The development of interlocking models of lightweight bricks and shear failure assessment of its wall structures

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Abstract. In this paper the development of interlocking models of lightweight bricks is proposed and its shear failure assessment in wall structures has been studied. Walls are a brittle infill structures and quiet vulnerable to collapse compared among all building components when a strong earthquake occurs. An interlocking system approach is such a simple method that is proposed to make sure the wall behave keep strong and stiff during seismic load. This research was performed to improve the shear capability and modelling of lightweight brick as well, which is interlocked each other. The data from the specific gravity testing results and its compressive strength then inputted as one of the modelling parameters. An experiment was carried out utilizing the Taguchi method to find out the optimum mixture used in shear testing in medium scale of walls. The compressive strength and shear strength testing methods follow the Indonesian code of SNI 03-1974-1990 and ASTM E2126-2011. The cube specimens of 15x15x15cm were used for compressive experiments, while a set of wall structures of 100x100 cm that was surrounded by reinforced concrete practical frame of columns and beams of 13x13 cm was used as shear test specimens. From shear testing results that using cyclic loads, it was found that the system can resist a maximum load of 45 kN by a lateral deflection of 45 mm. The results also obtained elastic stiffness of 2.55 kN / mm, the yielding behaviour occurs at the load, lateral deflection, ductility factor Δf/Δy and shear strength of 38.25 kN, 14,961 mm, 2.61 and 35,714 kN / mm respectively, which means that each width of 1 mm wall can be resist a shear load of 35,714 kN. It can be simply concluded that in cyclic shear loads, the more the wall is getting damaged or cracked, the structural stiffness will decreased as shown in a hysteresis behaviour.

1. Introduction
Masonry walls are a brittle structure and one of the most vulnerable to collapse of the entire building components during a strong earthquake shaking. A simple method that makes wall behaves strongly and stiffly during earthquake is to make the wall behave in the same way as a box, together with the roof at the top and with the foundation at the bottom. In a construction, aspects are required to ensure the action of this box. One of them is the connection between the walls must be good. This aspect can be achieved by ensuring the masonry is interconnected [1].

Ramadhan has conducted research on interlocking masonry bricks, from this research, the results of static testing of the interlocking masonry brick wall portals showed that the specimen was able to receive a pushover load of 63931.2 N which resulted in an ultimate displacement of 35 mm with a crack thickness of 4 mm. The wall shear strength obtained is 21.31 N / mm. Based on the energy equivalent elastic plastic (EEEP) curve analysis, the wall elastic stiffness is 5905.88 N / mm, and the wall yield...
load is 57237.55 N with a yield displacement of 9.69 mm [2]. Based on the description above, it is necessary to conduct research to improve the interlocking lightweight brick model and test the shear strength of the walls made of interlocking lightweight bricks.

2. Materials

2.1. Shear failure
First failure type occurs at low normal stress and usually named by shear failure. Cracks often propagate follow stairs mode. Many researchers state that the failure occurs due to the damage of bond at bed joint or connection [3]. Several shear failure issues can be presented below.

2.1.1. Stepped cracks shear failure. Stepped cracks shear failure is shear damage along mortar connection in the wall in brick’s side and little cracks appear in the brick’s part (Figure 1).

2.1.2. Horizontal sliding shear failure. Horizontal sliding shear failure is shear damage along horizontal wall near or right on half infill wall panel (Figure 2) [3].

![Figure 1. Stepped cracks shear failure pattern.](image1.png) ![Figure 2. Horizontal sliding shear failure pattern.](image2.png)

2.2. Bricks stress failure
For moderate to high values of normal stresses, tensile failure of the brick generally occurs. These failure modes are called tensile failure cracks. The shear strength of the mortar joint increases due to the effect of normal compressive stress. Therefore, cracks appear in the brick instead of in the joint, as a result of the tensile stress caused by the compressive stress state. As observed in the Figure 3, the cracks follow the head joints and pass through the bricks with a tendency that depends on the orientation of the main stresses on the bricks.

