Paper:

Experimental Study on Dynamic Behavior of Unreinforced Masonry Walls

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The dynamic behavior of an unreinforced masonry wall is investigated through a shaking table test of two specimens. In order to represent a non-engineering one-story house, the first specimen consists of a C-shaped structure with masonry walls connected only at their ends. The second specimen is built to represent an upper story, so the C wall is connected at the top by a wooden diaphragm floor, and a weight is suspended onto it. The test results show each specimen exhibits different behaviors. In the first specimen, an out-of-plane failure mode governs. In the second specimen, a shear failure mode governs.

Keywords: masonry wall, shaking table test, out-of-plane failure

Fig. 1. URM house.

Fig. 2. Building with URM wall.

1. Introduction

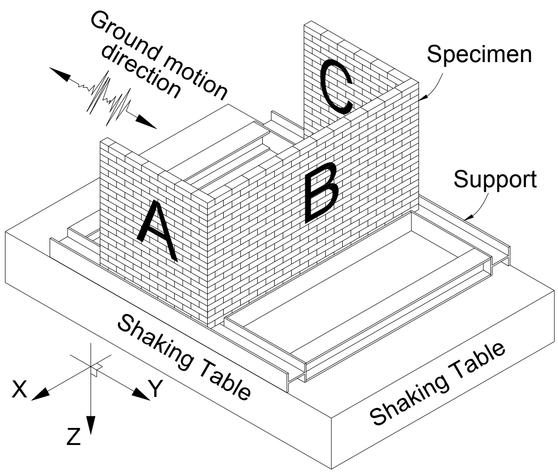
The main reason behind the extensive earthquake damage in developing countries is the collapse of unreinforced masonry (URM) houses. Because of large variations in material properties and construction accuracy, as well as the brittle characteristics of brick materials, it is very difficult to develop engineering models of masonry buildings.

A fundamental purpose of this study is to mitigate the seismic hazard of URM walls. This concern is relevant to Peru because residential buildings located in areas with low economic resources are mostly non-engineering houses. **Fig. 1** illustrates a non-engineering house built with URM walls and without a floor diaphragm. **Fig. 2** illustrates typical URM exterior walls of a masonry building, which could injure people around it when they collapse during an earthquake.

As for in-plane failure properties, a number of static experiments have been done to capture failure mode. For out-of-plane failure properties, since both inertia forces from the floor and the wall panel must be produced, it is necessary to carry out shaking table dynamic experiments rather than static experiments. Very few such studies have been done.

The most extensive research on URM buildings was developed by ABK Joint Venture [1, 2]. It was developed based on structural systems with a flexible wood diaphragm. It is the primary source of guidelines developed by the Federal Emergency Management Agency [3–5]. The weakest shape of failure in URM walls is the out-of-plane failure; in those tests it consisted of horizontal cracks located at the bottom, top, and around the middle wall.

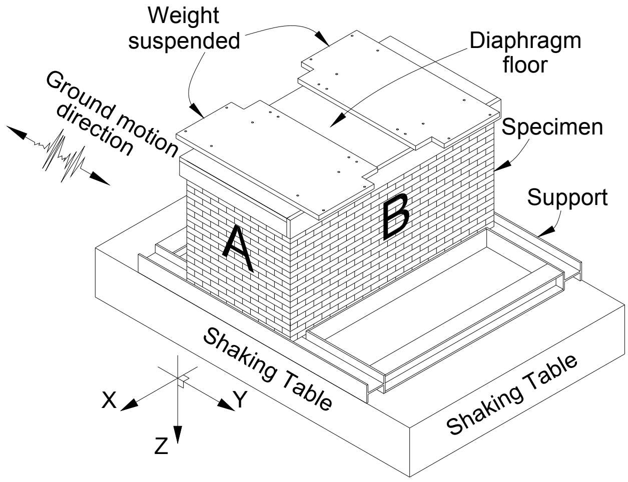
An URM building model that included a floor diaphragm as well as in-plane and out-of-plane wall components was developed by Simsir et al. [6]. In that test, the in-plane and out-of-plane walls were connected only



