International Journal on
Advanced Science
Engineering
Information Technology

Vol.13 (2023) No. 2
ISSN: 2088-5334

Study on the Behavior of a Simple House Partially Retrofitted Using Ferrocement Layers due to Earthquake Loads

Febrin Anas Ismail [a,*], Fauzan [a], Abdul Hakam [a], Aditya Alfajri [a]

[a] *Department of Civil Engineering, Faculty of Engineering, Andalas University, Limau Manis, Padang, West Sumatra, 25163, Indonesia*
*Corresponding author: *febrin@eng.unand.ac.id*

Abstract— **Earthquakes are a serious threat in Indonesia. Large-scale earthquakes that have occurred, such as the Aceh earthquake (2004), the West Sumatra earthquake (2009), the Lombok earthquake (2018), the Mamuju earthquake (2021), and most recently, the West Pasaman earthquake (2022), which caused many fatalities and damaged infrastructure and building houses, especially houses of the economically weak community. These houses were generally built using adobe bricks using the ½ brick masonry method without structural elements such as columns and beams that do not meet earthquake-safe house standards. In an effort to mitigate earthquake disasters, a strengthening method was developed in this study, namely by using ferrocement layers. In this research, a simple house model with adobe walls with a scale of 1:4 will be made, which will be partially strengthened using ferrocement layers tested on a vibrating table and given an earthquake load. Furthermore, numerical analysis was carried out to validate the results of experimental testing. The results of the tests show that the partial reinforcement has contributed significantly to increasing the shear capacity of the adobe brick walls. This is evidenced by the fact that there were no cracks in the reinforced walls up to the acceleration of the earthquake of 1.5 g, while the other walls of the house that were not reinforced experienced cracks and even collapsed.**

Keywords—**Earthquake; brick house; retrofitting; ferrocement layers; shaking table; shelter.**

Manuscript received 5 Jan. 2022; revised 26 Nov. 2022; accepted 16 Feb. 2023. Date of publication 30 Apr. 2023.

I. INTRODUCTION

Earthquakes are a natural phenomenon that often occurs in Indonesia. The USGS recorded that, from 2004 to 2009, approximately 14 large-scale earthquakes hit Indonesia [1]-[5]. Another earthquake occurred in Indonesia in 2018, namely the Lombok earthquake. In 2021 there was the Mamuju earthquake, and most recently, in 2022, the West Pasaman earthquake. These earthquakes resulted in a large number of casualties and damage to infrastructure and buildings, especially simple residential buildings/houses for the economically weak community [6]–[11] (see Fig. 1).

Most houses were built using brick or hollow bricks and built by the community or local craftsmen based on practical experience. They did not meet earthquake-resistant building standards [12]–[16] (see Fig. 2). Such house is certainly very dangerous for the community because the hollow bricks have heavy characteristics as they are made of a mixture of mortar and have brittle properties and almost no ductility, which can cause sudden collapse when an earthquake occurs [17]–[22]. To mitigate disaster and anticipate an upcoming earthquake, it is suggested to strengthen the houses as a whole [23], [24].

However, on account of the relatively high cost and economic limitations of the community to reinforce, a simple, cheap, and strong reinforcement was developed in this study. This method can help the community, especially people with economic limitations, strengthen their houses so they are safe against earthquakes.

Fig. 1 Damage Simple Residential Houses Due to Earthquake

The reinforcement in question is partial reinforcement of one of the rooms in the house. In this case, one bedroom is reinforced in the corner sides of the room or on the sides, considered structural elements with the ferrocement layers method*, s*o that the room can be used as a shelter for homeowners. Ferrocement layers are a type of thin wall reinforced concrete made of cement mortar reinforced with continuous wire mesh, a tight layer, and a relatively small wire size [25]–[28].

Fig. 2 Simple House

Fig. 3 Construction for Layer Ferrocement Reinforcement

II. MATERIAL AND METHOD

In this study, the test was carried out by making a simple model house with hollow brick walls scaled 1:4 from its original size, which was partially reinforced using ferrocement layers and tested on a shaking table by providing earthquake loads. The scaling was conducted, given the limitation of the size of the shaking table. The test was carried out by providing three variations of earthquake acceleration, namely 0.6 g, which simulated a strong earthquake, then 1.0 g and 1.5 g, which simulated a very strong earthquake. This study aimed to determine the behavior of simple house hollow brick wall partially reinforced using ferrocement layers tested on a shaking table by providing an earthquake load and performing numerical analysis to validate the test results. This research contributes to the development of construction science, especially in strengthening existing community houses vulnerable to earthquakes to have a shelter to save lives.

This research starts from the preparation stage, specimen design stage, specimen manufacturing stage, experimental testing stage, and numerical analysis. After experimental testing and numerical analysis have been carried out, the results will be analyzed and discussed, and the last stage is conclusions and suggestions.

A. Preparation Stage

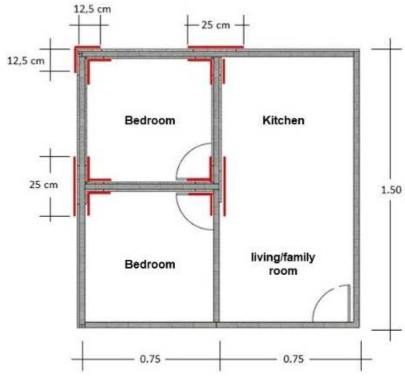
Prepare materials and tools that will be used in making simple house specimens with brick walls.

- Preparation of brick material (hollow *brick*). The brick material is made on a 1:4 scale from its original size with a ratio of 1:4 cement and sand mixture.
- Equipment preparation. Preparation of all equipment used in the manufacture of specimens.

B. Specimen Design Stage

The simple house modeled in this study is a type 36 hollow brick house with a size of 600 cm x 600 cm x 400 cm. The limitations of the testing equipment, both in terms of the area of the shaking table and the capacity of the motor drive, means the specimen is modeled on a 1:4 scale from its original size to 150 cm x 150 cm x 100 cm, as shown in Fig. 3a while Fig. 3b, 3c, 3d, 3e, 3f shows the appearance of the reinforced specimen housing.