When panels are horizontally reinforced or when the condition of the panel-frame joint is improved, as occurs in frame pairs, cracks are usually small and distributed in wide zones along the diagonal. In other cases, the damage is concentrated in one or two large cracks.

![Figure 3. Diagonal cracks due to the bricks tensile stress failures.](image3.png)

Mahdizadeh suggests that damage to masonry walls is usually characterized by cracks [4]. The crack category based on its dimensions for the pair wall structure can be divided into 2 categories. The first category has no effect on the structure except the aesthetics of the building, these crack sizes range from
0.1 mm to 2.0 mm. The second category of cracks that will affect the use and service of the building needs to be repaired if necessary because it can lead to building collapse. The dimensions of the cracks start from 2.0 mm until the most dangerous is 25 mm.

3. Methodology

3.1. Foamed bricks

In this study, several experiments on the mixture composition of lightweight bricks along with compressive testing were carried out, developing a new model of interlocking lightweight bricks, apply the interlocking lightweight brick model as a masonry wall, and testing the shear strength of the masonry wall with the cyclic load. The sample in this study were 16 cube specimens with dimensions of 15x15x15 cm and 10 units of interlocking lightweight bricks. Materials and equipment that will be used for the manufacture of lightweight bricks are water, white cement, fiberglass, and foam agent.

3.2. Wall infill reinforced concrete frame

Whereas for the manufacture of masonry reinforced concrete frame in the wall shear test is 4D10 mm for the main reinforcement and Ø6 mm for stirrups with 200 mm spacing between stirrups, the composition of the portal concrete mixture is 1 cement: 2 sand: 3 gravel. The equipment for testing the compressive strength is the compaction testing machine, while the test equipment for testing the shear strength is the loading frame, dial gauge, hydraulic jack and hydraulic jack pump. The following are 16 plans of composition variations for the trial mix obtained from the Taguchi method.

| Run | Cement (gram) | Fiberglass (gram) | Paste Water (ml) | Water for foaming (ml) | Foam Agent (ml) |
|-----|---------------|-------------------|-----------------|----------------------|----------------|
| 1   | 2500          | 25                | 416.7           | 833.3                | 41.7           |
| 2   | 2500          | 37.5              | 416.7           | 833.3                | 55.6           |
| 3   | 2500          | 50                | 416.7           | 833.3                | 66.7           |
| 4   | 2500          | 62.5              | 416.7           | 833.3                | 83.3           |
| 5   | 2500          | 50                | 458.3           | 916.7                | 45.8           |
| 6   | 2500          | 62.5              | 458.3           | 916.7                | 61.1           |
| 7   | 2500          | 25                | 458.3           | 916.7                | 73.3           |
| 8   | 2500          | 37.5              | 458.3           | 916.7                | 91.7           |
| 9   | 2500          | 62.5              | 500.0           | 1000.0               | 50.0           |
| 10  | 2500          | 25                | 500.0           | 1000.0               | 66.7           |
| 11  | 2500          | 37.5              | 500.0           | 1000.0               | 80.0           |
| 12  | 2500          | 50                | 500.0           | 1000.0               | 100.0          |
| 13  | 2500          | 37.5              | 541.7           | 1083.3               | 54.2           |
| 14  | 2500          | 50                | 541.7           | 1083.3               | 72.2           |
| 15  | 2500          | 62.5              | 541.7           | 1083.3               | 86.7           |
| 16  | 2500          | 25                | 541.7           | 1083.3               | 108.3          |

The procedure for making lightweight bricks is putting water and cement in a row into the bucket and stirring with an electric drill, making foam using a foam generator, putting the foam into the bucket, put the fiberglass, and then stirring until well mixed, check the wet density of the lightweight brick mixture, then put the lightweight brick mixture into the mold. Remove the lightweight bricks from the mold then put it in the curing tank. After 28 days, the compressive strength test is carried out based on SNI 03-1974-1990. The compressive strength of concrete load is the amount of load per unit area, which causes the concrete specimen to collapse when loaded with a certain compressive force, which is generated by a compression machine [5]. Specific strength is the ratio of strength to density of material. This means that the material has a light weight, but it also has high strength [6].
3.3. Setup of wall-RC frame test