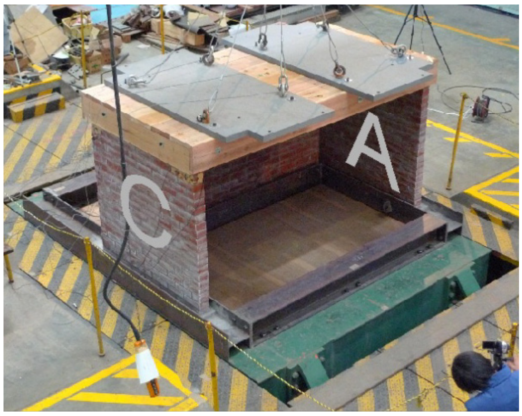
(a) Scheme of the test set up

(b) Specimen of the shaking table

Fig. 3. The first specimen (specimen without floor).



(a) Scheme of the test set up



(b) Specimen of the shaking table

Fig. 4. The second specimen (specimen with floor).

(a) Compression

(b) Shear

Fig. 5. Test of masonry prism.

Fig. 6. Connection between wall and diaphragm.

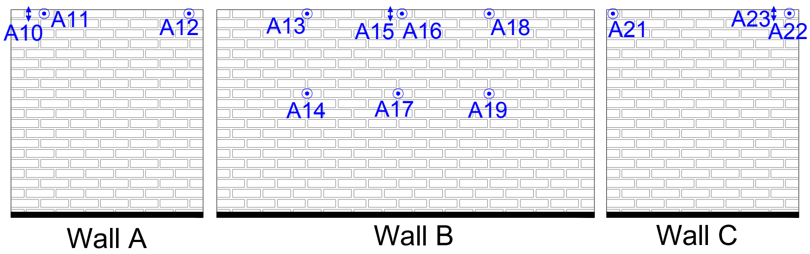
by the flexible diaphragm, and an axial load was applied to the out-of-plane walls. Instead of the mid-height horizontal crack observed in ABK research and others, a horizontal crack located at approximately 70% of the wall height from the base was observed.

This paper summarizes a study that aimed to improve understanding of the interaction between in-plane and out-of-plane walls when they are connected by their ends (i.e., when they have continuity at the corners). The wall test was carried out in the Structural Engineering Laboratory at the Building Research Institute, Japan.

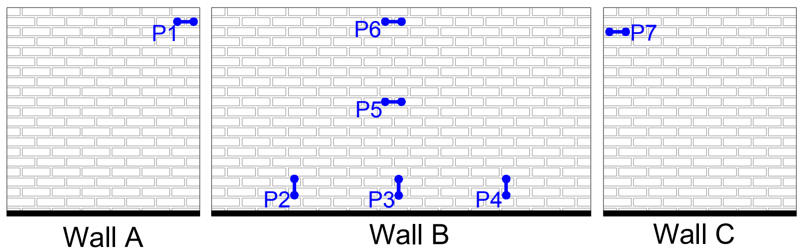
2. Shaking Table Test

In January 2012, two specimens were constructed on the shaking table of the Structural Engineering Laboratory at the Building Research Institute. **Figs. 3** and **4** illustrate the idealized models, which represent a URM wall of a single-story building and an upper level of a multistory building, respectively. Each specimen consists of three masonry walls: A, B, and C.

The wall B was 1440 mm high × 2850 mm wide × 100 mm thick. The orthogonal walls (A and C) were



(a) Accelerometers



(b) Pi-gages

Fig. 7. Instrumentation for the wall test.

Table 1. Shake table runs and recorded peak values for the 1st specimen.