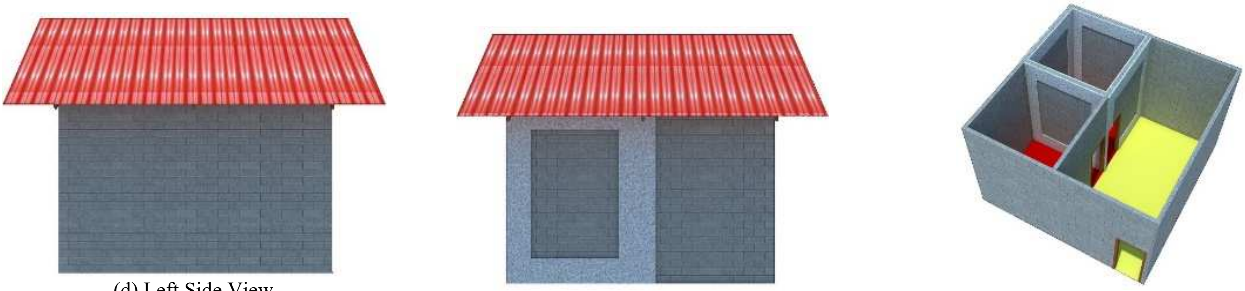
Reinforcement in the house is given partially using ferrocement layers*;* in this case, the reinforcement is given to one bedroom by coating the corners of the bedroom or on the sides, which are considered structural elements with ferrocement layers. Schematics and details of the installation of woven wire in the reinforcement area (Fig. 4 a, b, c, d, f and g).



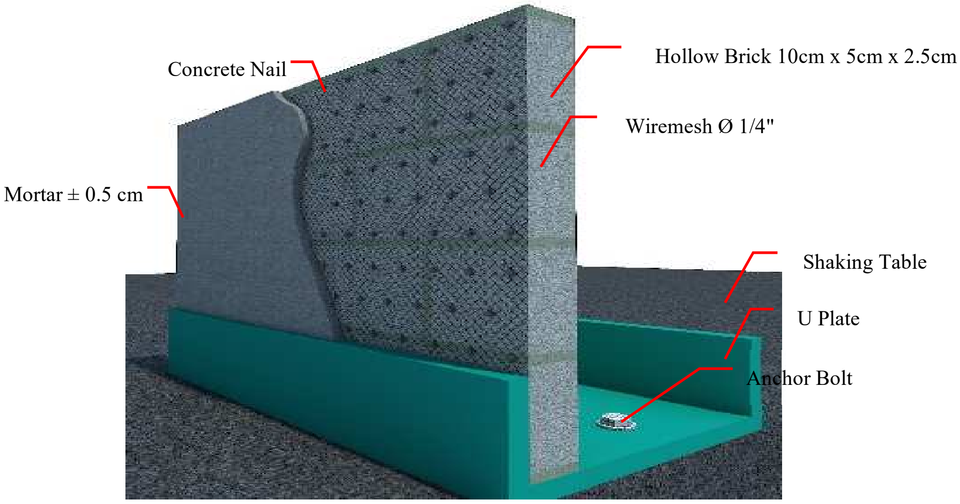
(a) Plan of the Specimen House Retrofitting Using Ferrocement Layers

(b) Front View

(c) Rear View



(d) Left Side View (e) Right Side View (f) Specimen Perspective



(g) Schematic of the installation of wire mesh in the reinforcement area

Fig. 4 Specimen and Schematic of the installation of woven wire in the reinforcement area

C. *Construction of Specimen*

The position of the specimen on the shaking table refers to the Earthquake Loading Codes for Buildings and Other Structures (SNI 1729-2019), point 7.5.3 " *the load is applied separately in all orthogonal directions. The effect of the most critical load due to the direction of application of earthquake forces on the structure is considered fulfilled if the components and foundations are designed to carry the following combination of applied loads: 100 percent (100%) force for one direction plus 30 percent (30%) force for perpendicular* [29]. Then the inclination of the specimen on the shaking table is set at 16° along the x-axis (Fig. 5).

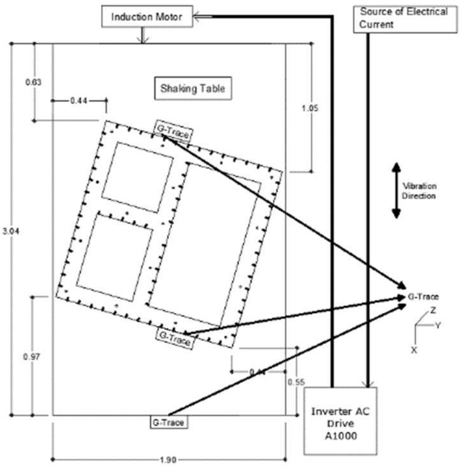


Fig. 5 Position of the U plate on the Shaking table

The hollow bricks are arranged on a U plate with a height of 1 m with a specific thickness of 0.5 cm. The model is made from a 1:4 mixture of cement and sand (Fig. 6 and Fig 7).

Fig. 6 Hollow Brick Wall Construction Process

Fig. 7 Hollow Brick Wall Construction Process High 50 cm

Nails are installed around the wall that will be given reinforcement. Nails are installed alternately with a distance of ± 5 cm. The woven wire is installed by tying it to a nail with a bendrat wire (Fig. 8).

Fig. 8 Wire Mesh Installation Process

The part of the wall that has been lined with wire mesh is plastered with a mixture of cement and sand 1:4 with a thickness of 0.5 cm (Fig. 9).

Fig. 9 Plastering Process in Retrofitted Area

The roof frame is made of 4/6 wood as the trusses, while the roof covering is made of zinc roof with a thickness of 0.25 mm (Fig. 10). After the specimen-making process is complete (fig. 11), the specimen is ready to be tested on the shaking table.

Fig. 10 Roof Truss Making Process

Fig. 11 Specimen After Construction

D. Experimental Testing Stage

TABLE I

WEIGHT SPECIMEN WITH SCALED 1:4

Material	Weight
Hollow brick	170 kg
Mortal	268 kg
Roof Truss and Roof Covering	68 kg
(qs) Total weight of the specimen	506 kg

The specimen of a simple partially reinforced hollow brick house scaled 1:4 from its original size and made on a shaking table is shown in Table 1. The original house with the actual size has the following weight, shown in Table 2.

