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EXPERIMENTAL INVESTIGATION OF HOLLOW BRICK UNREINFORCED MASONRY BUILDING RETROFITTED BY FERROCEMENT LAYERS

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ABSTRACT: A retrofitting method for hollow brick Unreinforced Masonry (URM) buildings has been developed using ferrocement layers with the bandage system. An experimental study on hollow brick URM houses with and without ferrocement layers was conducted. Two specimens of a quarter-scale hollow brick house model consisting of four walls with the size 104cm x 110cm were constructed. The first model (B1) is the original hollow brick URM house without mortar plaster, and the second model (B2) is the same masonry house retrofitted by providing bandage ferrocement layers on both sides of the walls, which act as sandwich structures. Both specimens were tested by using a shaking table (304x190) cm^2 with input motions from 0.3g to 0.6g. The test results show that the damage to the original URM house model was initially found near the door opening at input motion 0.3g and the applied additional uniform load of 200 kg on the top of the specimen. Then, the cracks were developed and spread to the east side of the wall with the increase of the uniform load, and finally, the house model collapsed at input motion 0.6g and 500 kg additional uniform load. Meanwhile, the hollow brick URM house strengthened by using bandage ferrocement layers shows excellent performance without any damage up to input motion 0.6g. These results indicated that the ferrocement layer significantly enhanced in ductility of the hollow brick URM house model, and it was effective in preventing the collapse of the hollow brick masonry walls when earthquakes happen.

Keywords: Unreinforced masonry (URM) building, Hollow brick, Earthquake, Retrofit, Ferrocement layer

1. INTRODUCTION

Unreinforced masonry (URM) is the most commonly used building material in many other developing countries, including Indonesia. Most URM buildings were not specifically designed and built to resist seismic loads [1]. Commonly people use non-engineered buildings for houses, especially those classified as simple residential houses. Non-engineered buildings can be defined as buildings that are built without involving construction experts such as architects and civil engineers [2]. URM houses, as non-engineered buildings, have been damaged in most large past earthquakes due to poorly constructed buildings [3]. Therefore, the knowledge and skills of the builders or workers to build a safe house are important factors in realizing earthquake risk reduction [4].

In general, community houses are built with brick URM masonry buildings, which have a wall thickness of around 10cm, as shown in Fig.1 [5]. The hollow brick house without reinforcement, as shown in Fig.1, is not strong against earthquake load because the house has no structural elements such as beams and columns and the wall thickness is not in accordance with building standards. The house only has non-structural components such as walls, roof and ceiling. The non-structural component of a simple building is not part of the main load working on a structure, but this component can be the main cause of earthquake losses [6]. Hollow brick has a very heavy material because it is made of mortar. The behavior of the hollow brick material is brittle and it has almost no ductility, so the simple building of this brick wall has no resistance to horizontal load or earthquake load that occurs. Therefore, when an earthquake occurs, this building can collapse unexpectedly (Fig.2). For economic aspects, some of the people who have non-engineered houses decided to rebuild the collapsed houses. The better solution is by retrofitting the URM hollow brick houses using ferrocement layers are very efficient, effective, and relatively cheap.

A common method of seismic strengthening of URM buildings is the use of horizontal and vertical strips (known as bandages and splints, respectively) of ferrocement on both sides of walls. The horizontal 'bandages' are applied continuously on all the walls at the lintel, sill, floor, and roof levels, whereas the vertical 'splints' are applied at corners and junctions of walls and along the jambs of the openings [3,8]. Ali [9] studied and adapted steel mesh on masonry walls for strengthening a non-structural masonry wall to avoid collapse in Pakistan. Meguro [10] uses polypropylene band (PP–band) for strengthening URM buildings in developing countries.

Fig.1 Hollow brick community house [5]

Fig.2 Collapse of a hollow brick building [7]

The selection action for home improvement is certainly influenced by economic aspects. For the sake of the realization of a habitable home, some of the people who choose to build a simple house were destroyed first and then rebuilt, but such a solution will cost a lot. Another solution is that a simple house made of hollow brick is reinforced in the form of woven wire mesh. Such a solution is very efficient and effective because the price of wireless is relatively low and the work can be done by a local handyman [11]. In addition, the reinforcement using wire mesh encased in cement mortar or commonly called ferrocement layer can also be done on houses that have been built without reinforcement.