After the curing has completed, then a shear testing was performed to measure its strength of the lightweight masonry wall in relation to the dimensions (1.0 x 1.0 x 0.125) m which is placed above the tie beam according to the setting layout to make sure that there is no lifted tie beam occurs during the test. The process of making the specimen wall done by assembling the beam anchored to the loading frame, then pouring the tie beam with a size of 0.13 m x 0.13 m. First, the installation of interlocking lightweight brick walls is carried out by pouring the interlocking lightweight brick with the tie beam. Then arrange interlocking lightweight brick without using mortar. Then, a 0.13 m x 0.13 m column, and then the entire surrounding RC frame of 0.13 m x 0.13 m poured simultaneously, when all the bricks had been installed. The shear test for the masonry wall specimen then was performed after 7 days.

The shear strength test for interlocking lightweight brick masonry walls with cyclic loads refers to ASTM E2126-11. The setting of the shear strength test with cyclic loads is done by installing a hydraulic jack on the upper corner on the surrounding RC frame, placed parallel to the in-plane wall and repeated cyclic loading in both directions of the wall, from the left loads and vice versa. While the front side of the hydraulic jack is installed with a dial gauge to measure the lateral displacement that occurs due to cyclic loads. The load is given alternately on the left and right of the wall specimen and added gradually with the same increment interval of 5 kN, 10 kN, 15 kN and so on until the wall collapses. Each load increase for each bar is recorded by the dial load, dial indicator, observing the crack pattern that occurs and marked it directly on the specimen wall as the loading increased and the cracks were propagated. The test setup of the hydraulic jack can be seen in Figure 4.

![Figure 4. The test setup for the shear strength of the interlocking lightweight masonry brick.](image-url)

The first observation is made after the loading of the first cycle from the left to the right, after that the second observation is made in the first cycle from the right to the left, and so on until the last cycle. The following is the modeling and results of interlocking lightweight brick casting (Figure 5 and Figure 6).

![Figure 5. a-3D shape model, single interlocking brick.](image-url)

![Figure 6. Interlocking system of lightweight brick masonry wall structures.](image-url)
Figure 7 and Figure 8 show respectively, the interlocking lightweight single brick and masonry bricks wall that its best composition based on strength has been determined using the Taguchi method after the compressive test results has finished.

Figure 7. Pouring result, interlocking lightweight bricks.  
Figure 8. Installation result, interlocking lightweight brick masonry wall.

4. Results and discussion
Before the implementation of wall shear testing, a preliminary test is carried out on the trial mix of cube specimens that optimum specific strength will be selected among results and will be used as an interlocking lightweight brick from the selected optimum mix composition. The trial mix test covered density compressive strength testing. The test specimen is cube 15 cm x 15 cm x 15 cm. The following of regarding results of the trial mix cube specimens were depicted in Table 2.

| Run | w/c ratio | Foam/water ratio | Fiberglass content | Weight (kg) (A) | Volume (m$^3$) (B) | Density (kg / m$^3$) (C)=(A/B) |
|-----|-----------|-----------------|-------------------|----------------|------------------|------------------------|
| 1   | 0.50      | 1:20            | 1%                | 3              | 0.003375         | 888.93                 |
| 2   | 0.50      | 1:15            | 1.5%              | 2.85           | 0.003375         | 844.44                 |
| 3   | 0.50      | 1:12.5          | 2%                | 2.6            | 0.003375         | 770.40                 |
| 4   | 0.50      | 1:10            | 2.5%              | 3.07           | 0.003375         | 909.67                 |
| 5   | 0.55      | 1:20            | 2%                | 2.7            | 0.003375         | 800.00                 |
| 6   | 0.55      | 1:15            | 2.5%              | 2.45           | 0.003375         | 725.93                 |
| 7   | 0.55      | 1:12.5          | 1%                | 3              | 0.003398         | 883.00                 |
| 8   | 0.55      | 1:10            | 1.5%              | 3.3            | 0.003353         | 984.34                 |
| 9   | 0.60      | 1:20            | 2.5%              | 2.45           | 0.003353         | 730.80                 |
| 10  | 0.60      | 1:15            | 1%                | 3.1            | 0.003375         | 918.52                 |
| 11  | 0.60      | 1:12.5          | 1.5%              | 2.35           | 0.003398         | 691.69                 |
| 12  | 0.60      | 1:10            | 2%                | 3.5            | 0.003375         | 1037.0                 |
| 13  | 0.65      | 1:20            | 1.5%              | 1.8            | 0.003375         | 533.33                 |
| 14  | 0.65      | 1:15            | 2%                | 2              | 0.003375         | 592.59                 |
| 15  | 0.65      | 1:12.5          | 2.5%              | 2.5            | 0.003375         | 740.77                 |
| 16  | 0.65      | 1:10            | 1%                | 3.12           | 0.003375         | 924.44                 |