TABLE II

WEIGHT ORIGINAL HOUSE

Material	Weight
Hollow brick	10938 kg
Mortal	43030 kg
Roof Truss and Roof Covering	718 kg
(qs) Total weight of specimen	15958 kg
(qa) Deal load weight original house	443 kg/m^2

Based on the building area scale, the weight of the specimen should be as follows:

$$Ls \times qa = qs \qquad (1)$$

where,

Ls: Specimen Area (m ^{2})

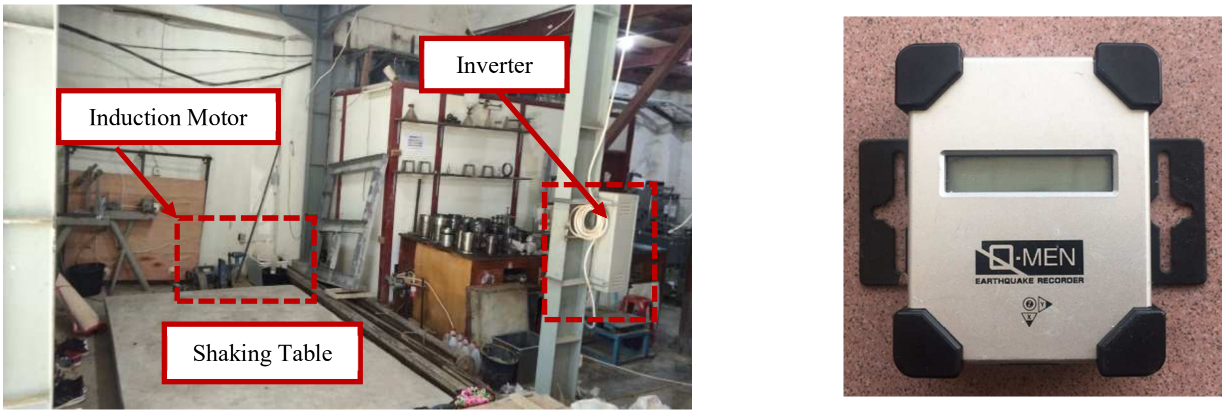
qa: Original House Weight (kg/m ^{2})

qs: Specimen Weight (kg)

So, 2.25m^2 × 443kg/m^2 = 997 kg. Then it was found that the specimen weight was less than it should be: 500 kg. Therefore, the specimen was given an additional dead load of a maximum of 500 kg in the form of a sack filled with sand placed on top of the specimen.

E. Testing Tool Set-Up

Before testing, the shaking table tool is connected to the inverter (Fig. 12 a, b, c, and d). The inverter functions to regulate the frequency of vibrations that will be given to the shaking table so that it can produce vibrations according to the earthquake acceleration planned in this study.



(a) Shaking Table (b) G-men Gravity Shock Recorder (G-Trace)

(c) (G-Trace Tool Position in Front Specimen (d) (G-Trace Tool Position in Rear Specimen

Fig. 12 Set Up Shaking Table Tool and G-Trace Position

F. *Experimental Testing*

The test is done by giving three variations of earthquake acceleration. Where the test begins by providing an earthquake acceleration of SE (Strong Earthquake) 0.6 g for 20 seconds. Then in the second stage, the variation of earthquake acceleration is increased by SE (Strong Earthquake) 0.6 g for 20 seconds. The third stage, the earthquake acceleration is increased by VSE (Very Strong Earthquake) 1.5 g for 20 seconds. The fourth stage, the specimen is given another acceleration of VSE (Very Strong Earthquake) 1.5 g until the specimen collapses.

G. *Numerical Analysis Testing*

Numerical analysis was performed using finite element software to validate experimental test results. Numerical analysis was carried out by making the same model as the experimental test (Fig. 13).

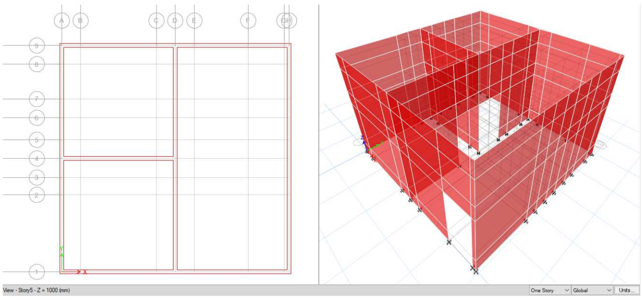


Fig. 13 Specimen modeling in numerical analysis

In the numerical analysis modeling of the specimen, there are three specified materials. The first is hollow brick with a specific gravity of 1600 kg/m^3, compressive strength (fc') 2.5 MPa, modulus of elasticity 7431.36 Mpa, and shear modulus of 3096.4 Mpa. Both plasters have a specific gravity of 1600 kg/m^3, a compressive strength of 9.9 MPa, an elastic modulus of 14788.2 Mpa, and a shear modulus of 6161.75 Mpa. Third is Stainless Steel with ultimate tensile strength (fu) 620 Mpa, yield tensile strength (fy) 275 Mpa, specific gravity 8.0 g/cm^3, and shear modulus 187500 Mpa [30], [31].

In numerical analysis, the specimens were analyzed using the time history of earthquake loads. Earthquake acceleration in time history analysis is based on recordings of earthquake acceleration during experimental testing, which was recorded using a G-trace tool mounted on a shaking table (BASE).

III. RESULT AND DISCUSSION

A. *Specimen Behavior on Earthquake Acceleration 0.6 g*

At an earthquake acceleration of 0.6 g with an additional dead load of 500 kg and a displacement maximum 1.2 cm, the specimen has small cracks in an area that is not reinforced, namely at the opening of the living room door (Fig. 14). In other parts of the wall, such as the back wall, left side, and right side as well as the reinforced wall, there is no crack or damage at all.