Ferrocement-brick composite consists of brick core and ferrocement casing, which is a form of cement mortar reinforced with steel wire meshes [12]. Ferrocement is a plastering layer (mortar) woven with a wire mesh, so the ferrocement layer has unique properties, such as a high tensile strength-to-weight ratio, superior cracking behavior, lightweight and moldability to any shape [13]. This ferrocement layer is placed in the position of the beam and column as a substitute for the structural elements, or called the bandage system. Boen [14,15] introduced a retrofitting method for non-engineering buildings using ferrocement with wire mesh as strengthening layers and used a sandwich construction analogy. The ferrocement layers consist of mortar and wire mesh, and the wire mesh was encased in the mortar. This retrofitting method uses ferrocement skin layers on walls as bandaging or jacketing [16].

Imai [17] found that the significant effect of retrofitting on the clay brick URM buildings by using a ferrocement overlay as bandaging with galvanized was successfully demonstrated by the shaking table test. Strengthening a clay URM house using full ferrocement layers on both sides of the walls also has been conducted, with the result showing that the ferrocement layers significantly improve the performance of the clay brick URM building [18].

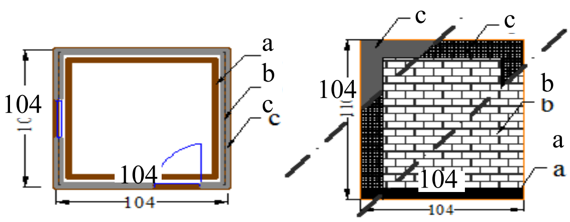
In this study, the behavior of two mortar hollow brick URM houses with and without bandage ferrocement layers on both sides of the walls under the shaking table test was investigated.

2. RESEARCH SIGNIFICANCE

Unreinforced masonry (URM) building is the most common building for residential houses in developing countries. The previous earthquakes proved that the damage and collapse of URM buildings, including residential houses, were caused by the construction, which is not in accordance with the URM earthquake-resistant structures, especially the thickness of the URM walls. In this study, a retrofitting method using a ferrocement layer with a bandage system has been proposed to retrofit the hollow brick URM houses. The behavior of hollow brick URM houses with and without ferrocement layers under simulated seismic loading was investigated. The obtained data and findings will be useful for the design and analysis of the URM houses retrofitted with ferrocement layer.

3. TEST SPECIMENS

Two hollow brick URM house models were built on the shaking table in the soil mechanical laboratory of Andalas University. Both models have a 1:4 scale of the actual building due to the limitation of the shaking table area. The first model (B1) is the original of a URM house, and the second (B2) is the same URM house strengthened by providing bandage ferrocement layers on both walls which act as sandwich structures.



a : U plate (7.5 x 14) cm
b : Masonry hollow brick (10 x 5 x 2.5) cm
c : Ferrocement layer, wire mesh ∅ 1/4”, mortar

Fig.3 Plan and section of the specimen B2

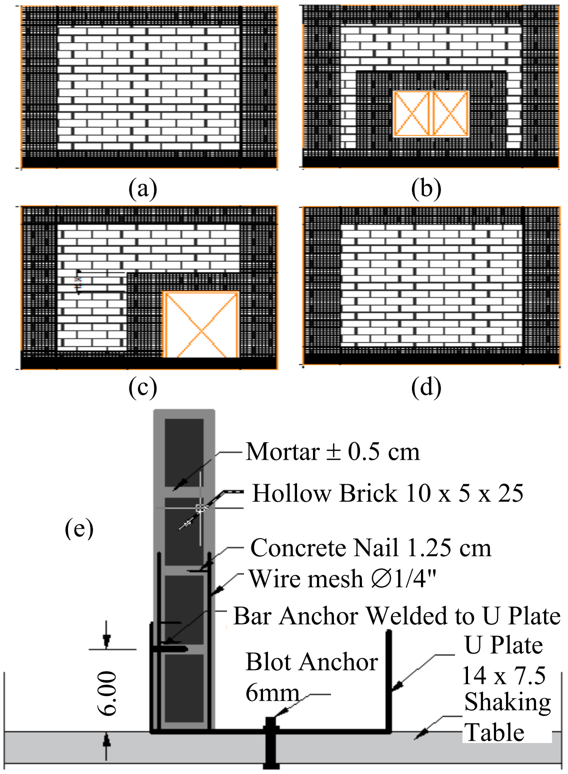


Fig.4 Schematic drawings of the test specimen for model B2, (a) back side wall, (b) left side wall, (c) front side wall, (d) right side wall, and (e) detail section of mortar brick wall with ferrocement layers

