Experimental Study on Typical Confined Masonry Structure under Cyclic Lateral Load

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SUMMARY:
An experimental study was conducted to evaluate the behavior of confined masonry structures under earthquake loads. The one-story full-scale model was built based on local standard in Indonesia. Lateral cyclic loads were applied to the model with increasing displacement. Parameters evaluated were crack pattern, failure mechanism, lateral capacity, energy dissipation, ductility, and overall structural performance. The study reveals that initial crack occurred at corners of openings and truss mechanism was later developed for walls. Test shows that the model could withstand 3.5% drift without collapse. The masonry infill walls provided significant strength and ductility, and out of plane walls provided additional restraints for wall movements and improved structural performance. Proper detailing allowed frames to provide confining action to masonry walls, while anchorage of walls to columns limited damage area on walls. The results confirm that structures built according to the standard will behave satisfactorily under the design earthquake load.

Keywords: Confined masonry wall, residential building, experimental study, collapse mechanism

1. INTRODUCTION

Past earthquakes have shown that residential buildings are prone to damage. The typical houses in Indonesia are of stone masonry foundation, reinforced concrete frames (columns and beams), with infill brick masonry wall. These structures are commonly known as non-engineered structures. The structural performance of this type of structure under earthquake loads varied due to differences in material qualities, and construction techniques. Observations shows that failures and damages of non-engineered structures were mostly caused by inadequate connection between infill walls and confining frames, poor detailing of elements and connections, insufficient structural elements, as well as poor materials and workmanship. Considering that two-thirds of buildings in Indonesia are residential buildings, improving the performance of residential buildings under seismic loads has become the priority to reduce fatalities and socio-economic losses due to earthquake. Thus, local guidelines and standards have been published to ensure that residential structures will behave satisfactorily due to earthquake loads.

Various research have been conducted to better understand the seismic performance of non-engineered buildings. It has been known that masonry wall plays significant role in non-engineered structures, and several experimental studies were conducted on the subject. Most of these studies focused on structural elements, such as masonry properties, mortars and concrete used, as well as detailing of masonry wall confined by reinforced concrete frame. Few studies were conducted on a complete typical house structure. Hence, the effect of 3D structures with out-of-plane walls and better structural integrity was unobserved. Therefore, an experimental study was conducted with the objectives of: (i) to evaluate the performance of a typical non-engineered structure due to earthquake load; (ii) to validate the seismic performance of such structure built using a local standard.

The one-story structural model was constructed based on typical houses built using standard published by the Indonesian Ministry of Public Works (Boen, et al, 2009). The full-scale model was tested under cyclic loading test with increasing displacements. The observed parameters were collapse mechanism, lateral load and displacement capacities, ductility, and dissipated energy. Experiments were also conducted on construction material, i.e. masonry unit, mortar and frame concrete, steel reinforcement bar, to obtain the actual material properties. The results from the experimental study are presented in this article, and subsequently used to develop numerical models to further understand the behavior of non-engineered structures under seismic loads (Suarjana et al, 2012).

2. MATERIAL PROPERTIES

The structural model was constructed using moderate quality red bricks and reinforced concrete frames with concrete mixture of 1:2:3 (volume of cement, sand and coarse aggregate, respectively), and water being added as much as 100% of the cement volume. The volume of water was controlled by taking a slump value of 12~15cm. The red brick unit size was 55 × 100 × 205 mm. Mortar spacing between bricks was approximately 15 mm thick with a mixing composition of 1:5 (volume of cement and sand, respectively), using the same volume of water as cement. Similar mixture of mortar was used for plaster, which was approximately 20 mm thick as part of finishing. Frame reinforcements used a nominal diameter 10 mm plain steel bar for main/longitudinal rebars, and a nominal diameter 8 mm plain bar for transverse rebars. The 8 mm plain rebar was also used for anchorage between masonry walls and columns.

The material tests were intended for analysis and verification on numerical models based on the experimental study. Tests of materials were carried out in line with the schedule of testing of structural model. Figure 1 shows some examples of testing for materials. The complete results of material tests and material properties obtained from these tests are presented in Table 1.

