are verified by means of shaking table test of small size model constructed with small wooden blocks and without mortar. For small wall length, it was found that the collapse starts with the in plane failure of the perpendicular walls that are used to restrain the test wall. For large wall length, the failure starts with the collapse of the upper part of the wall like a failure by bending of a slab with 3 restrained borders. The simulation could be used to clarify the out of plane behavior of masonry walls as an educational tool to understand the collapse mechanism of unreinforced masonry. Then, shaking table test of a real size masonry wall is conducted in Building Research Institute to confirm the collapse behavior observed by the small size model. Also, a simulation of the collapse of unreinforced masonry walls during earthquake motion is performed by using proposed discrete element models. The results of simulations are compared with those of shaking table tests for both small size model and real size model.

Keywords: Masonry, Shaking table test, Collapse simulation, Discrete element method

1. INTRODUCTION

Brick masonry is widely used for housing construction in many places of the world and majority of non-engineered houses in developing countries are constructed by unreinforced masonry. This type of structure is known quite vulnerable to earthquake and must be constructed properly to resist earthquake loads both in-plane and out-of-plane of masonry walls. The out-of plane behavior is critical even in the case of reinforced masonry or confined masonry. In many masonry design codes, the effective height of the walls is calculated according to the thickness of the wall and recommended to be around 20 times the thickness of the wall. Then if the length of the wall is taken as twice the height of the wall or less than this value, it is considered that no verification is required for out of plane behavior. This assumption does not have enough theoretical background and therefore the objective of the present study is to analyze the out of plane behavior of the masonry walls with different wall-length to wall-height ratios.

As a first step to clarify the out-of-plane behavior of unreinforced masonry, the characteristics of the collapse are verified by means of shaking table test of small size model constructed with small wooden blocks and without mortar. For small wall length, it was found that the collapse starts with the in plane failure of the perpendicular walls that are used to restrain the test wall. For large wall length, the failure starts with the collapse of the upper part of the wall like a failure by bending of a slab with 3 restrained borders. The simulation could be used to clarify the out of plane behavior of masonry walls as an educational tool to understand the collapse mechanism of unreinforced masonry.

Shaking table test of a real size masonry wall was conducted in Building Research Institute to confirm the collapse behavior observed by the small size model. The specimen was constructed trying to keep the critical height to length ratio (length of the wall equal twice the height of the wall). Harmonic input motion was used to determine the dynamic characteristics of the specimen and then random white noise signal were input to produce the collapse of the wall specimen.

The experimental results are compared with analytical results to calibrate the analysis tools developed specifically to simulate the collapse of masonry structures. The simulation of the collapse of unreinforced masonry walls during earthquake motion is performed by using proposed discrete element models.

2. SMALL SIZE SHAKING TABLE TEST

To investigate the effect of the length height ratio on the out-of-plane behavior of the wall, two models were prepared to be subjected to sine wave on small shaking table. The small shaking table has an area of 400 mm400 mm. The model were prepared using small wooden blocks which dimensions are 75 mm×25mm×14.5 mm. Model 1 has a length height ratio of 1.5 approximately and model 2 has a length height ratio of 2.1 approximately. Harmonic waves of 2.5 Hz, 5 Hz and 10 Hz of frequency respectively were used as input motion. The amplitudes of the waves were increased gradually until the collapse of the models.

Figure 1 shows the collapse progress of the model 1. The direction of the shaking is perpendicular to the objective wall which appears in the front of the figure. Since the length of the wall is relatively small, the out-of plane collapse occurs together with the shear (sliding) failure of the transversal walls.

Figure 1. Collapse pattern of model 1 (length height ratio = 1.5)

Figure 2. Collapse pattern of model 2 (length height ratio = 2.1)

In Figure 2 the collapse pattern of model 2 is presented. It can be observed that the failure of the starts in the central upper part of the wall. The out-of plane behaviour is dominant as can be appreciated in the final stage of the test where the objective wall has failed completely while the transversal walls (shear sliding) still remain.

This small size shaking table test could be to understand the collapse mechanism of unreinforced masonry walls and due to its portability could be use also as educational tool for structural analysis courses.

3. FULL SCALE SHAKING TABLE TEST

Full scale masonry test specimen was constructed with length height ratio approximately equal to 2. This ratio is the limit specify in many masonry code to ovoid the checking of the out-of plane behavior of the masonry wall. That is than when this ratio is smaller than 2 verification of the out-of-plane behavior of the masonry is not required. These criteria probably have been established from experience of behavior of masonry during past earthquakes and therefore some theoretical and experimental validation is required.