Test	Type wave	Frequency (hz)	Amplitude (mm)	Peak Table Acceleration (g)	Displacements (mm)		Accelerations (g)	
					Top	Mid-height	Top	Mid-height
1	sweep	0.8 - 20	0.5	0.01	0.13	0.09	0.05	0.03
2	sweep	0.8 - 20	0.5	0.43	2.74	1.75	2.15	1.56
3	sweep	0.8 - 20	0.5	0.40	2.31	1.83	2.02	1.37
4	random	5 - 20	0.5	0.02	0.21	0.15	0.11	0.08
5	random	5 - 20	10.0	0.67	3.34	2.92	3.10	2.18
6	random	12 - 20	5.0	0.28	1.21	0.77	0.88	0.45
7	random	12 - 20	5.0	0.24	1.33	0.76	1.06	0.47
8	random	12 - 20	10.0	0.67	2.75	1.7	2.31	0.88
9	random	12 - 20	15.0	1.21	4.93	2.56	5.01	1.41
10	random	10 - 15	5.0	0.17	1.58	0.62	1.18	0.23
11	random	10 - 15	10.0	0.39	3.16	1.41	1.96	0.55
12	random	10 - 15	15.0	0.66	7.46	2.78	3.33	0.97
13	sweep	0.8 - 20	0.5	0.25	3.12	1.03	1.47	0.33
14	random	5 - 15	10.0	0.70	4.91	2.01	2.69	1.17
15	random	5 - 15	20.0	1.01	8.39	4.12	5.00	1.50
16	random	5 - 10	20.0	0.45	7.68	2.93	2.45	0.91
17	random	5 - 10	30.0	0.60	9.39	3.38	3.24	1.22
18	random	5 - 10	40.0	0.73	12.94	5.17	4.89	1.69
19	random	5 - 10	50.0	1.18	11.49	6.18	5.73	2.59
20	random	3 - 8	70.0	---	---	---	---	---

1440 mm high × 1450 mm wide × 100 mm thick. The above dimensions give a slenderness ratio of 14.4.

Solid bricks and type O mortar (cement : sand ratio of 1 : 6) were used in the specimen. The average compression strength of the masonry prism with four bricks was found to be 6.09 MPa from the test, as shown in **Fig. 5(a)**. Diagonal compression tests according to the ASTM E519 were carried out on 430 mm × 410 mm specimens, as shown in **Fig. 5(b)**. The average shear strength of the masonry was found to be 1.28 MPa.

The specimen was constructed on a steel frame support and hoisted up to set on the shaking table. The first specimen has no floor at the top. On the other hand, the second specimen has a wooden diaphragm floor and steel weights at the top. The diaphragm was connected to the masonry wall by sandwiching it between two plates as shown in **Fig. 6**.

The ground motion was applied perpendicular to wall B. Therefore, walls A and C would behave in-plane and wall B would behave out-of-plane. In the second speci-

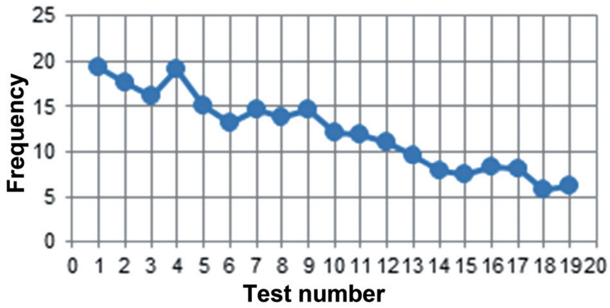


Fig. 8. The first natural frequency of the 1st specimen.

men, a constant axial load of approximately 18kN was applied by means of steel weights suspended over the floor diaphragm

Fourteen accelerometers, seven pi-gauges, and a data acquisition system were used to record the dynamic characteristics of the walls in the specimens.

Figure 7(a) shows the positions of the accelerometers. The A10, A15, and A23 accelerometers recorded vibrations in the up-down direction, and all the others recorded vibrations in the direction perpendicular to the wall where they were located. Assuming that the wall "B" would fail due to out-of-plane behavior, it was decided that the pi-gauges would be arranged as illustrated in **Fig. 7(b)**.

Most of the accelerometers were placed on wall B because previous researchers showed the out-of-plane mode of failure to be the weakest. Three additional accelerometers were placed over the floor diaphragm for the second specimen. One accelerometer located at the middle of the diaphragm recorded acceleration in the same direction as the shaking table, and the other two accelerometers, which were located at the ends, recorded up and down acceleration.