Figure 1 Testing of Materials for Non-Engineered Structural Model

Table 1. Material properties

No	Material	Properties	Test Result
1	Concrete	Compressive strength (fc’)	17.2 MPa (tie beam), 17.1 MPa (ring beam), 22.7 MPa (column)
2	Steel rebar	Actual diameter	9.8 mm (longitudinal)l, 7.6 mm (transversal)
		Yield stress (fy)	355.6 MPa (longitudinal), 335.9 MPa (transversal)
3	Brick	Compressive strength (σb)	3.8 MPa
4	Mortar	Compressive strength (fm)	19.8 MPa (mortar), 15.3 MPa (plaster)
5	Brick-Mortar Bond	Shear strength (fk0)	0.47 MPa (plastered), 0.21 MPa (unplastered)
		Diagonal shear strength (fk45)	2.11 MPa (plastered), 0.59 MPa (unplastered)

From the material test results, some key findings are as follows:

i. The compressive strengths of concrete and mortar are vary from one structural component to another, The discrepancies were due to variation of water volume used in the mixture.
ii. Tests on steel reinforcement bars show that the actual diameters are smaller than nominal values. The measurement of actual diameter was conducted using the method of measurement weight of rebar, which yielded smaller values than the nominal dimensions.
iii. The result of shear stress and diagonal shear stress on brick-mortar bond show that the application of plaster significantly increased the shear strength of the walls.

The results from material tests were subsequently used to develop numerical model for the test specimen, and presented in the companion paper (Suarjana et al, 2012).

3. STRUCTURAL TEST SET-UP

A 6 x 6m with 3m height non-engineered house was tested in full scale as a prototype of a simple house structure without roof elements. Completed with tie beams and ring beams, columns were provided at every wall intersections, thus limiting the wall area into less than 10 m^2. Proper detailing of beam-column connection was specified with development length and seismic hook. For wall to column connection, anchorage was provided for masonry walls for every six brick layer using a plain bar with diameter 8 mm with the length of 40 times diameter. The interior and exterior masonry walls were plastered with mortar of 2 cm thick. Openings (doors and windows) were provided as in real structure, and framed with wood. The planar geometry layout of the specimen is given in Figure 2. The vertical layout for the masonry infill wall confined by reinforced concrete frame is presented in Figure 3, while Figure 4 shows the detailing of beam column connection.