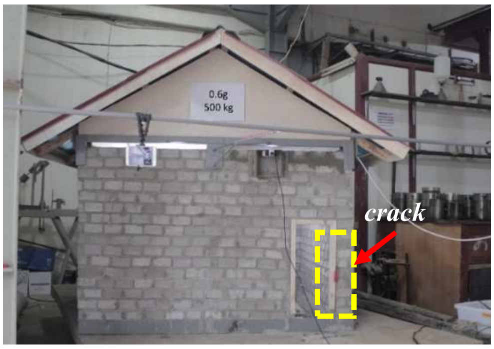


Fig. 14 The Condition of the Front of the Specimen at the time of an earthquake acceleration of 0.6 g

The acceleration response was obtained from the recording of the G-Trace device attached to the specimen. At the time of the earthquake acceleration of 0.6 g, the response of the earthquake acceleration (Fig.15)**.** The blue line represents the acceleration response on the table (BASE), the red line represents the response on the unreinforced specimen wall (FRONT) and the green line represents the acceleration response on the reinforced wall (BACK). When the earthquake acceleration is 0.6 g, the maximum acceleration that occurs at BASE is 1.9 g, the maximum acceleration in FRONT is 2.5 g, and the maximum acceleration in BACK is 2.1 g.

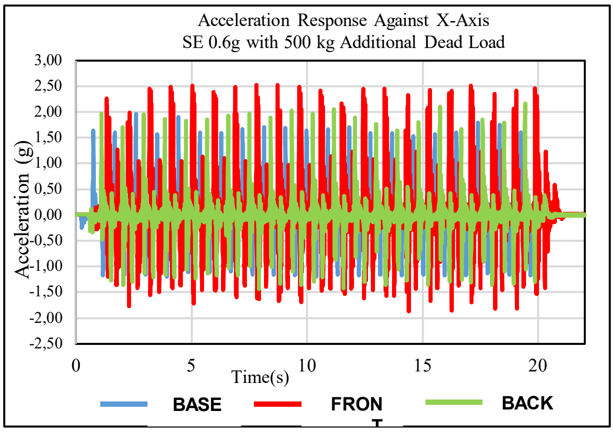


Fig. 15 Graph of 0.6 g . earthquake acceleration response

Based on the results obtained experimentally, to find out the numerical behavior that occurs in the specimens, numerical analysis is carried out using the 2016 ETABS computer tool (Fig. 16).

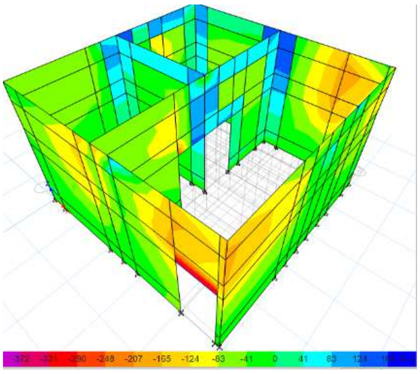


Fig. 16 Stress Patterns On The Wall Due to an Earthquake Acceleration of 0.6 g

From the results of the analysis on ETABS 2016, it can be seen that the distribution of tensile stresses is around the opening. For walls that are not reinforced, the maximum tensile stress value that occurs at the first crack point is 0.25 Mpa, where the tensile stress value is greater than the tensile stress of the hollow brick, which is 0.20 Mpa in equation (2).

$$
\begin{aligned}
f_r &= 8\%\ fc' \\
f_r &= 8\%\ 2.5\ \text{Mpa} \\
f_r &= 0.20\ \text{Mpa.}
\end{aligned}
\tag{2}
$$

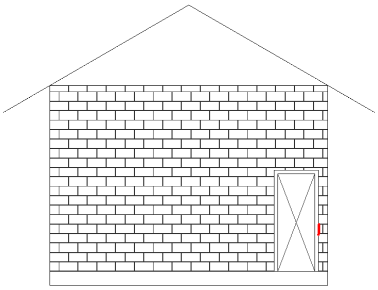
where,

f_r = Tensile Stress (Mpa)

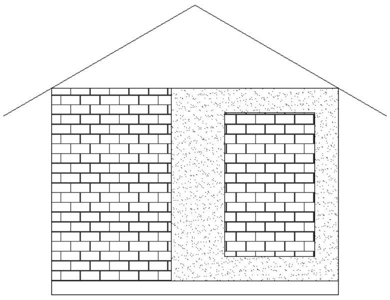
fc' = Compressive stress of brick (Mpa)

This results in cracks in the unreinforced walls. Meanwhile, on the bedroom wall, which is reinforced with ferrocement layers, the tensile stress value that occurs is smaller than the tensile stress on the unreinforced wall, which is 0.18 Mpa on brickwall and 0.08 Mpa on plastering, where the stress is smaller than the tensile stress of the hollow brick and the tensile stress of the plaster so that it does not cause cracks in the walls.

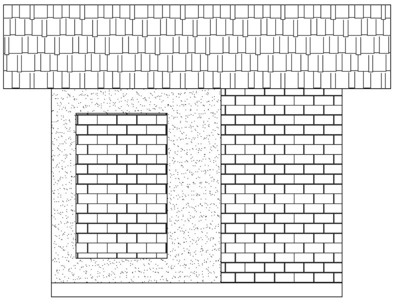
The crack pattern occurs during an earthquake acceleration of 0.6 g for 20 seconds (Fig. 17 a, b, c, d, and e). There is a small crack on the front wall, namely in the door opening in the area that is not given reinforcement, which is depicted in red.