Each model consisted of four walls with a size of 1.04m x 1.1m. Figure 3 shows the plan and section of the test specimen for model B2 which is built on the shaking table. Figure 4 shows the schematic drawing of masonry walls for model B2. The masonry walls were made of hollow brick (100x50x25) mm, with a ratio of cement to sand 1/5 by volume, and bonded by using mortar joints with a ratio of cement to sand 1/4 by volume. The thickness of the mortar joints is 5mm. The width of the ferrocement bandage layer is 125mm. The wire mesh was covered by mortar plaster with a thickness of 5mm. The compressive strength of the hollow brick was approximately 2.5 MPa and the compressive strength of mortar to construct the hollow brick wall and ferrocement layer was 9.9 MPa. Figures 5 and 6 show the construction process of specimens B1 and B2.

Fig.5 Construction process of the specimen B1

Fig.6 Construction process of the specimen B2

According to the Indonesian Seismic standard, SNI 1726–2019, clause 7.5.3, the load was applied separately in all two orthogonal directions. The most critical load effect due to the direction of earthquake forces application to the structure is considered to be fulfilled if the components and foundations are designed to carry the following set load combinations: 100 percent force for one direction plus 30 percent force for perpendicular directions [19]. Therefore, the slope of the specimens was set up at 16° in the direction of the positive X-axis, as shown in Fig.7.

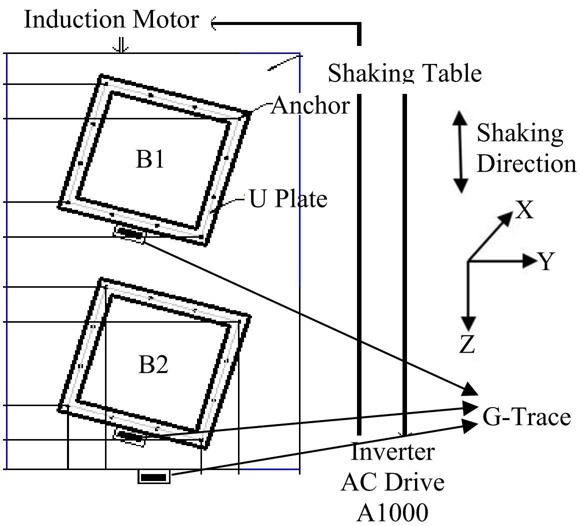


Fig.7 Set-up of specimens on shaking table

4. TEST PROCEDURES

In this study, both specimens were tested by using a horizontal uniaxial movement type of shaking table in the soil mechanic laboratory of Andalas University [20]. Table 1 shows the input motions with varying frequencies of earthquakes, such as the medium earthquake (ME) and strong earthquake (SE), that were used as input motions for this test. The input motion of 0.6g is the Peak Ground Acceleration (PGA) of Padang City based on the Indonesia Earthquake Map 2019.

The excitation is given to the specimens, a = 2.94 m/s^2 and 5.88 m/s^2 for ME and SE, respectively.

Table 1 Variation of the input motions

Type of input motions	a (m/s^2)
ME (0.3g)	2.94
SE (0.6g)	5.88

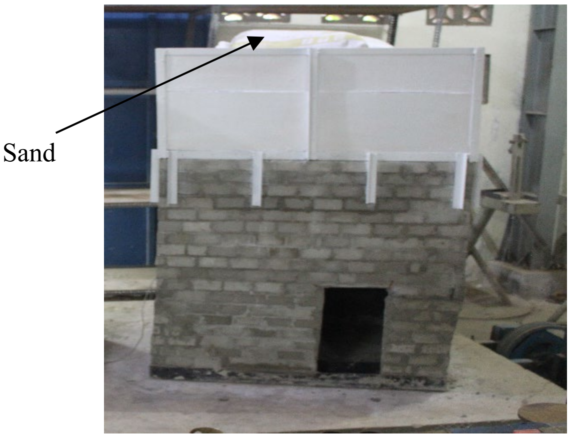


Fig.8 Specimen with additional uniform load using sacks filled with sand (sandbags)