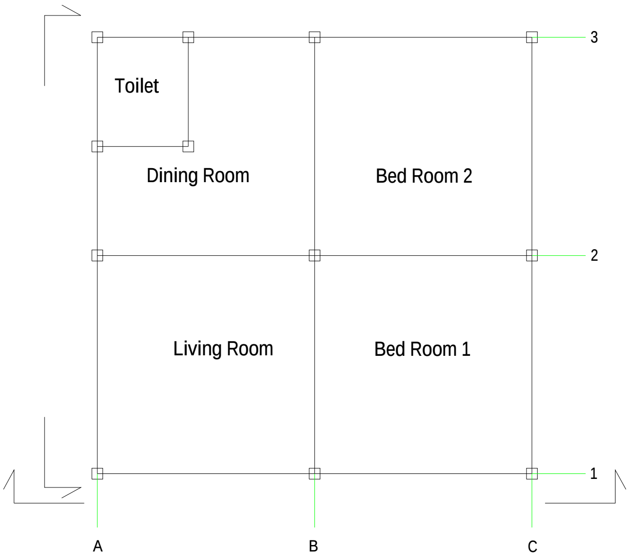
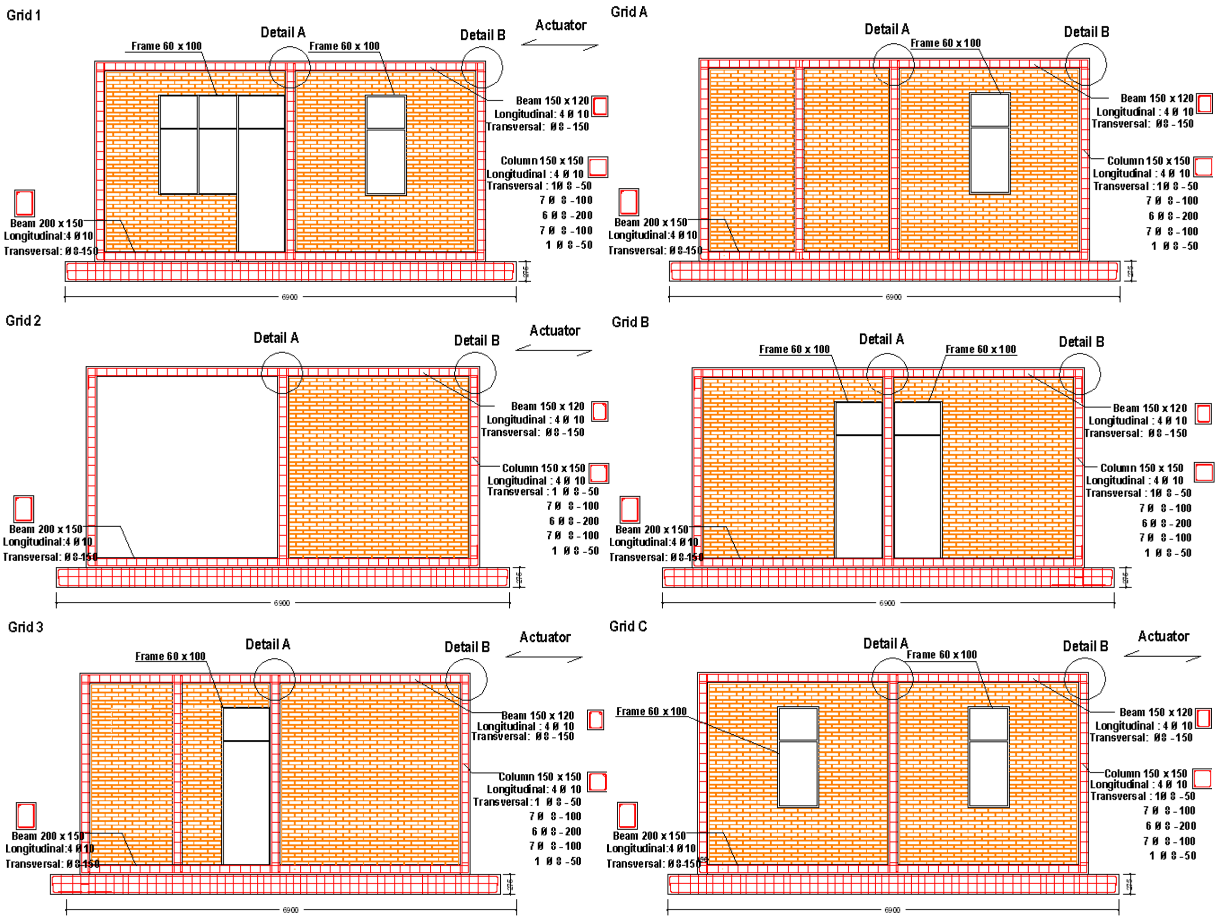


Figure 2 Plan Layout of Non-Engineered Structural Model



(a) Grids 1, 2, 3

(b) Grids A, B, and C

Figure 3 Vertical Layout of Non-Engineered Structural Model

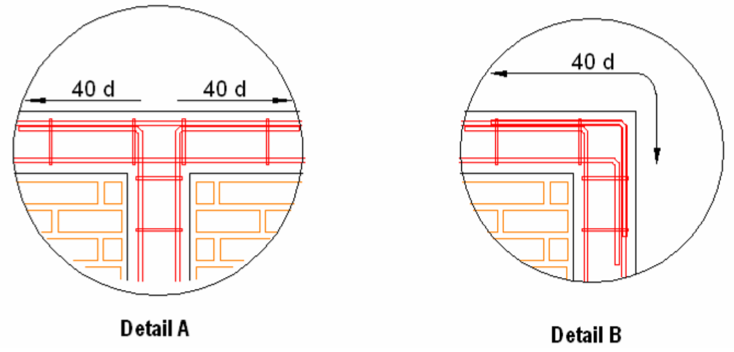


Figure 4 Detailing of Connections for Non-Engineered Structural Model

The structural model was based on a typical residential structure built using the standard published by the Ministry of Public Works (Boen, et al, 2009). Available for public after the devastating 30 September 2009 West Sumatra earthquake, this guideline was intended as a technical assistance for home owners and workers for reconstruction projects. It is equipped with clear illustrations on how to build typical confined masonry structures, including good construction materials, as well as proper detailing for connections and structural elements. It is envisioned that residential building constructed following requirements in this standard can be considered as an improved confined masonry structure, and will perform satisfactory under earthquake loading. Figure 5 shows various stages of construction of the test model. The construction includes the making of structural foundation as the base.