Figure 3 shows the general layout of the specimen where the wall B is the target wall to investigate its out-of-plane behavior, while walls A and C are perpendicular or transversal walls to resist the shear force originated by the horizontal input motion. As can be observed the specimen is constructed of unreinforced brick masonry. To facilitate the investigation and to induce more easily the out-of-plane behavior of the target wall, weak mortar with a cement-sand ratio of 1:6 was used to construct the specimen. The response of the specimen to the input motions was monitored by means of accelerometers distributed on the walls surfaces. In addition " π " shape displacement transducer were set up at selected places were large strain was supposed to occur.

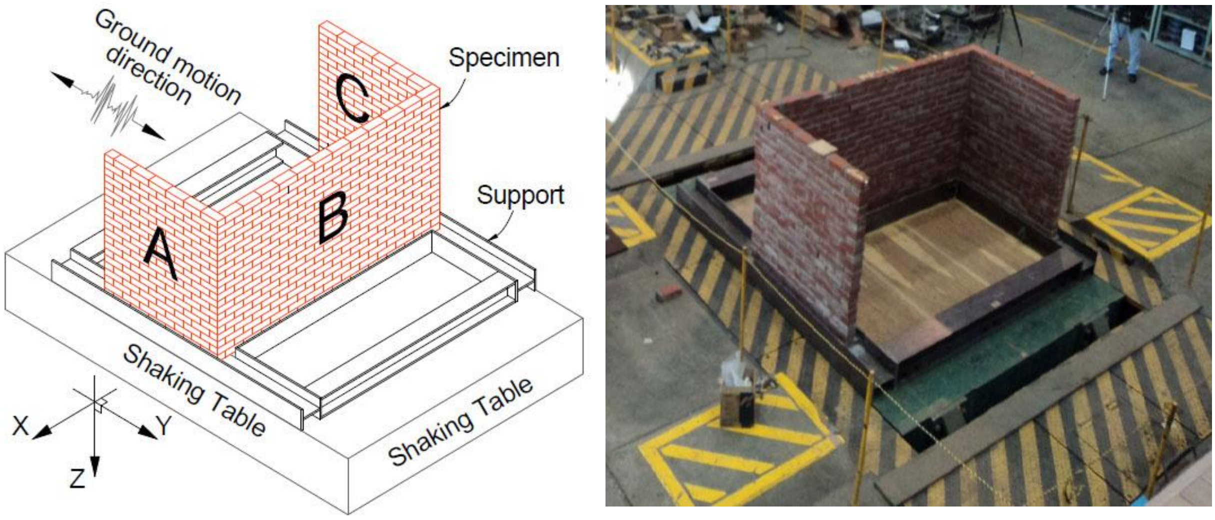

Figure 3. Full scale specimen layout and photo of the specimen on the shaking table

A series of input motion were used to test the specimen until the collapse of the target wall. In table 1 the list of the input motion are shown. In total 20 runs were employed to obtain the vibration characteristics of the specimen and to investigate the collapse mechanism of the target wall (out-of-plane behavior). Sweep waves correspond to harmonic signals with constant amplitude that change their frequencies constantly from specified lower value until specified upper value. With this frequency sweeping it is possible to detect the resonance frequency and therefore the predominant frequency of the specimen. In the case of the random wave the frequency content of the signal is randomly selected however these frequencies fall between specified values.

The maximum response corresponds to the response of the central upper part of the target wall (wall B). Using the data obtained in this point, the out-of-plane vibration characteristics of the specimen is investigated and the variation of the predominant frequency during the test series was obtained. This change of the frequency is shown in Figure 4 where a decreasing frequency is observed according to the progress of the test runs. This decreasing indicates the progressive deterioration of the specimen according to the successive input motions.