3. Test Procedure and Results

3.1. First Specimen

A total of twenty unidirectional signals were applied at the base of the first specimen. For each test, the type of signal, the amplitude of the table shake, the peak table acceleration, the maximum measured displacement, and acceleration at the top and mid-height of Wall B are given in **Table 1**. The displacements shown are relative to the base; the accelerations are absolute values.

Two types of signals were applied over the tests: the frequency sweep test and frequency random test. The frequency sweep test was useful to monitor the shift in the natural frequency of Wall B. As a result of the damage caused in the specimen during the tests, the natural frequency of the specimen decreased continuously. As shown in **Fig. 8**, which is the record of the accelerometer placed at the middle top of Wall B, the natural frequency decreased from an initial value of 19.34 Hz to 6.29 Hz by the end of the 19th dynamic test run.

Although most cracks were observed over the out-of-plane wall component, the crack patterns before the failure were different from those in previous investigations. As shown in **Fig. 9**, the first cracks were observed after the 5th test, and they were located at the middle top of Wall B and also at the tops of the corners. After the 9th test, the initial cracks became wider, and a diagonal crack appeared over Wall B. Such a diagonal crack had not been seen in previous research. Another diagonal crack appeared in the same wall after the 19th test.

Besides, the cracks located at the upper corners became larger, and they reached the half-height of the wall. Finally, when the connections between in-plane and out-of-plane walls were partially lost, a horizontal crack formed at the middle of the wall; this wall corresponds to the collapse of the specimen (see **Fig. 10**).

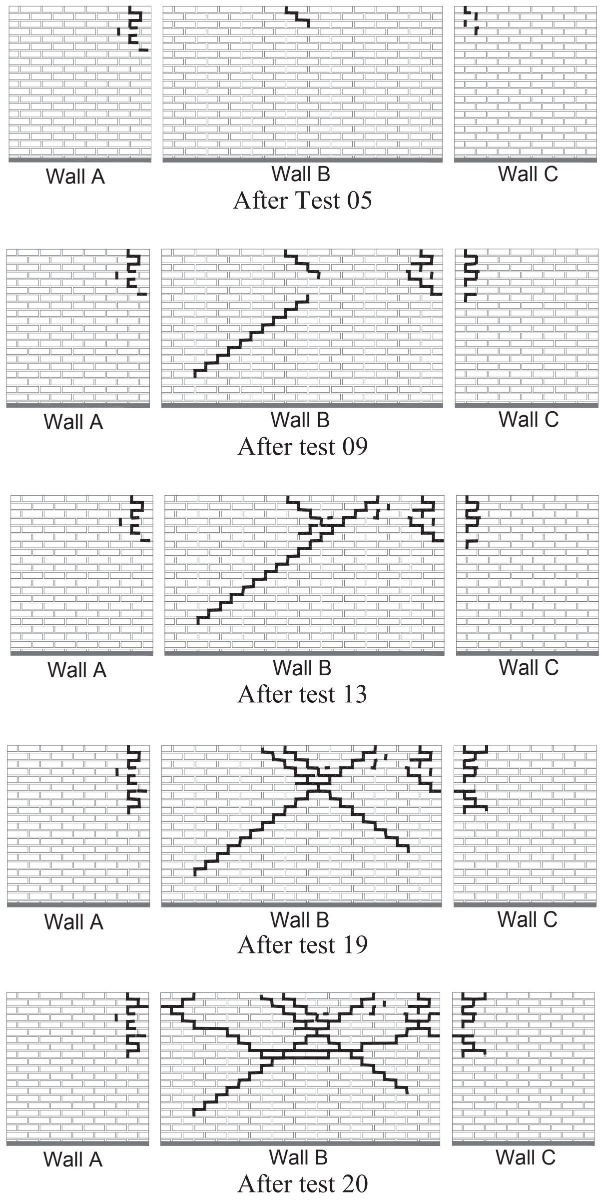


Fig. 9. Crack patterns developed in the 1st specimen.