Figure 5 Construction Stages of Non-Engineered Structural Model

Considering the limitations of the testing facility, cyclic lateral loads were applied using servo-controlled hydraulic actuator at the ring beam elevation. To transfer the pulling force on the specimen into the reverse direction, 4 stiff steel rods were installed on the beams to accommodate the process. To transfer the lateral loads from the actuator to the middle wall (Grid 2), H-beam was installed on the beam. However, the exact lateral load that was applied to the middle wall could not be obtained due to some flexibility of the H-beam.

The applied load was measured using load cells. To obtain structural responses, strain, shear strain, deformation, and joint rotation were measured using strain gauges and LVDTs. Data were collected using a 100-channels data acquisition system (data logger) in the experiment. In addition, visual data were obtained from documentations and drawings of cracks on the exterior walls of the specimen. The test set up is illustrated in Figure 6.

The test protocol was such that lateral testing was conducted by applying quasi-static load in the direction parallel to Grids 1,2, and 3 (in-plane grids). Thus, cyclic testing loads were applied on the upper beam of the specimen, as two point loads on the corners of the structure. Loading mechanism used displacement control, of which displacement control was determined by maximum deformation measured using 3-way LVDT on the specimen. Strokes were applied in cyclic ways and stopped when the specimen has reached 25% reduction of its strength or drift 3.5%., due to the limitations of testing facility and instrumentations.

The loading scheme used in the experiment was applied following FEMA 450 recommendation for testing of structure, and presented in Figure 7. For each displacement, 3 cycles were applied to the model, with a smaller cycle in between the 3 cycles.