From the Table 2, it can be noted that the smallest density is 533.33 kg/m$^3$ and the biggest is 1037.03 kg/m$^3$. All specimens can float in the water due to their low density compared to water. Then, the compressive test was performed to all specimens and hence, the results of the resisted compressive strength can be shown in Table 3.
Table 3. The trial mix compressive strength results of the cubic specimen.

| Run | w/c ratio | Foam/water ratio | Fiberglass content | Compressive Strength (kg / cm²) |
|-----|-----------|------------------|--------------------|-------------------------------|
| 1   | 0.50      | 1:20             | 1%                 | 27.66                         |
| 2   | 0.50      | 1:15             | 1.5%               | 29.98                         |
| 3   | 0.50      | 1:12.5           | 2%                 | 27.84                         |
| 4   | 0.50      | 1:10             | 2.5%               | 38.20                         |
| 5   | 0.55      | 1:20             | 2%                 | 25.70                         |
| 6   | 0.55      | 1:15             | 2.5%               | 23.56                         |
| 7   | 0.55      | 1:12.5           | 1%                 | 32.03                         |
| 8   | 0.55      | 1:10             | 1.5%               | 40.59                         |
| 9   | 0.60      | 1:20             | 2.5%               | 21.56                         |
| 10  | 0.60      | 1:15             | 1%                 | 47.11                         |
| 11  | 0.60      | 1:12.5           | 1.5%               | 23.56                         |
| 12  | 0.60      | 1:10             | 2%                 | 72.16                         |
| 13  | 0.65      | 1:20             | 1.5%               | 12.85                         |
| 14  | 0.65      | 1:15             | 2%                 | 17.13                         |
| 15  | 0.65      | 1:12.5           | 2.5%               | 21.42                         |
| 16  | 0.65      | 1:10             | 1%                 | 59.42                         |

From the Table 3, it can be summarized that the largest compressive strength is 72.16 kg / cm² and the smallest is 12.85 kg / cm². Based on SNI 03-0349-1989 and the results of the trial mix compressive strength test, the optimal cube specimen is included in category II [7]. The following Figure 9 represent the relationship between lightweight bricks specimen of compressive strength and its density.

From Figure 9 above, it can be pointed out that the increase in density is slightly proportional to the value of compressive strength. It exhibits that the larger the density of lightweight bricks, the larger the compressive strength value will. The following is the trial mix specific strength was shown in Table 4.

Based on Table 4, it can be denoted that RUN-12 has the largest specific strength, which means that it has a quite small weight but has the largest strength. Shear testing of an interlocking lightweight brick wall system that surrounded by reinforced concrete frame then carried out when the brick’s age reach 28 days.
### Table 4. Specific Strength of the trial mix.