Table 1. List of input motions for full scale shaking table tests

Test Number	Type of input	Frequency (Hz)	Amplitude (mm)
1	sweep wave	0.8 - 20	0.5
2	sweep wave	0.8 - 20	0.5
3	sweep wave	0.8 - 20	0.5
4	random wave	5 - 20	0.5
5	random wave	5 - 20	10
6	random wave	12 - 20	5
7	random wave	12 - 20	5
8	random wave	12 - 20	10
9	random wave	12 - 20	15
10	random wave	10 - 15	5
11	random wave	10 - 15	10
12	random wave	10 - 15	15
13	sweep wave	0.8 - 20	0.5
14	random wave	5 - 15	10
15	random wave	5 - 15	20
16	random wave	5 - 10	20
17	random wave	5 – 10	30
18	random wave	5 – 10	40
19	random wave	5 – 10	50
20	random wave	3 - 8	70

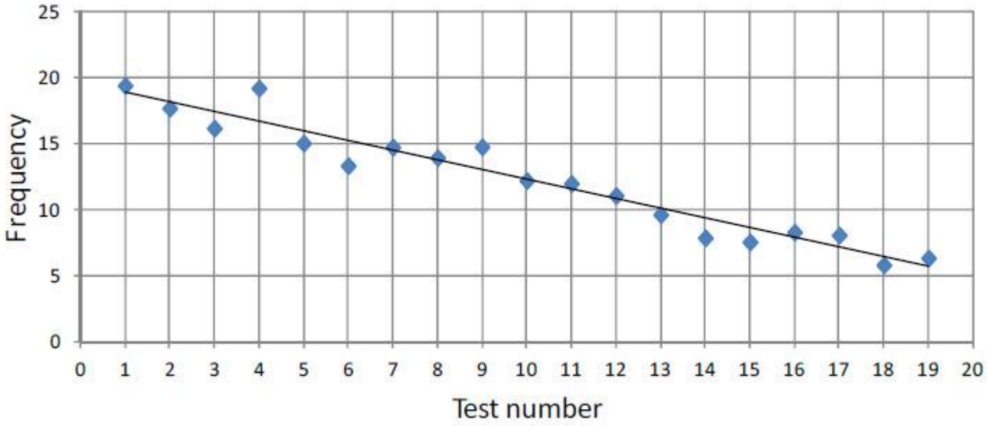

Figure 4. Decreasing of the predominant frequency with the successive dynamic loading

The crack pattern was recorded for each run and in Figure 5 the corresponding condition after test 10 and test 20 are presented. After test 19 the crack pattern indicates that the cracks started at the top central part of the wall B and then propagate diagonally. Therefore in the upper part of the wall is formed a portion that is separated from the bottom part and this portion will collapse. The collapse of this portion can be observed in the figure corresponding to after the test 20. Similarly in this figure a larger separated portion was formed and imminent collapse of this portion is evident.

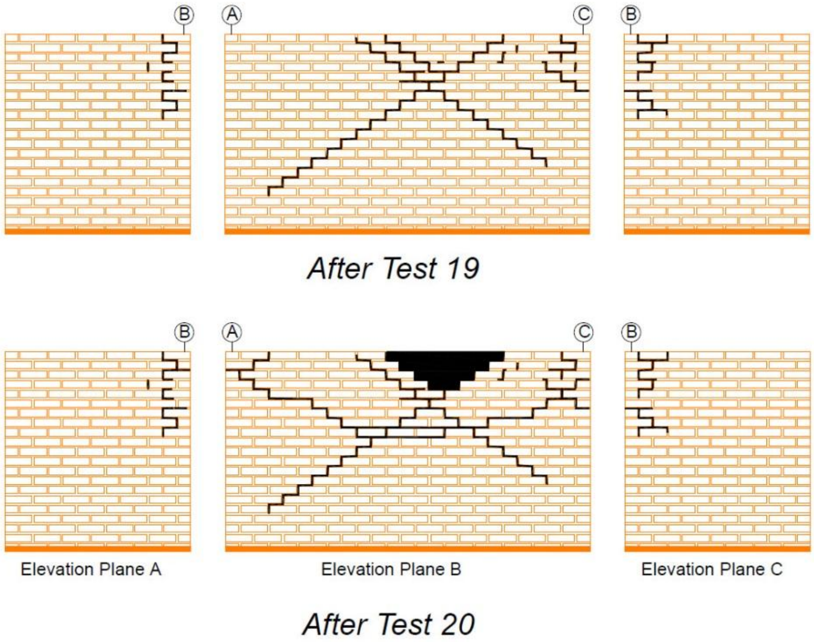

Figure 4. Crack and collapse pattern during shaking table test series

4. DISCRETE ELEMENT METHOD FOR COLLPASE SIMULATION

To simulate the collapse of unreinforced masonry structures (walls), computer application was developed for this purpose. The program is called STERA-BRIQ and is based on discrete element method where the masonry is simulated as brick units connected by springs that simulate the mortar. The springs consider normal stress behaviour and shear stress behaviour and the collapse is originated when the strain of the springs exceed specified limits.