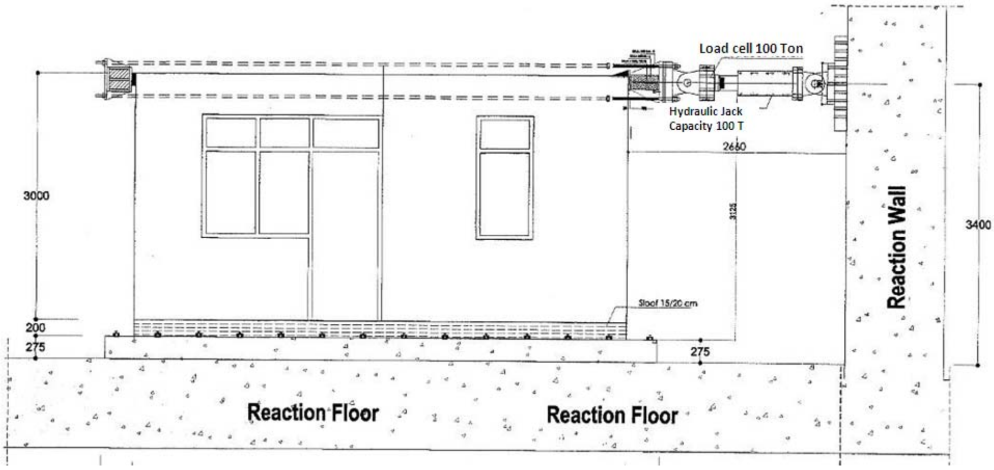


Figure 6 Test Setup for Non-Engineered Structural Model

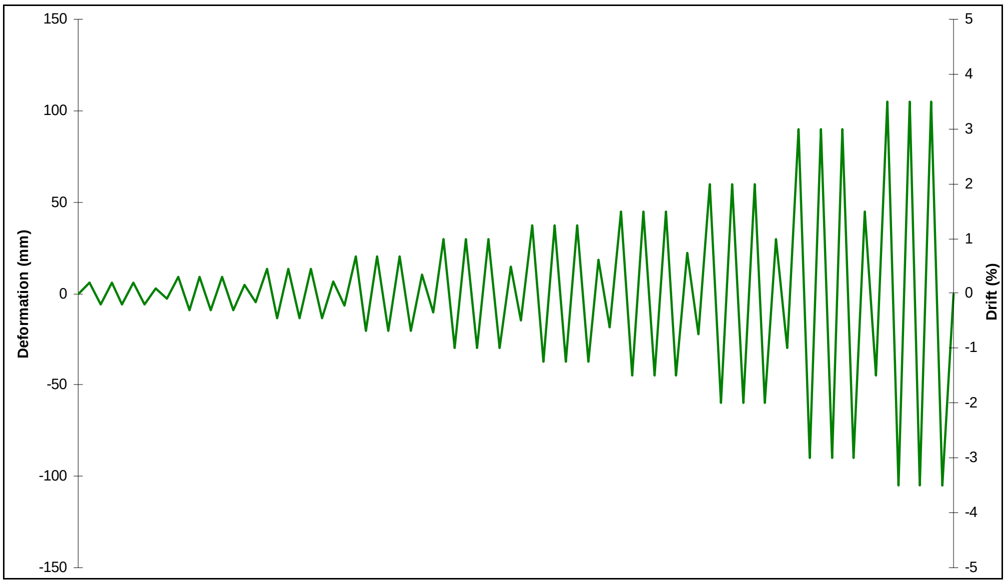


Figure 7 Test Loading Scheme

4. EXPERIMENTAL RESULTS

The strength analysis of a confined masonry structure is very much associated with its failure mode. The cyclic lateral test was conducted with increasing displacement up to the structural drift of 3.5% due to the limitation of the test facility. At the end of test protocol, the structure remained standing with no elements (columns, beams, and masonry walls) collapsed, although some elements suffered heavy damage. The final condition suggested that if the test were continued, larger displacement could be achieved for the structure. Figure 8 shows damages of the model at the final stage.

For in-plane grids, first cracks occurred at drift 0.031% at the corners of wall openings at Grid 1. It is expected since Grid 1 had the least wall area and columns, thus the stiffness of Grid 1 is lower than those of Grid 2 and Grid 3. The next cracks mostly occurred on wall area that was clear from anchorage and also at the corners of openings, with vertical cracks of walls were initiated at the end of anchorage. Later, visible diagonal cracks occurred at masonry walls, and truss mechanism was developed for Grid 1 and Grid 2. Grid 3 showed small cracks and the least amount of damage, due to the largest wall area in the in-plane direction. At the final stage (drift 3.5%), the columns at Grid 1 were deformed and bent in-plane outwards, thus confirming flexural behavior of the columns.

