Experimental Study on Confined Brick Masonry in Indonesia

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SUMMARY:
The authors have been working on “non-engineered” houses, which are main causes of casualties by earthquakes, and conducted field surveys on affected houses, monitoring of construction practice on site, and shaking table tests of full scale specimens. Based on these results, the authors conducted cyclic loading tests to verify effects of several proposals to improve seismic safety. A benchmark model has been set up which is usually found in construction sites in Indonesia. Six types of proposals of seismic designs were made by adding reinforcements, improving detailing or others with small additional cost. Total of nine specimens (including two of usual construction practice) of walls with dimension of 3m x 3m were tested by in-plane cyclic loading. The tests showed that some proposals are effective and some others need further improvement as they showed unexpected and undesirable behaviours.

Keywords: confined masonry, experimental study, cyclic loading test, seismic design, Indonesia

1. BACKGROUND

Every large-scale earthquake causes widespread social damage and, most tragically, human casualties in developing countries. The main cause of human casualties is collapse of houses of usual people, often called “non-engineered” houses because they are built with little or no intervention by engineers. In spite of this critical situation, few researchers and engineers have paid attention to such houses. The report “Living with Risk: 2004 Version” by the UNISDR (United Nations International Strategy for Disaster Reduction), clearly describes the situation: “It remains something of a paradox that the failures of non-engineered buildings that kill most people in earthquakes attract the least attention from the engineering profession.”
The authors have been involved in several projects on safer non-engineered houses, conducted collaborative research with researchers in Asian countries, and recognize that appropriate seismic technology is necessary, which is affordable to people of low/middle income, feasible to local conditions with limited tools and facilities and acceptable to local construction workers. In order to contribute to develop affordable seismic technologies, we conducted a series of experiments.

2. OBJECTIVES AND DESIGNS OF SPECIMENS

2.1. Objective structure type

The authors chose confined masonry structure as the target structure type, which is one of the most commonly adopted worldwide. This is a construction type that four ends of masonry walls are enclosed by relatively small section of reinforced concrete (RC) members just like surface of the walls and RC members are usually in the same plain. Masonry walls could be made of solid brick, hollow brick, concrete block or others. In the experiments we followed construction practice in Indonesia, where thin solid brick walls (stretcher bond with width of about 10cm) are enclosed by RC columns and beams of 10cm of width. Construction procedures are 1) laying bricks 2) form works for concrete placing 3) concrete placing. This type of construction is expected to have certain level of resilience compared with unreinforced brick structure but often suffered from earthquakes such as Central Java Earthquake 2006 and Padang Earthquake 2009. It is widely adopted by people and also international organizations

2.2. Policy of experiments

The authors have conducted various field surveys on damaged buildings, and monitoring surveys on construction practice from earthworks to finishing in Indonesia and Peru. Based on the results and discussion the authors got several proposal designs to reduce vulnerabilities, which are described below. A benchmark model has been set up to compare with each of the proposed designs. The experimental method is cyclic loading of lateral force following ACI374,1-05, to wall specimens of dimension 3mx3m.

Fig. 1 Failure of a joint of RC members by Central Java Earthquake 2006 （Special Province of Yogyakarta, Indonesia）

Fig. 2 Failure of a joint of RC members by Kashmir Earthquake 2005 (North West Frontier Province, Pakistan)

Fig. 3 Insufficient compaction of concrete of a reconstruction house in Banda Aceh, Indonesia

Fig. 4 Scratched paper in a concrete column which was filled in gap between form panel to prevent concrete leaking in Banda Aceh,

Fig. 5 Separation of RC members and walls resulting failure of brick walls in Banda Aceh, Indonesia