Figure 6 shows the main window of the application where the model can be constructed interactively and after compiling the data collapse pattern can be analysed.

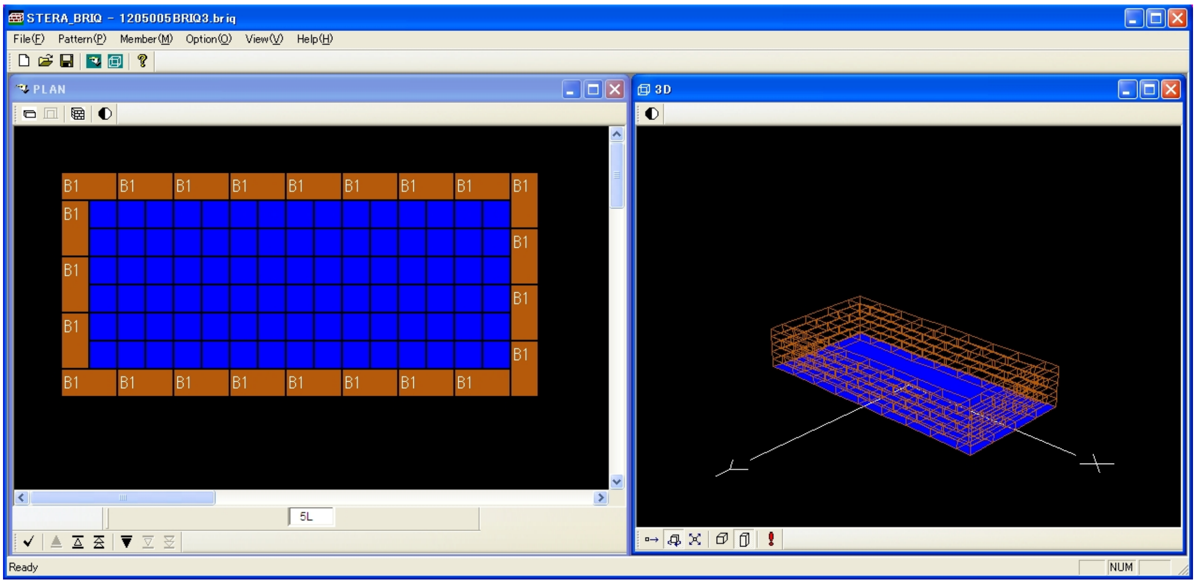

Figure 6. Main window of the application for collapse simulation of masonry structures

The computer program for collapse simulation was used first to verify the test of the small models on small size shaking table. Since the specimens consist of wooden blocks without mortar, values close to cero was considered for spring characteristics. In Figure 7 the collapse simulation of the model 2 is presented. In general the analysis results resemble well the collapse pattern that was observed during the experimental test on small size shaking table.

Figure 7. Collapse simulation of small specimen on small size shaking table

In the case of full scale specimen the characteristics of the spring were setup considering the strength characteristics of the mortar. In Figure 8 the analytical collapse pattern is show and compared with the final condition of the specimen after full scale shaking table test series. This condition was obtained by removing the upper part of the specimen which, as was described previously, represents the portion of imminent collapse.

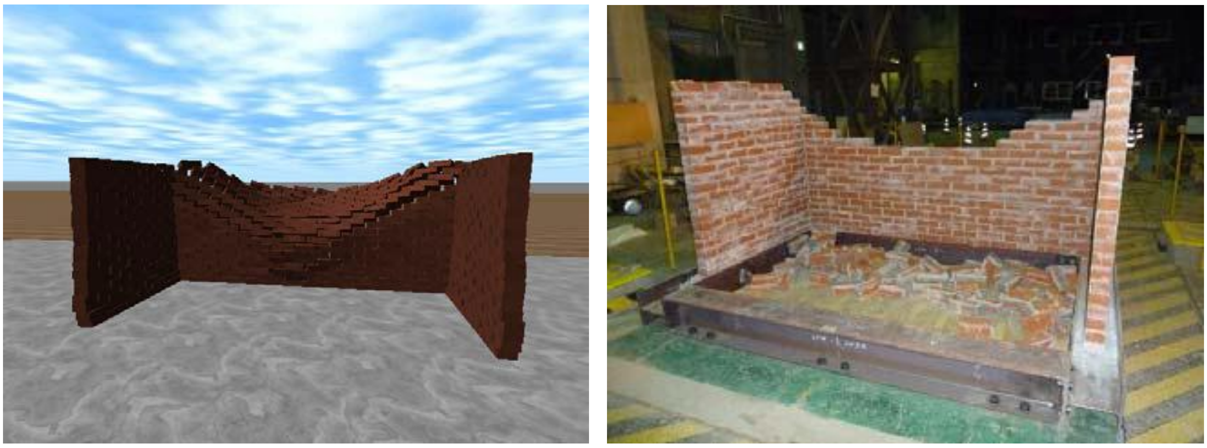

Figure 8. Comparison of analytical collapse and final condition of test after shaking table test series