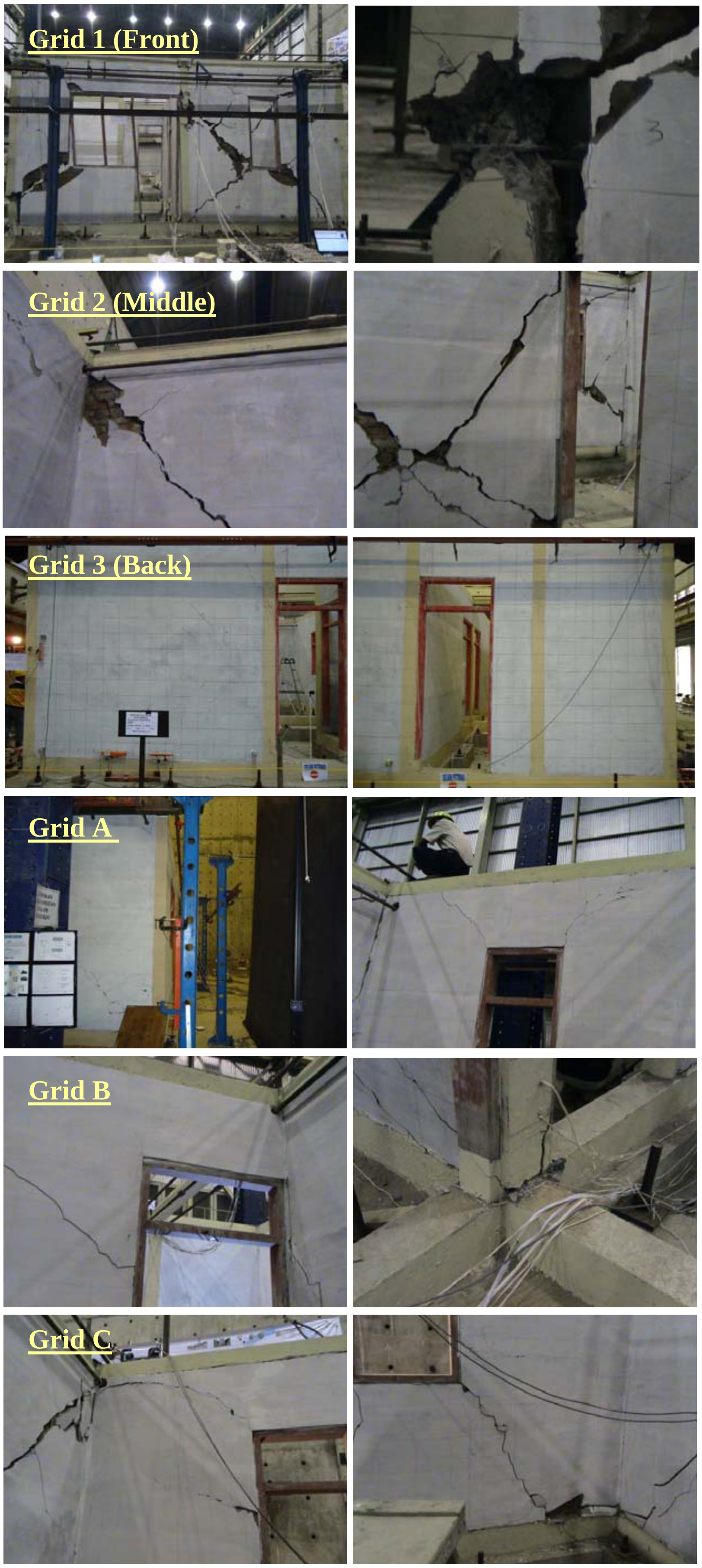
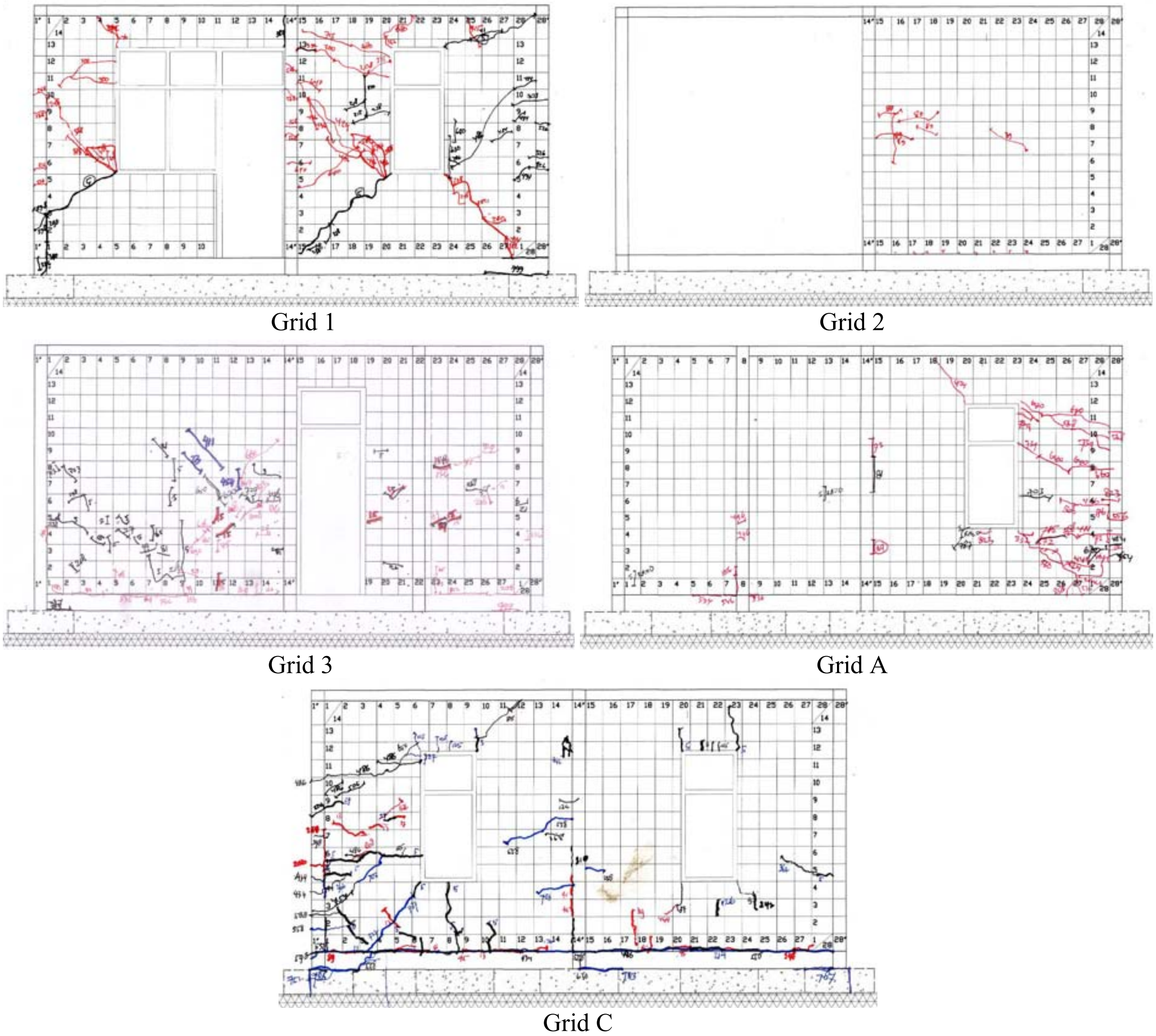