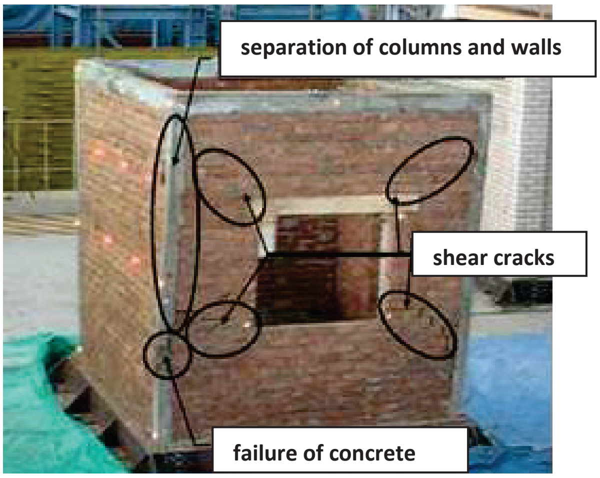


Fig. 6 Failure procedure of confined masonry structure reproduced in shaking table test in National Research Institute for Earth Science and Disaster Prevention (NIED) in Tsukuba in 2008, Japan

<Vulnerability observed in the field surveys>

- coming off of longitudinal rebar (without breaking) which often causes total collapse of structures (Figure 1)
- breaking at connection of structural members (Figure 2)
- failure of structural members caused by insufficient dimension in section area and defective concrete placing (Figure 3,4)
- separation of RC members and walls (Figure 5,6)
- collapse of brick walls in in-plane and out-of-plane (Figure 5,6)

3. DESIGN OF SPECIMENS

3.1. Bench mark specimen (Model B)(Table 1)

The design of the benchmark is similar to that of reconstruction houses for Central Java Earthquake 2006 recommended by the local government. The outline is described below. There is a difference between the benchmark model and the government recommendation that there is an absence of anchors between columns and walls in the benchmark model for clear comparison with other models.

- dimension of column section: 15cmx15cm
- longitudinal rebar: round bar ϕ 10mm (average quality in market)
- hoops and stirrups: round bar ϕ 6mm @200 (average quality in market)
- brick: average quality in market

Basic data common to all the specimens are as follows.

- compression strength of concrete: 18.08N/mm^2
- compression strength of brick: 4.16N/mm^2

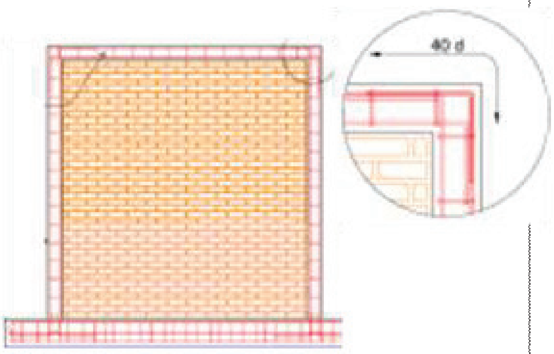
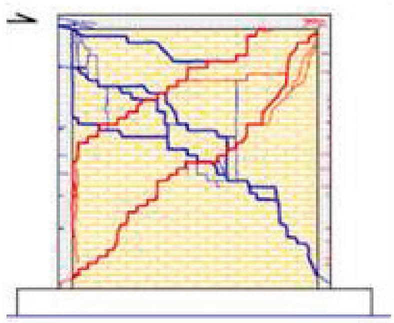
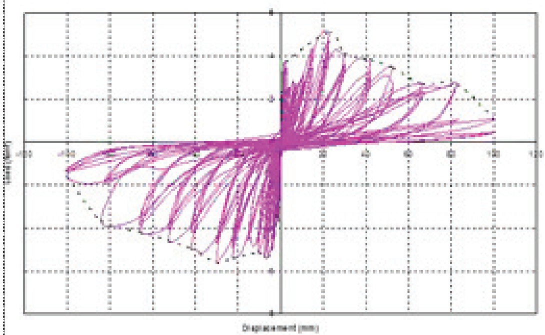
3.2. Specimens of usual construction practice (Table 2)

3.2.1 Usual construction practice 1(Model I)

This model reproduces usual construction practice on construction sites. Difference from the benchmark model (Model B) is as follows,

- No anchorage of longitudinal rebar into connecting structural members by bending 90 degree designed in Model B. This detailing is quite difficult on site where usual construction procedures are 1) build up box section of rebar on ground 2) placing the box to the designed location, shown in Figure 7 and 8. The ends of rebar just got hooked as shown in Figure 1 and Table 2.