The specimens were tested in five stages. In the first stage (P1), both specimens were tested with ME (input motion 0.3g). For the second until fourth stages (P2-P4), the specimens were tested with an additional uniform load using sacks filled with sand on the top of specimens (Fig.8) that is 200 kg, 400 kg, and 500 kg, respectively. All specimens on P1 to P4 were tested with ME (input motion 0.3g). In the last stage (P5), the specimens were tested with 500 kg additional load and input motion 0.6g until the specimen collapsed.

5. RESULTS AND DISCUSSION

The experimental results presented in this section include the observed failure development and accelerations response of the shaking table that causes the crack on the specimens.

5.1 Test Specimens without Additional Uniform Load (P1)

The result of the first stage test with input motion 0.3g shows that there is no crack appearing on both specimens, as shown in Fig.9. From the analysis, the input motion is not strong enough to damage the specimen.

Fig.9 The specimens without additional uniform loads (P1) after testing

5.2 Test Specimens with 200 kg Additional Uniform Load (P2)

In this test, both specimens were applied an additional uniform load of 200 kg on the top of the specimens and tested by input motion 0.3g. The result shows that cracks started to appear in the door openings at the front walls on specimen B1 (red marker), while specimen B2 with bandage ferrocement layers still survived without any damage, as shown in Figs.10 and 11.

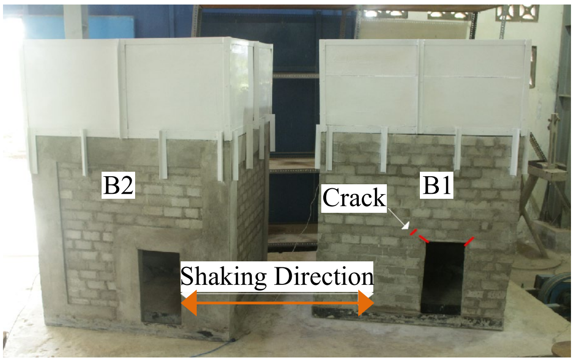


Fig.10 The specimens with 200 kg additional uniform loads (P2) at the front side after testing

Fig.11 The specimens with 200 kg additional uniform loads (P2) at the east side after testing

5.3 Test Specimens with 400 kg Additional Uniform Load (P3)

In this stage, the applied additional uniform load was increased by 400 kg in both specimens while the applied input motion was the same as those with the P1 and P2 tests (0.3g). It can be seen in Figs.12 and 13; the cracks on specimen B1 were developed near the door opening and spread on the east side of the wall (blue marker). Meanwhile, there are no cracks observed on specimen B2.

Fig.12 The specimens with 400 kg additional uniform loads (P3) at the front side after testing

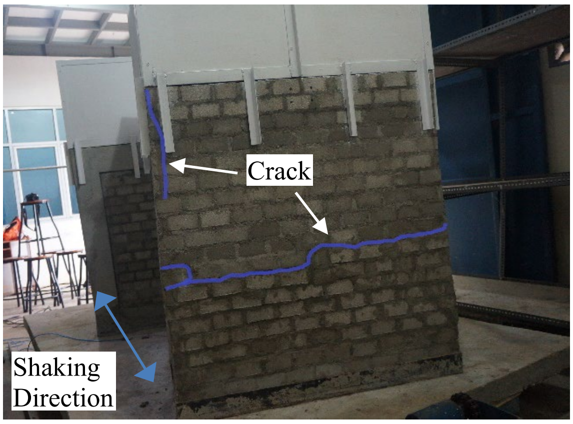


Fig.13 The specimens with 400 kg additional uniform loads (P3) at the east side after testing

5.4 Test Specimens with 500 kg Additional Uniform Load (P4)

In this test, both specimens were applied 500 kg uniform load with input motion 0.3g. In this phase, the cracks on specimen B1 were developed in the same location as the P3 test and other cracks were observed in the walls of the building, especially on the front and the east sides' walls (black marker). Specimen B2, on the other hand, still survived without any damage to the specimen, as shown in Figs.14 and 15.