Figure 8 Damages on Non-Engineered Structural Model (Final Stage)

The structural model shows that wall separation in the form of vertical cracks was developed in addition to regular diagonal shear mechanism at Grids 1 and 2. The experiment shows that additional anchorage of wall to column prevented separation of columns and wall and limited damage area.

For out-of-plane grids, Grids A, B, and C were also damaged due to unsymmetrical layout of the model, translated into different stiffnesses of Grid 1, Grid 2, and Grid 3, which caused torsion effect and rotation to the model during cyclic loading. Since Grid 1 has the lowest stiffness, the maximum deformation occurred on this grid. Therefore, most cracks at Grid A and Grid C were developed at the corners of openings in the adjacent areas to Grid 1. For Grid B, columns suffered damage at the bottom of structure and cracks were found at the corners of openings. As in the case of in-plane grids, providing anchorage of wall to column greatly reduced damage area on out-of-plane walls. The crack patterns of non-engineered house model at the final stage are presented in Figure 9.



Grid 1

Grid 2

Grid 3

Grid A

Grid C

Figure 9 Crack Pattern on Exterior Walls of Non-Engineered Structural Model (Final Stage)

For in-plane grids, crack patterns were recorded for Grids 1, and 3, as well as Grid 2 up to certain drift. Grid 1 is the most damage one due to large opening provided in the masonry walls. Clear diagonal truss was formed on the right panel of Grid 1, while the left panel shows damage concentrated on the area next to the opening with shear mechanism developed in that panel. Grid 3 shows the effect of out-of-plane walls in reducing damage of the panels. Although opening was provided on the right panel, the additional column and out-of-plane wall prevented damage near the opening, and diagonal truss was not developed for this grid. Due to technical difficulties in obtaining crack pattern for interior walls, development of cracks could not be reported. However, the final stage shows that the absent of wall on the left panel has significant effect in damage of structural elements, and diagonal truss was observed on the right panel.

In the out-of-plane grids, crack patterns were recorded for Grid A and C only, due to technical difficulties in obtaining crack patterns for Grid B during the test. As explained previously, the majority of cracks occurred due to rotational movement with respect to lower stiffness of Grid 1 compared to Grid 3. With less opening and having an additional wall perpendicular to it, damage observed on Grid A was less than Grid C.

The responses of confined masonry structure under lateral cyclic loading were presented in load-displacement hysteretic curve. The lateral displacements were obtained from LVDT reading on the top of the specimen, whereas loads were obtained from the load cell of the actuators. Figure 10 shows the hysteretic curve obtained from this study. From the hysteretic curve, the structural model demonstrated some energy dissipation capacity. Moreover, the structure behaved inelastic with some ductility, illustrated by the minor strength reduction after first yield occurred. The structure was able to maintain its strength capacity well beyond the yield displacement. Evaluation on strain gages reveals that the longitudinal reinforcement bars started to yield when the drift reached 0.35%. However, the yielding of rebars only occurred on beams and columns of Grids 1 and 2.