Table 2. Shake table runs and recorded peak values for the 2nd specimen.

Test	Type wave	Frequency (hz)	Amplitude (mm)	Peak Table Acceleration (g)	Displacements (mm)		Accelerations (g)	
					Top	Mid-height	Top	Mid-height
1	sweep	0.8 - 20	0.5	0.15	0.91	0.48	0.33	0.23
2	sweep	0.8 - 20	0.5	0.15	1.37	0.21	0.33	0.24
3	random	5 - 20	0.5	0.02	0.14	0.10	0.04	0.03
4	random	10 - 15	0.5	0.01	0.11	0.13	0.02	0.02
5	random	10 - 15	2.0	0.04	0.27	0.10	0.10	0.07
6	random	10 - 15	10.0	0.23	1.31	0.42	0.59	0.49
7	random	10 - 15	15.0	0.52	1.92	1.17	0.94	1.13
8	random	10 - 15	15.0	0.90	2.06	1.45	0.98	2.89
9	random	12 - 15	20.0	0.78	3.38	1.36	0.90	2.25
10	Kobe earthquake	---	0.2*	0.19	13.87	0.13	0.20	0.20
11	random	12 - 15	20.0	1.13	2.66	1.44	1.16	2.72
12	sweep	0.8 - 20	0.5	0.17	0.97	0.29	0.33	0.49
13	random	5 - 15	30.0	1.35	5.27	2.38	1.14	4.19
14	random	5 - 15	30.0	1.44	4.25	2.99	1.09	4.32
15	random	5 - 15	30.0	1.82	4.20	5.45	0.96	3.65
16	sweep	0.8 - 20	0.5	0.20	1.18	0.86	0.22	0.43
17	random	5 - 15	30.0	1.52	4.70	6.25	1.08	3.96
18	random	5 - 15	40.0	1.97	5.32	9.04	1.17	4.75
19	random	5 - 15	40.0	2.11	4.87	6.34	0.89	4.73
20	random	5 - 15	40.0	2.05	5.24	8.18	1.10	4.96
21	random	5 - 10	50.0	---	---	---	---	---
22	Kobe earthquake	---	0.5*	---	---	---	---	---

Fig. 10. Shape of failure of the 1st specimen.

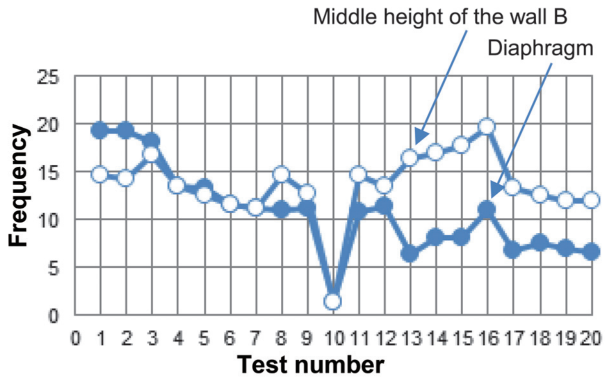


Fig. 11. The first natural frequency of the 2nd specimen.

3.2. Second Specimen

A total of 23 unidirectional signals were applied at the base. **Table 2** shows the type of signal, the amplitude of the table shake, the peak table acceleration, the maximum measured displacement, and acceleration at the top and mid-height for the second specimen. However, while the values of displacement and acceleration at the top are from the wooden diaphragm, the values at mid-height are from Wall B.

There is no information on the maximum values of displacement or acceleration for tests 21 and 22 because the accelerometers had been removed prior. Three types of signals were applied over the tests: a frequency sweep test, a frequency random test, and a Kobe earthquake test. As mentioned above, a frequency sweep test was used to ascertain the shift in the natural frequency of the specimen.

The change in the natural frequency can be used as a trace of the damage caused in the specimen. **Fig. 11** illustrates how the natural frequency of the accelerations recorded over the diaphragm decreased. However, the natural frequency recorded at the mid-height of Wall B did not decrease significantly.