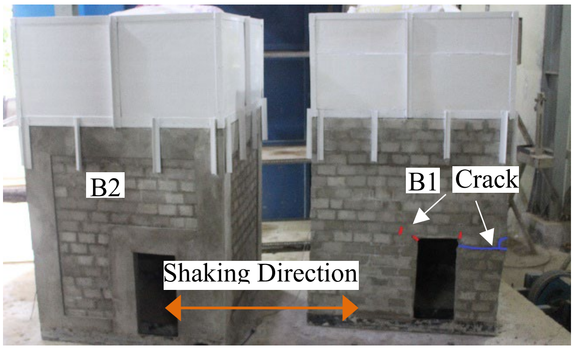


Fig.14 The specimens with 500 kg additional uniform loads (P4) at the front side after testing

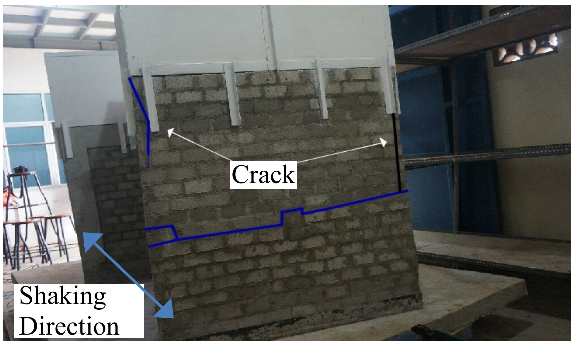


Fig.15 The specimens with 500 kg additional uniform loads (P4) at the east side after testing

5.5 Test Specimens with 500 kg Additional Uniform Load and 0.6g Input Motions (P5)

In order to observe the failure mode of the specimens, the applied input motion was increased by 0.6g while the additional uniform load was the same as those in the P4 test (500 kg). In this stage, the collapse of specimen B1 was observed (4.5 seconds shaking), while no cracks or damage was found on specimen B2, as shown in Figs.16 and 17. This indicates that the ferrocement layers enhance the seismic behavior (ductility) of the URM house and prevent the collapse of the hollow brick URM building even at a big shaking.

Fig.16 The specimens with 500 kg additional uniform loads and 0.6g input motions (P5) at the front side after testing

Fig.17 The specimens with 500 kg additional uniform loads and 0.6g input motions (P5) at the east side after testing

5.6 Acceleration Responses to Cracks

The pattern of the cracks on the B1 specimen was observed based on video camera recording for each step. The failure mechanism for specimen B1 on 0.6g and 500 kg additional load test (P5) can be seen in Fig.18. Figure 19 shows the schematic of the pattern of the crack on specimen B1 until it collapses.