5. CONCLUSIONS

Small shaking table test and full scale test were carried out to investigate the out-of-plane behaviour of unreinforced masonry walls. These test were used to calibrate and validate the collapse simulation computer program develop in this study.

As initial step, the characteristics of the collapse pattern of unreinforced masonry were verified by means of shaking table test of small size model constructed with small wooden blocks and without mortar. For small wall length, it was found that the collapse starts with the in plane failure of the perpendicular walls that are used to restrain the test or target wall. For large wall length, the failure starts with the collapse of the upper part of the wall like a failure by bending of a slab with 3 restrained borders. This test on small specimens could be used to clarify the out of plane behavior of masonry walls as could be used also as an educational tool to understand the collapse mechanism of unreinforced masonry.

Shaking table test of a full size masonry wall was conducted in Building Research Institute to confirm the collapse behavior observed by the small size model. The specimen was subjected to a series of input motion until the collapse of the target wall.

From small specimen test result and from full scale shaking table test it was verified that length height ratio affects the collapse pattern of unreinforced masonry walls. A limit value of 2 of this ratio to proceed with the verification of the out-of-plane behaviour could be appropriate and practical value.

Simulation of the collapse of unreinforced masonry walls during earthquake motion is performed by using proposed discrete element model implemented in a computer program develop in this project. The results of simulations are compared with those of shaking table tests for both small size model and real size model and good agreement between analytical and experimental results was observed.

AKCNOWLEDGEMENT

The authors acknowledge JST/JICA, SATREPS for the support of the research for Enhancement of Earthquake and Tsunami Disaster Mitigation Technology in Peru, under which this investigation was conducted.

REFERENCES

Peruvian Ministry of Construction. Masonry Code. *Technical Code E070 for Masonry Constructions in Peru*, 2006 (in Spanish).

Peruvian Ministry of Construction. Adobe Code. *Technical Code E080 for Adobe Masonry Constructions in Peru*, 2006 (in Spanish).

K. Sugiyama, C. H. Cuadra and Y. Fujiwara. Characteristics of peak acceleration and attenuation during the 2008 Iwate-Miyagi earthquake. *Proceedings of the 14th European Conference on Earthquake Engineering*, August 30 ~ September 3, 2010, Ohrid, Macedonia.

Cuadra, C. and Tokeshi, J. Lessons learned from the 2007 Pisco earthquake (Peru) and recommendations for disaster mitigation. *Proceedings of the The 14thWorld Conference on Earthquake Engineering*, October 12-17, 2008, Beijing, China

A. Gupta and B.M. McDonald. Performance of building structures during the October 15, 2006 Hawaii earthquake. *Proceedings of the The 14thWorld Conference on Earthquake Engineering*, October 12-17, 2008, Beijing, China

J. Kanai, K. Tokeshi, C. Cuadra, and M.B. Karkee. (2006). Vibration characteristics of buildings using microtremor measurements. *First European Conference on Earthquake Engineering and Seismology (a joint event of the 13th ECEE & 30th General Assembly of the ESC)*, Geneva, Switzerland, 3-8 September 2006, Paper Number: 708.

C. Cuadra, Y. Sato, J. Tokeshi, H. Kanno, J. Ogawa, M. B. Karkee & J. Rojas. (2005). Evaluation of the dynamic characteristics of typical Inca heritage structures in Machupicchu. *Ninth International Conference on Structural Studies, Repairs and Maintenance of Heritage Architecture, STREMAH IX*, Malta, Jun. 2005, pp. 237-244.

Sunuwar, L., Karkee, M., Tokeshi, J., and Cuadra, C. Applications of GIS in Probabilistic Seismic Hazard Analysis of Urban Areas. *Proc. Of the Fourth International Conference of Earthquake Engineering and Seismology*, Tehran, Iran, 2003.