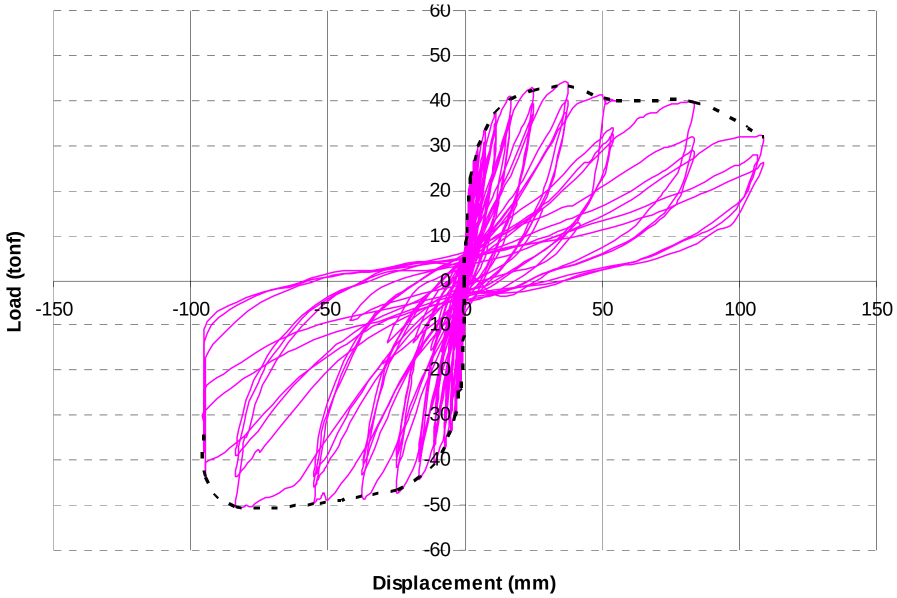


Figure 10 Hysteretic Curve of Non-Engineered Structural Model

The maximum strength of the confined masonry structure model is found to be 43.5 ton-force, occurred at a displacement of 37.3 mm (drift 1.191 %.) This force is larger than the design seismic load for this type of structure. At 80% of the maximum strength (20% strength reduction), i.e. a strength of 34.8 ton-force, the correlated displacement is approximately 100 mm (drift 3.2%). This drift is larger than 2%, which is commonly used as the limit of structural inelastic response.

The cyclic lateral test was stopped at 3.5% drift, with the structure remained standing and no elements (columns, beams, and masonry walls) were collapsed, albeit some suffered heavy damage. The final condition strongly indicated that larger displacement could be achieved without total collapse of the structure. It should be noted that as long as the reinforced concrete frames could provide confinement to the masonry walls, the strength reduction could be prevented, and the structure was able to undergo further displacement without collapse. Therefore, proper detailing is important to ensure the durability of reinforced concrete frames.

In general, the structural model shows that it can resist lateral loads and undergo large displacement (more than 3.5%) without collapse. Therefore, the study confirms that the structural model built according to the standard published by Ministry of Public Works can be considered as an improved confined masonry structure, and is expected to behave satisfactorily under earthquake loads.

5. CONCLUDING REMARKS

The experimental study was conducted to study the behavior of confined masonry structure subjected to cyclic lateral load, and can be used to validate the local standards to ensure that the structure will perform satisfactorily under earthquake loads. The experimental study concludes that:

1. Confined masonry infill wall significantly improved strength and stiffness on the structural response. More masonry walls will provide additional strength and ductility to the structure.
2. Most cracks were developed at the corners of openings. These cracks contributed to the development of diagonal truss on the masonry wall, provided that these openings had rigid frames (wooden or reinforced concrete).
3. The out-of-plane walls that are perpendicular to the direction of loading provided additional restraints for the in-plane wall movements, and improved the structural performance in general.
4. Proper detailing of confining frame elements and connections is important to prevent structural damage on the frame, thus prolonged confining action to the masonry walls.
5. Anchorage of masonry walls to column elements limits damage area on the masonry walls, and moreover, prevents damage in the out-of-plane direction.

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