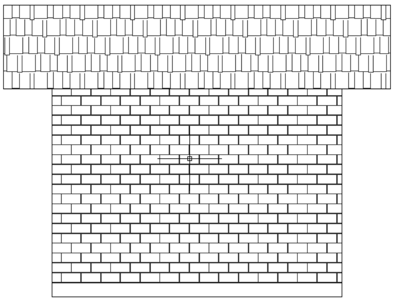
a. Front View



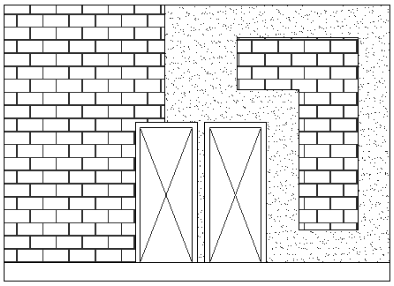
b. Rear View



c. Right Side View



d. Left Side View



e. Bedroom

Fig. 17 Crack Pattern Schematic During Earthquake Acceleration 0.6 g

B. *Specimen Behavior During Earthquake Acceleration 1.0*

1.0 g earthquake acceleration with an additional dead load of 500 kg with a displacement occurred during the maximum acceleration of 3.11 cm. The cracks in the specimen increased occurred in the upper wall of the living room door opening (wall without reinforcement) (see Fig. 18). Cracks also occurred on the left side wall of the living room, namely in the meeting area between the walls (Fig. 19). In the bedroom area which was partially reinforced with the ferrocement method, no cracks or damage occurred at all.

Fig. 18 Condition of the Front of the Specimen at the time of an earthquake acceleration of 1.0 g

During an earthquake acceleration of 1.0 g, the acceleration response from the recording of the G-Trace tool occurred (Fig. 20). New cracks occurred in the 10 seconds of the experiment with the maximum acceleration value at t = 10 seconds of 1.9 g, which occurred in the BASE, 2.5 g which occurred in the FRONT, and 2.3 g which occurred in the BACK.

From the analysis of the distribution of the maximum compressive stress in the vicinity of the opening, (Fig. 21) shows that in unreinforced walls in the area where cracks occur, the maximum tensile stress value is 0.55 MPa, where the stress is greater than the tensile stress of the hollow bricks. Meanwhile, the maximum compressive stress is 6.62 MPa, greater than the bricks' compressive stress. So, this is what causes cracks in the walls without reinforcement. The maximum tensile stress value in the bedroom is 1.65 MPa for hollow brick and 0.13 MPa for plaster. Although the tensile stress on the hollow bricks is greater than the tensile stress of the bricks, the reinforcement of ferrocement layers can significantly increase the capacity of the hollow brick wall elements so that it does not cause cracks in the walls.

Fig. 19 Condition of the Left Side of the Specimen at the time of an earthquake acceleration of 1.0 g

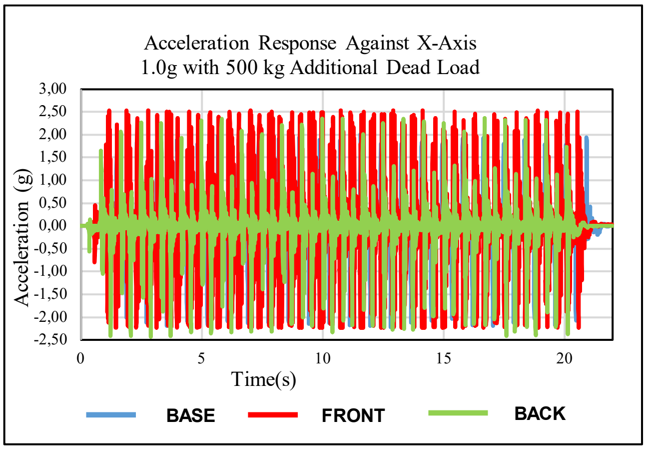


Fig. 20 Graph of 1.0g earthquake acceleration response

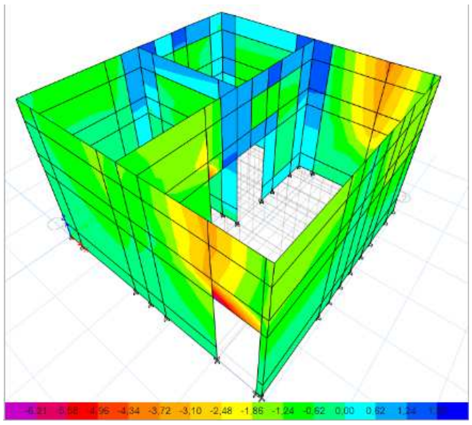
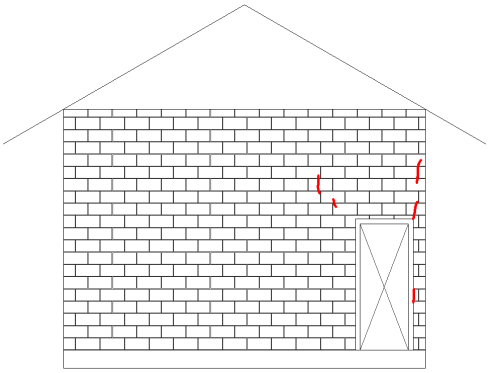
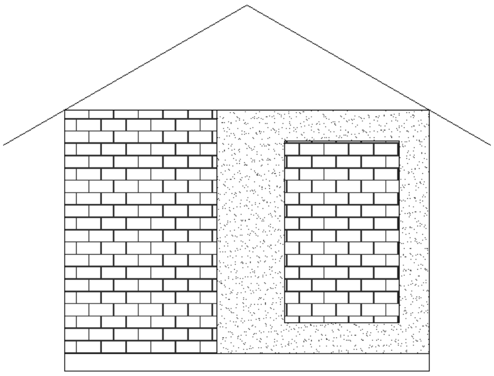


Fig. 21 Pattern of Stress on the Wall due to an Acceleration of an Earthquake 1.0 g

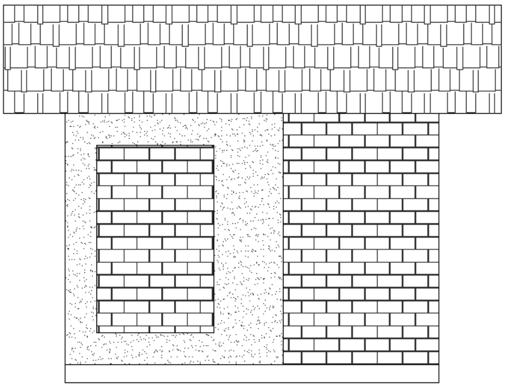
The crack pattern that occurs at the 1.0 g earthquake acceleration input for 20 seconds (Fig. 22). New cracks occur on the front wall, namely in the door opening in the area that is not given reinforcement, which is depicted in red.