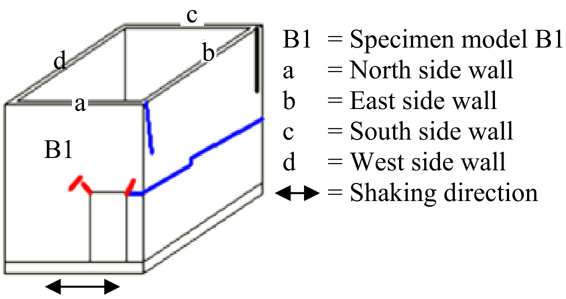


Fig.18 Failure mechanism of specimen B1 on 0.6g and 500 kg additional load test

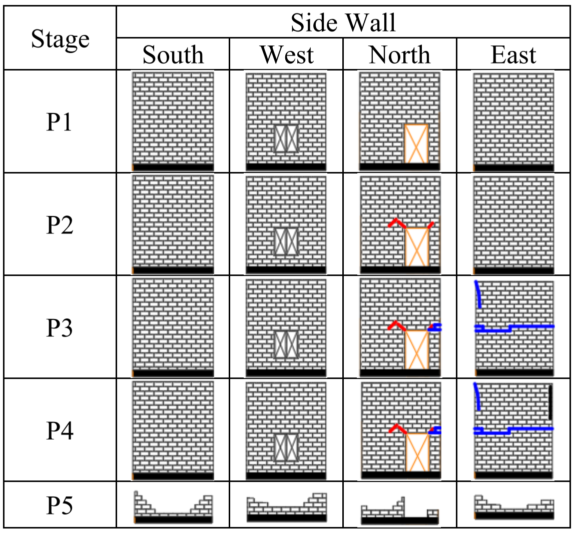


Fig.19 Schematic of cracks pattern on specimen B1

The acceleration response is obtained from the G-trace in the form of an acceleration graph versus time. Figures 20 to 24 show the acceleration response of both specimens on P1–P5 test. In these graphs, the blue lines represent the acceleration response on the shaking table, while the red and green lines represent the acceleration response of specimens B1 and B2, respectively.

In the P1 test (without additional load), both specimens (B1 and B2) have almost the same behavior of the acceleration responses, as shown in Fig.20. This might be due to both specimens still being in the elastic range without any cracks.

The acceleration response on the P2 test shows that at t=10s, the initial crack occurs on specimen B1 near the door openings with a max = -1.1g, as shown in Fig.21. In this stage, the max value of acceleration (a) on the specimen B2 was 0.96g.

For the P3 test, the response of specimen B1 is a little bit different from those in specimen B2 due to the development of cracks and additional new cracks in specimen B1 that occur 2.5 seconds after shaking. Specimen B1 has the maximum value of a = -0.72g, while the maximum value of a for specimen B2 is 0.86g, as shown in Fig.22.

Almost similar behavior with the P3 test was observed on the P4 test, as shown in Fig.23. At the P4 test. The crack appears 25 seconds after shaking. Specimen B1 has the maximum value of a = 0.82g, while in specimen B2, the maximum is 0.82g.

The increase of input motion from 0.3g to 0.6g causes the failure of specimen B1 at t = 4.5 seconds with a maximum of -1.76g (Fig.24). Meanwhile, for specimen B2, with a maximum = 1.8g, there is no crack observed. From Fig.24, the collapse of specimen B1 can be seen at sudden breaks of the response at the beginning of the test.

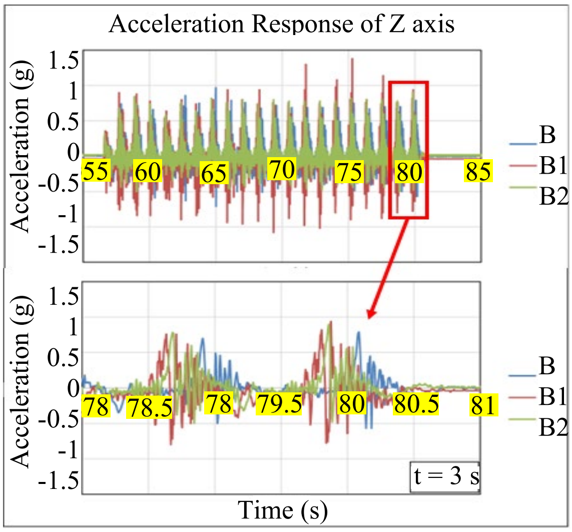


Fig.20 Acceleration response graph for base plat, specimens B1 and B2 without additional uniform loads (P1 test)

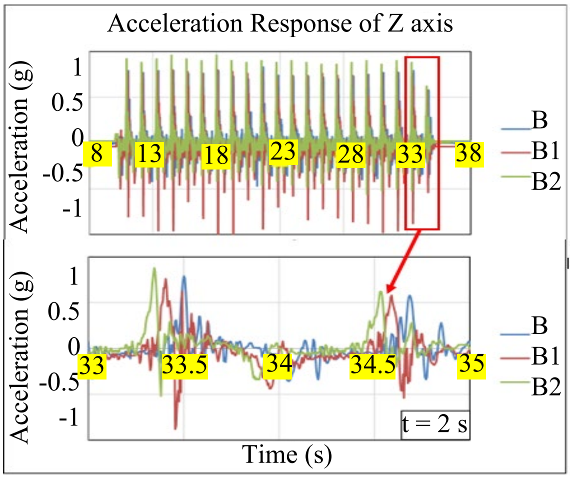


Fig.21 Acceleration response graph for shaking table plat (B), specimens B1 and B2 with 200 kg additional uniform loads (P2 test)