| RUN | Density (kg / m$^3$) | Compressive Strength (N / m$^2$) | Specific Strength (Nm / kg) |
|-----|-----------------------|----------------------------------|-----------------------------|
|     | (A)                   | (B)                              | (C) = (B / A)               |
| 1   | 888.93                | 2712136.42                       | 3051.02                     |
| 2   | 844.44                | 2940234.05                       | 3481.86                     |
| 3   | 770.40                | 2730338.68                       | 3544.03                     |
| 4   | 909.67                | 3780468.94                       | 4155.87                     |
| 5   | 800.00                | 2520200.61                       | 3150.25                     |
| 6   | 725.93                | 2310183.89                       | 3182.40                     |
| 7   | 883.00                | 3150 250.77                      | 3567.66                     |
| 8   | 984.34                | 4017098.29                       | 4081.01                     |
| 9   | 730.80                | 2114262,26                       | 2893.09                     |
| 10  | 918.52                | 4620367.79                       | 5030.24                     |
| 11  | 691.69                | 2310183.89                       | 3339.94                     |
| 12  | 1037.04               | 7140568.40                       | 6885.55                     |
| 13  | 533.33                | 1260 100.31                      | 2362.69                     |
| 14  | 592.59                | 1680133.74                       | 2835.23                     |
| 15  | 740.77                | 2100260.52                       | 2835.23                     |
| 16  | 924.44                | 5880468.10                       | 6361.08                     |

Cyclic loading is applied to the joints of beam-column of the wall specimen. A certain cyclic loading pattern applied to the loading jack actuator from left to right in repeated cyclic stages until the system was collapsed or reach cracks width of 4 mm, then was continued until the ultimate load and then the load was decreased (unloading), and repeated based on the cyclic loading pattern. The following hysteresis loop curve then obtained from the shear test results using cyclic loads such as depicted in Figure 10.

![Hysteresis curve and envelope curves of wall structures](image)

**Figure 10.** Hysteresis curve and envelope curves of wall structures.

From the results above in Figure 10, it can be concluded that the more the load increases, the more the lateral displacement will occurs, and a maximum load of 45000 N can be achieved by the masonry wall specimen. The test then stopped whenever the wall specimen is cracked by width of 4 mm [8]. At stopped loading, a load of 25000 N can be resisted by the wall and a lateral displacement of 13.44 mm was obtained. Then the repeated loading is carried out until the wall reach its maximum load and maximum lateral displacement.
From Figure 12 above, it seems that the lateral displacement at each cycle does not always return to 0 mm. This is behaving so due to decreasing of its stiffness as the cyclic load repeated and as the loading was increased, hence that the returning ability of the wall to its original position was decreased. Therefore, when the load is beyond than the elastic stiffness of 0.4P peak or 18000 N, obviously noted that the lateral displacement at zero load on the next cycle does not return to zero displacement.

Based on ASTM E 2126-2011 the data from the results of this test, namely the loads-displacement data, the values of elastic stiffness, shear strength, yield load, yield displacement, ductility, shear modulus and EEEP curve can be obtained respectively. The following are the results of the calculations obtained by the formula for the ASTM E 2126-2011 [9].

a) Elastic Stiffness
   \[ 0.4 \times P_{\text{peak}} = 0.4 \times 45000 \text{ N} = 18000 \text{ N} \]
   \[ \Delta_e = \text{Deviation at 0.4} \times P_{\text{peak}} = 7.04 \text{ mm} \]
   \[ \text{Elastic Stiffness} (K_e) = \frac{0.4 \times P_{\text{peak}}}{\Delta_e} = \frac{18000}{7.04} = 2556.82 \text{ N/mm} = 2556818.18 \text{ N/m} \]

b) Shear Strength
   \[ \text{Shear Strength (} v_{\text{peak}}) = \frac{P_{\text{peak}}}{L} = \frac{45000 \text{ N}}{1260 \text{ m}} = 35714,286 \text{ N/m} \]

c) Yield Load
   \[ \text{(curve area from autocad application calculation ) = 1209,525 Nm} \]
   \[ \Delta_u = 39.1 \text{ mm} = 0.0391 \text{ m} \]
   \[ P_{\text{yield}} = \left( \Delta_u - \sqrt{\Delta_u^2 - 2A/K_e} \right) = 38252.49 \text{ N} \]

d) Yield displacement
   \[ \left( \Delta_{\text{yield}} \right) = \frac{P_{\text{yield}}}{K_e} = \frac{38252.49 \text{ N}}{2556818.18 \text{ N/m}} = 0.01496 \text{ m} \]

e) Cyclic Ductility Ratio
   \[ (D) = \frac{\Delta_{\text{ultimate}}}{\Delta_{\text{yield}}} = \frac{0.0391}{0.01496} = 2.61 \]

From the results of the analysis above, these values can be described as the equivalent energy elastic plastic curve as depicted in Figure 13 below:
Figure 13. EEEP curve of interlocking lightweight brick masonry wall.