This time, most of the cracks developed in the in-plane walls. It seems that the axial load produced by the weight suspended at the top improved the flexural strength of Wall B.

Furthermore, the floor diaphragm and the roof provided a type of confinement. As shown in **Fig. 12**, at the beginning, the crack patterns that developed over the in-plane wall components were totally different. After the 15th

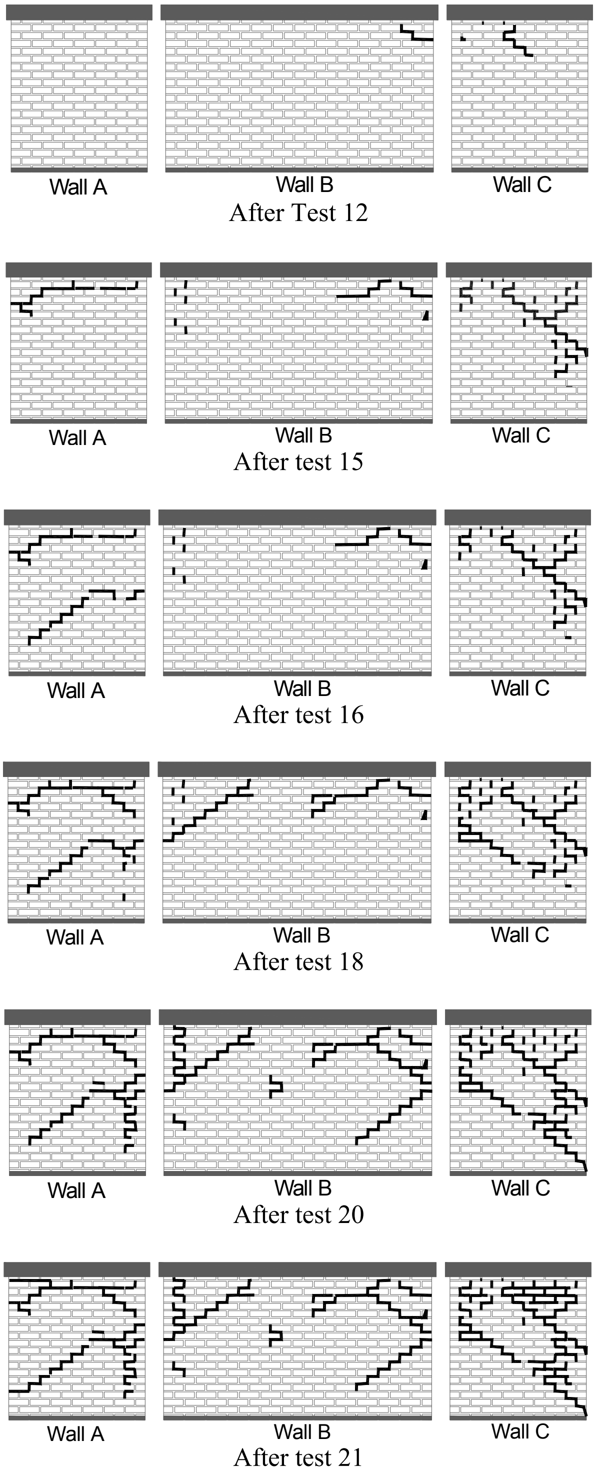


Fig. 12. Crack patterns developed in the 2nd specimen.

test, a bed-joint sliding on a horizontal plane located at the top developed in Wall A. Meanwhile, a sliding on a stair-stepped diagonal crack developed in Wall C. Due to the difference in behavior between the in-plane wall components, torsional movements developed in the specimen. After the 18th test, diagonal cracks, which began in the in-plane walls and ended up on wall B, developed because of the torsional behavior. Finally, the shape of failure can be seen in **Fig. 13**.