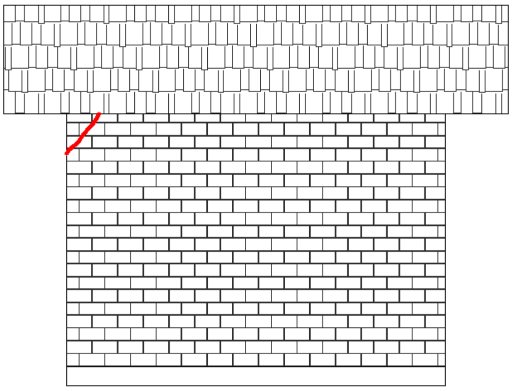
a. Front View



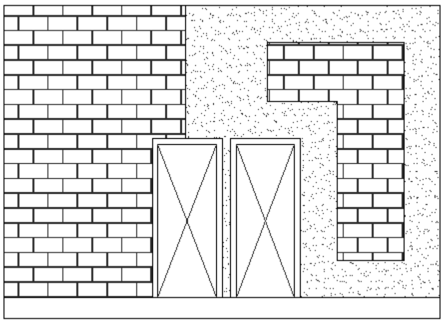
b. Rear View



c. Right Side View



d. Left Side View



e. Bedroom

Fig. 22 Crack Pattern Schematic During Earthquake Acceleration 1.0 g

C. *Specimen Behavior During Earthquake Acceleration 1.5*

By increasing the earthquake acceleration to 1.5 g, after 20 seconds of experimentation, the specimen was severely damaged with displacement at maximum acceleration of 4.88 cm. The living room wall (unreinforced wall) in the front, precisely the wall above the door opening area, collapsed. Cracks also occurred vertically at the meeting of the living room wall with the bedroom wall without reinforcement (Fig. 23).

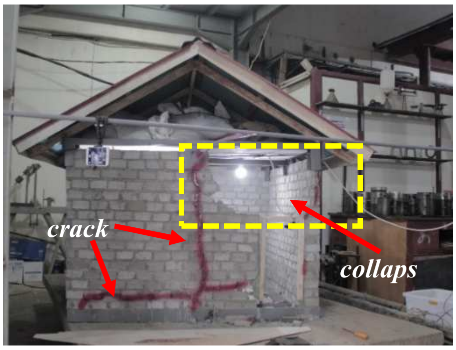


Fig. 23 Condition of the Front of the Specimen during an earthquake acceleration of 1.5 g

Meanwhile, on the back wall of the living room there were cracks in the area where the walls meet (Fig. 24). Cracks also occurred on the left side wall of the living room (Fig. 25). The unreinforced bedroom wall also had cracks on the right and left sides. In the right-side wall, the crack occurred horizontally at the top (Fig. 26). On the left side wall, cracks occurred diagonally at the door opening area and horizontal cracks at the bottom.

Fig. 24 Condition of the Back of the Specimen during an earthquake of 1.5 g

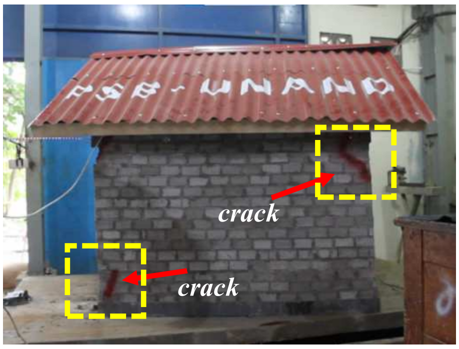


Fig. 25 Condition of the Left Side of the Specimen during an earthquake acceleration of 1.5 g

Fig. 26 Condition of the Right Side of the Specimen at the time of the 1.5 g earthquake acceleration

When the earthquake acceleration is 1.5 g with an additional dead load of 500 kg, the graph of the earthquake acceleration response t = 20 seconds (Fig. 27). Where a new crack occurred during the five seconds of the experiment with the maximum acceleration value at t = 5 seconds of 2.5g which occurred in the BASE, 2.4g which occurred in the FRONT and 2.5g which occurred in the BACK. Meanwhile, the specimen undergoes initial collapse at time t = 15 seconds. The maximum acceleration value at t = 15 seconds is 2.5 g, which occurs at BASE, 2.4g in FRONT and 2.6g in BACK.

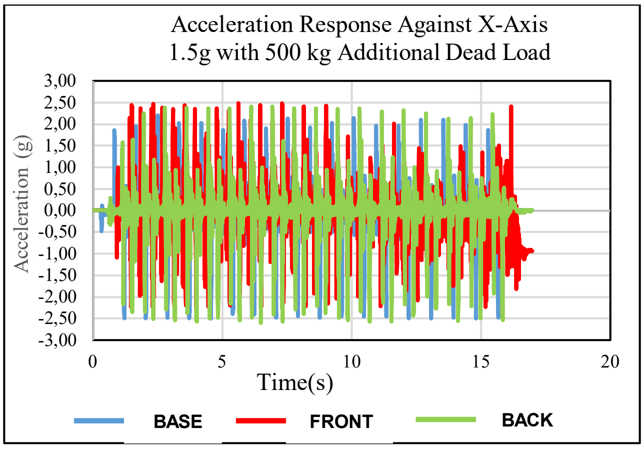


Fig. 27 Graph of 1.5 g earthquake acceleration response

The analysis (Fig. 28) shows compressively tensile stress in the cracked area. In the area that experienced a collapse, the maximum tensile stress value on the hollow brick wall was 1.38 MPa, where the stress was greater than the tensile stress of the hollow brick. While the maximum compressive stress, which is the most dominant stress, is also greater than the compressive stress of the hollow bricks, which is 7.58 Mpa. So, this is what causes the collapse and new cracks in the walls without reinforcement. In bedroom walls, the maximum tensile stress on brick walls is 2.33 MPa and on plaster is 0.93 MPa, although the tensile stress on the hollow brick walls is greater than the tensile stress of the hollow bricks with the reinforcement of ferrocement layers so that it does not cause cracks in the walls.