The following is a FE analysis and modeling that show that axial compressive stress $S_x$ of 0.648 MPa occurs in lightweight brick due to the loading tip position of surrounding RC frame, such as depicted in Figure 14.

Figure 14. Maximum compressive stress $S_x$ that occurs in interlocking lightweight masonry wall.

The cracked pattern of interlocking lightweight brick masonry wall was indicated after a shear test was carried out at maximum load and with maximum displacement. The crack pattern was observed after loading in each cycle and the crack pattern that occurred then was drawn on the masonry wall using a marker.

The first crack pattern occurs at the load of 10 kN to the right with a displacement of 1.8 mm which results in hair cracks in the lower left corner. At the first crack occurs, the wall stiffness still at 5555.56 N / mm. Then a hair crack in the lower right corner also occur at the increased load of 15 kN and a displacement of 3.62 mm with a wall stiffness of 4143.65 N / mm. Accordingly, at a load of 25 kN to the right, the crack width occur at 4 mm and the interlocking joints between the 3rd and 4th layer bricks is broken and its resulting in 5 mm gap joints with a stiffness of 1860.12 N / mm. At a load of 30kN with a displacement of 17.56 mm the gap width of the interlocking joints increases to 8 mm and the wall stiffness can be measured as 1708.43 N / mm.
Figure 15. Crack pattern at ultimate load of interlocking lightweight brick masonry wall.

Figure 16. Maximum load crack pattern of interlocking lightweight masonry walls at left to the right direction of cyclic loading.

Figure 17. Maximum load crack pattern of interlocking lightweight masonry walls at right to the left direction of cyclic loading.

From shear test results, it can be concluded that the more the wall is damaged or cracked, the stiffness of the structure will obviously decrease, and this was already occurs the first crack appeared, where the wall still had a stiffness of 5555.56 N/mm, but when the crack width reached 4 mm, the wall stiffness decreased by 66.52% to 1860.12 N/mm. Also, as the load get larger of 30 kN, its crack width become 8 mm and consequently, the wall stiffness decreased to 1708.43 N/mm. This was also stated by Li that before cracking, the stiffness would be constant as elastic behavior, such as the reduction of stiffness when loading applied has not occurred, but if the concrete has cracked due to external loads, the stiffness of the structure will also obviously decreased with the addition of crack width [10].

5. Conclusion
- From the of specific gravity results of the trial mix, it was found that the larger both of the water-cement ratio and the fiberglass content, the smaller the density, but the larger foam agent concentration to the water, the larger the density of the specimen will be found. From the compressive strength results, it was found that the larger both of the water-cement ratio and the fiberglass content, the smaller the compressive strength will be, and contrary with that, the larger the foam agent concentration to the water, the larger the compressive strength value is obtained.
From the results of the shear strength test of interlocking lightweight brick masonry wall (surrounding by RC frame) with a density of 782 kg / m³ and a compressive strength of 31.7 kg / cm², the shear strength of interlocking masonry wall structures is 35.71 kN / mm, by means that each width of 1 mm wall can resist loads of 35.71 kN. The elastic stiffness is 2.55 kN / mm, the yield displacement is 14.96 mm, its ‘yield’ load was around 38.25 kN and its ductility was 2.61. From shear test of wall system, it can be concluded that obviously the more the wall is damaged or cracked, the less the structural stiffness will be.

A new development of an improved interlocking bricks model is proposed, and resulted in low density as a lightweight material, and its wall structures can overcome shear cyclic loading very well and results in a good hysteresis curve which means have a good ductility as well in the seismic resisted structures.

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