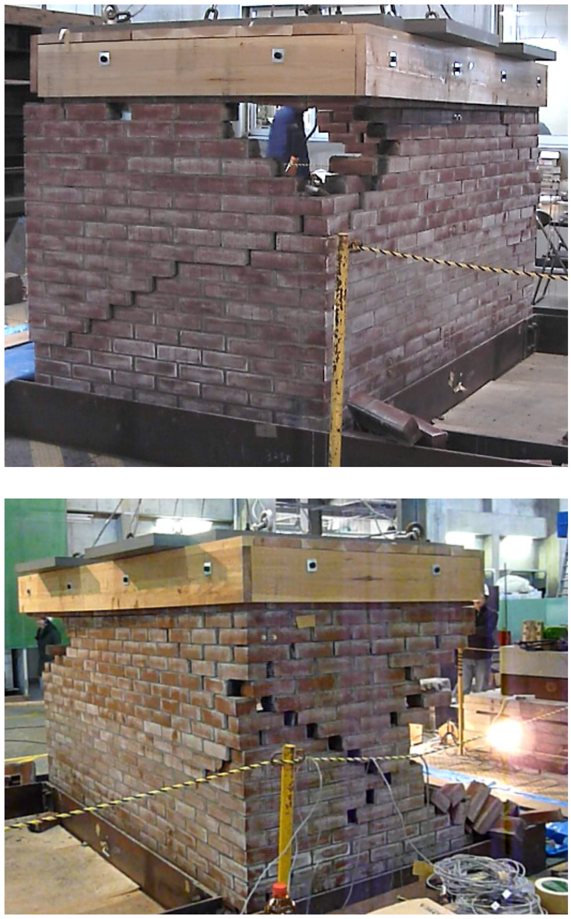


Fig. 13. Shape of failure of the 2nd specimen.

4. Conclusions

The interaction between the in-plane and out-of-plane components of a URM wall when they are connected by their ends (corners) has been studied. To do this, two specimens were tested on a shaking table.

The shape of failure of the first specimen, which simulated a single-story building, was found to be out-of-plane. However, at the beginning, the crack patterns were different than those in the previous research due to the influence of the in-plane walls.

On the other hand, the damage in the second specimen was observed on the in-plane walls. It is presumed that the floor diaphragm and the axial load produced by the weight suspended at the top enhanced the stability of the out-of-plane wall component.

As happened in the second specimen, the possibility of different modes of behavior in the in-plane wall components of a building produced torsional movements. Besides, the URM walls have several shear behavior modes, such as wall-pier rocking, bed-joint sliding, spandrel-joint sliding, and rocking/toe crushing, among others.

Almost all the cracks observed were located in the mortar. The brick units did not break. Therefore, analytical models based on simulations of rigid body dynamics could give us a good estimate of the dynamic behavior of URM buildings.

Acknowledgements

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References:

[1] ABK, "Methodology for Seismic Hazard in Existing Unreinforced Masonry Buildings: Wall Testing, Out-of-Plane, Topical Report 04," ABK Joint Venture, California, December 1981.

[2] ABK, "Methodology for Seismic Hazard in Existing Unreinforced Masonry Buildings: The Methodology, Topical Report 08," ABK Joint Venture, California, January 1984.

[3] FEMA 306, "Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Basic Procedures Manual," Federal Emergency Management Agency, Washington, D.C., 1999.

[4] FEMA 307, "Evaluation of Earthquake Damaged Concrete and Masonry Wall Buildings, Technical Resources," Federal Emergency Management Agency, Washington, D.C., 1999.

[5] FEMA 356, "Prestandard and Commentary for the Seismic Rehabilitation of Building," Federal Emergency Management Agency, Washington, D.C., 2000.

[6] C. C. Simsir, M. A. Aschheim, and D. P. Abrams, "Out-of-Plane Dynamic Response of Unreinforced Masonry Bearing Walls Attached to Flexible Diaphragms," 13th World Conference on Earthquake Engineering, Vancouver, B.C., 2004.

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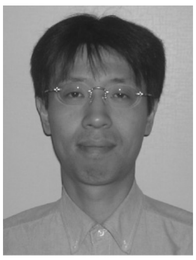

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