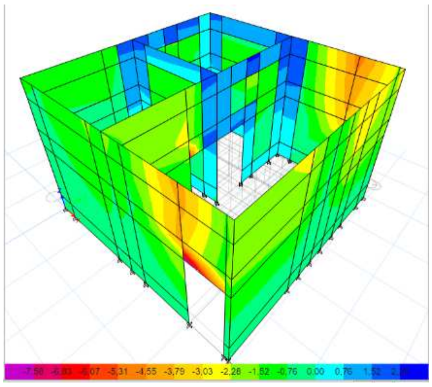
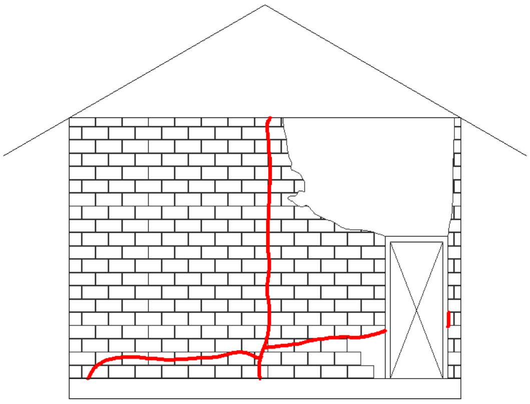
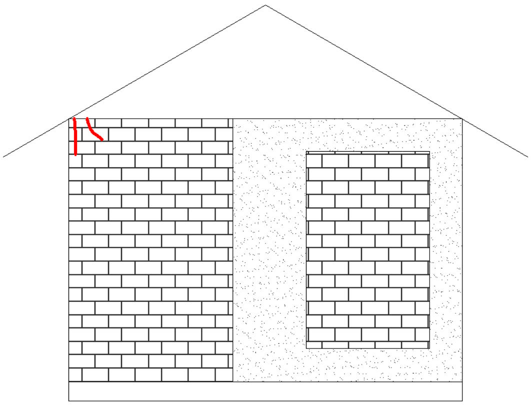


Fig. 28 Stress Pattern on Walls Due to Earthquake Acceleration 1.5 g

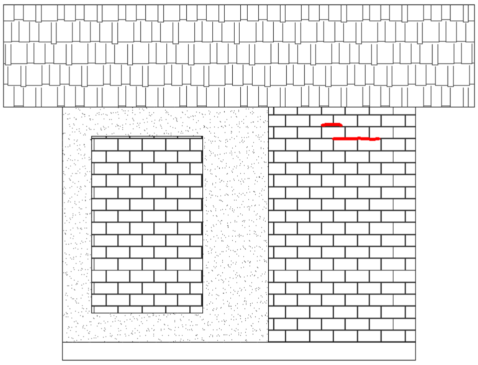
The crack pattern occurs in the specimen during an earthquake acceleration of 1.5 g (Fig. 29), where the specimen has new cracks and an initial collapse for 20 seconds of the experiment. The collapse occurred in the upper wall of the living room door opening.



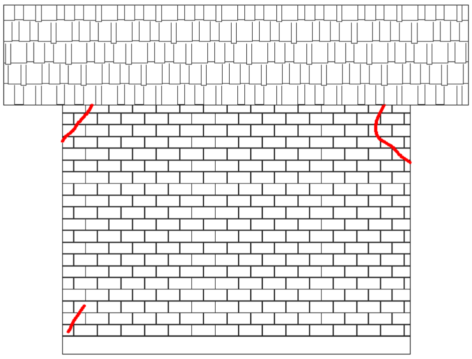
a. Front View



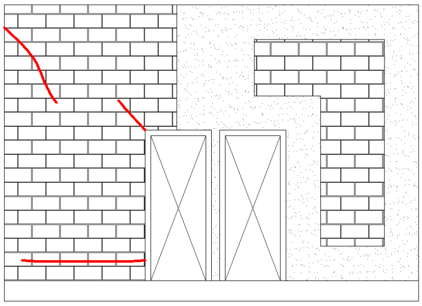
b. Rear View



c. Right Side View



d. Left Side View



e. Bedroom

Fig. 29 Crack Pattern Schematic During Earthquake Acceleration 1.5 g

D. *Specimen Behavior During Earthquake Acceleration 1.5g until Collapse*

The specimens were tested again with an earthquake acceleration of 1.5 g with an additional dead load of 500 kg until the specimens were severely damaged. Condition of the specimen at an acceleration of 1.5 g in the second experiment (Fig. 30 a, b, c, and d). Most of the unreinforced walls fail.

a. Condition of the Front of the Specimen during an earthquake acceleration of 1.5 g to Collapse.

b. Condition of the Back of the Specimen

c. Condition of the Left Side of the Specimen

d. Condition of the Inside of the Specimen

Fig. 30 Specimen Condition After Earthquake Acceleration 1.5 g Until Collapse

From the numerical analysis on the front wall of the living room (wall without reinforcement). Figure 31 shows that the maximum tensile stress is greater than the tensile stress of the hollow brick, which is 1.38 Mpa, and the compressive stress that occurs, which is the most dominant stress, is also greater than the compressive stress. Hollow brick is equal to 7.58. So, this is what causes the collapse of the wall. Figure 32 shows the stress distribution on the walls of a bedroom with reinforcement and a bedroom without reinforcement. In the bedroom without reinforcement, the maximum tensile stress on the hollow bricks is greater than the tensile stress of the hollow bricks, which is 0.60 Mpa, and the compressive stress is 5.33 Mpa, which is also greater than the compressive stress of the bricks. The stress in the wall exceeds the hollow brick's capacity, causing the unreinforced wall's collapse. While in the bedroom with a maximum tensile stress of 2.33 Mpa, the maximum stress is greater than the tensile stress of the hollow bricks, causing small cracks to occur in the area of the bedroom door opening but not causing a collapse.