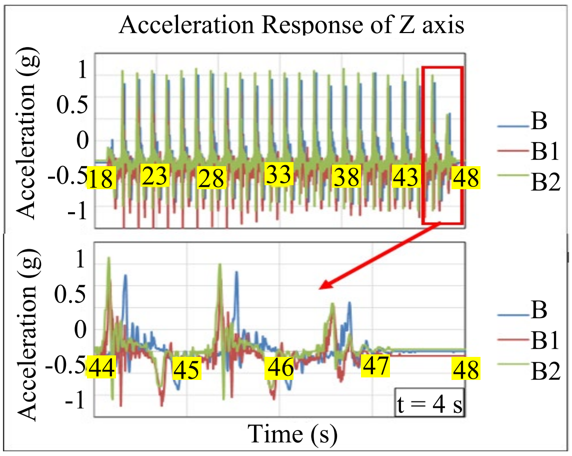


Fig.22 Acceleration response graph for shaking table plat (B), specimens B1 and B2 with 400 kg additional uniform loads (P3 test)

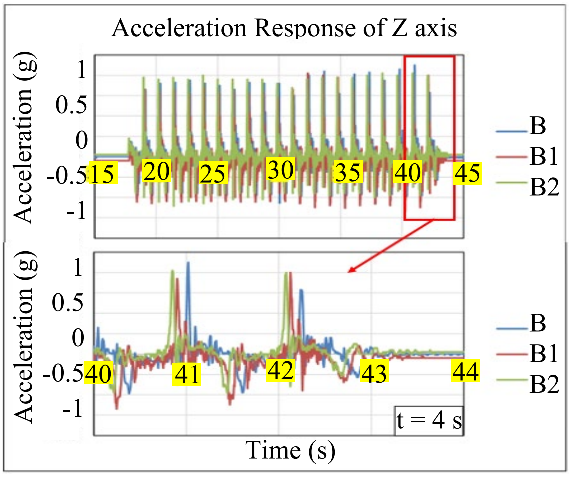


Fig.23 Acceleration response graph for shaking table plat (B), specimens B1 and B2 with 500 kg additional uniform loads (P4 test)

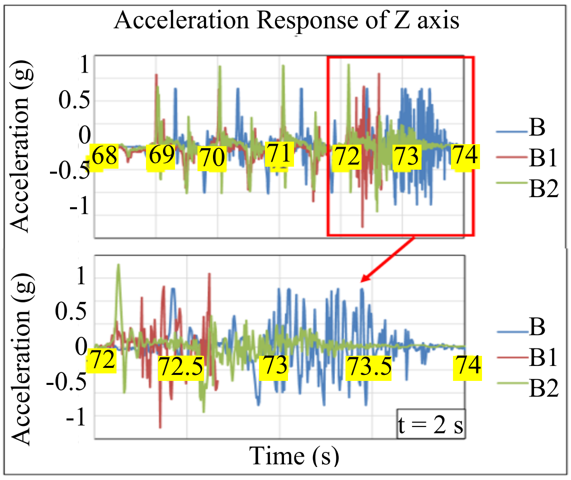


Fig.24 Acceleration response graph for shaking table plat (B), specimens B1 and B2 with 500 kg additional uniform loads and 0.6g input motions (P5 test, collapsed)

6. CONCLUSION

Based on the experimental results, the following conclusions can be drawn:

1. There is no damage observed for both specimens on P1 tests because the input motion is not strong enough to cause the crack of the specimen.
2. In the second stage (P2 test), cracks begin to appear in the door openings and in the front walls on specimen B1, while no crack appeared in specimen B2.
3. The crack was developed near the opening and spread on the east side of the wall on P3 and P4 tests.
4. Specimen B1 collapsed with input motions 0.6g and 500 kg additional uniform load, while no damage was observed on specimen B2 at this stage.
5. The results of this study indicated that the ferrocement layer significantly improves the seismic behavior of the hollow brick URM house model, and it is effective in preventing the collapse of the hollow brick URM walls when earthquakes occur.

7. ACKNOWLEDGEMENTS

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