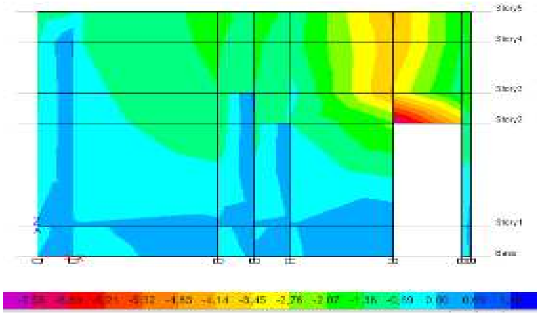


Fig. 31 Stress Distribution on the Front Living Room Wall

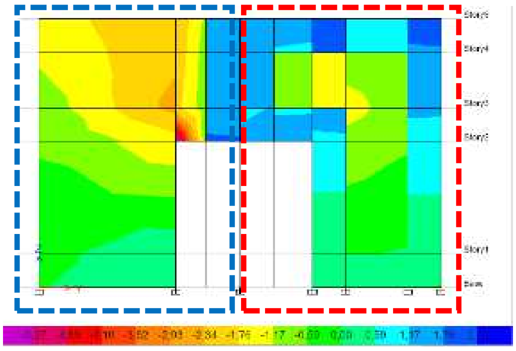
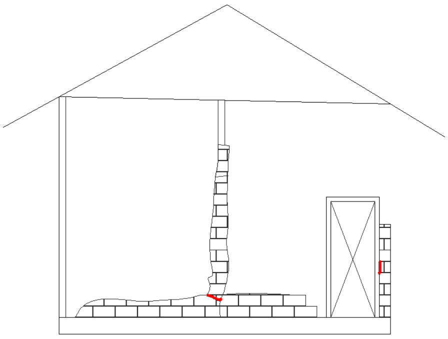


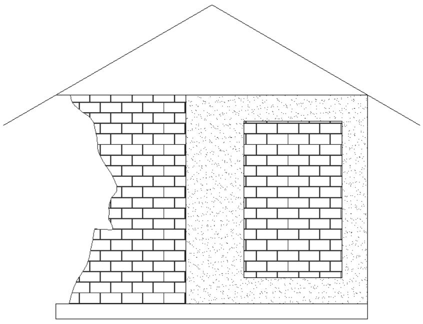
Fig. 32 Stress Distribution on Reinforced and Unreinforced Bedrooms

This, of course, visually proves that the reinforcement using the ferrocement layers method can significantly increase the capacity of the hollow brick wall elements, making the bedroom walls that are given reinforcement able to withstand and be safe against earthquake loads, even up to an earthquake acceleration of 1.5 g, so that homeowners, in this case, simulated being in a reinforced bedroom when the earthquake occurred also survived the earthquake. There were no casualties (Fig. 33).

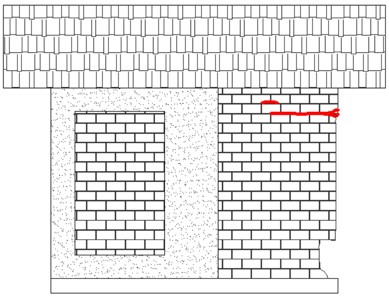
Fig. 33 Simulation of the owner of the house who was in the bedroom which was reinforced during an earthquake



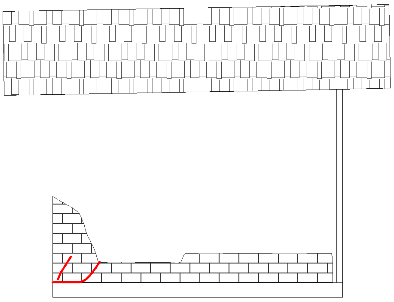
a. Front View



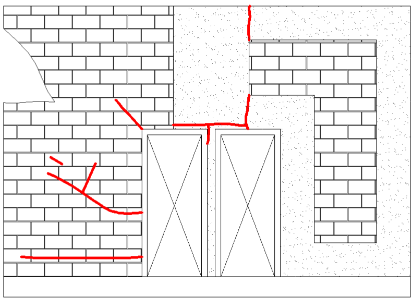
b. Rear View



c. Right Side View



d. Left Side View



e. Bedroom

Fig.34 Crack Pattern Schematic During Earthquake Acceleration 1.5 g Until Collapse

The pattern of cracks that occur in the specimen during the acceleration of the 1.5 g earthquake, where the specimen is tested until it is severely damaged (Fig. 34). During the 35 seconds of the experiment, the specimen was severely damaged, namely, the specimen collapsed suddenly on the unreinforced wall, while the reinforced wall only experienced small cracks and did not collapse.

IV. CONCLUSION

Based on the results of the study, it can be concluded that at an earthquake acceleration of 0.6 g with a displacement occurs during a maximum acceleration of 1.20 cm. The specimen has small cracks in the area of the living room door opening (unreinforced walls) with a maximum tensile stress value of more than the tensile stress of the hollow brick 0.25 MPa, which causes cracks to occur.

Specimens of a simple house with hollow brick walls partially reinforced with the ferrocement layers method experienced additional cracks in the living room wall (unreinforced wall) in the door opening area during an earthquake acceleration of 1.0 g with a displacement of 3.11 cm. Meanwhile, for reinforced walls, the reinforcement of ferrocement layers is able to significantly increase the capacity of the hollow brick wall elements so that the walls are not damaged or cracked. The numerical analysis shows that the cause of cracking at an acceleration of 1.0 g is that the maximum tensile stress value that occurs is greater than the tensile stress of the hollow brick.

At an earthquake acceleration of 1.5 g with a displacement of 4.88 cm, the specimen experienced an initial collapse in the area of the living room door opening (unreinforced walls). From numerical analysis, it is known that the cause of failure is the maximum tensile stress value that occurs is greater than the tensile stress of the hollow bricks and the maximum compressive stress that occurs is also greater than the compressive stress of the hollow bricks.

In the second experiment, severe damage and even collapse of the unreinforced specimen walls occurred at an earthquake acceleration of 1.5g. Most of the unreinforced walls collapsed, while the bedroom walls, which were reinforced with ferrocement layers were able to increase the capacity of the hollow brick wall so that there was no collapse and only cracks in the door opening area.

The results of this study indicate that the partial strengthening of one bedroom in the house by strengthening the corners of the room using the ferrocement layers method can save the occupants in the room so that the room can be used as a shelter when an earthquake occurs.

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