Table 1 Model B (benchmark): Design, crack pattern, load-drift curve and photo

Model	Model B	
Design No	Benchmark	
Type	similar to recommended design (difference: absence of anchor between columns and walls)	
Design features	columns and beams: 150mmx150mm	
	overlapping splice of rebar: 40d	
	reinforcement: usual	
Figures	Design	Crack patttern
		
Figures	Load-drift curve	Photo at final stage
		

3.2.2 Usual construction practice 2 (Model A)

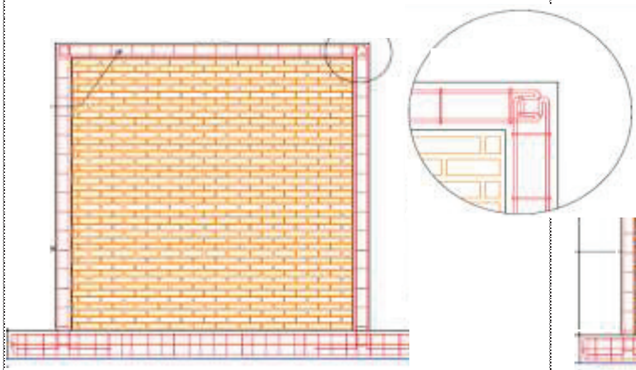
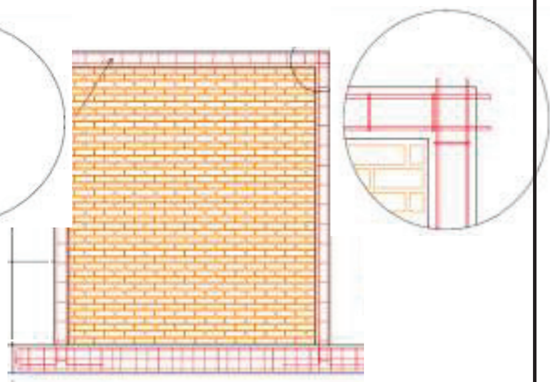
Model A is another type of usual practice. Differences from Model A are as follows,

- No anchorage of longitudinal rebar which just extended as shown in Table 2
- Dimension of column section: 10cmx15cm (The width of columns (10cm) is same as walls so that formwork for concrete placing becomes simpler)

Fig. 7 Bending work of rebar with simple tools for reconstruction houses in Banda Aceh, Indonesia

Fig. 8 Placing a box of rebar assembled on ground in Banda Aceh, Indonesia

Table 2 Designs of specimens of usual construction practice

Model	Model I	Model A
Design No	Usual construction practice 1	Usual construction practice 2
Type	connection of rebar: just hooked	connection of rebar: just extended
Design features	Columns and beams: 150mmx150mm ovewrlapping splice of rebar: none reinforcement: usual	Columns and beams: 100mmx150mm overlapping splice of rebar: none RC members: smaller than bench mark
Figures of design		

3.3. Specimens of proposed designs (Table 3)

3.3.1 Proposed design 1 (Model C: easier formwork)

In order to make formwork for concrete placing simple, width of columns and beams is reduced to 10cm, the same width of the walls. At the same time length increased to 22.5cm to have the same section area. This allows the formwork to be placed easily, reduces cost, and could contribute to prevent to fill scratched paper in gap between form panels like Figure 4.

3.3.2 Proposed design 2 (Model D: anchor between columns and walls)

In order to prevent separation of columns and walls like Figure 6, anchors of round bar of ϕ 6mm are placed every six layers of brick. These are also expected to contribute to prevent out-of-plane collapse of walls, which is one of most vulnerable failure mechanism of masonry structure.

3.3.3 Proposed design 3 (Model E:teething of wall ends)

In order to improve integration of columns and walls, bricks are laid to make side ends and upper ends to have teeth (zigzag shape). This is simpler and less expensive method than Model D or Model F.

3.3.4 Proposed design 4 (Model F:continuous anchor)

This is a model with further improvement of Model D by extending two of the anchors from column to column. The continuous anchors are placed at lintel and window sill level so as that windows could be installed without disturbance by the continuous anchors. The continuous anchors are round bars of 8mm.

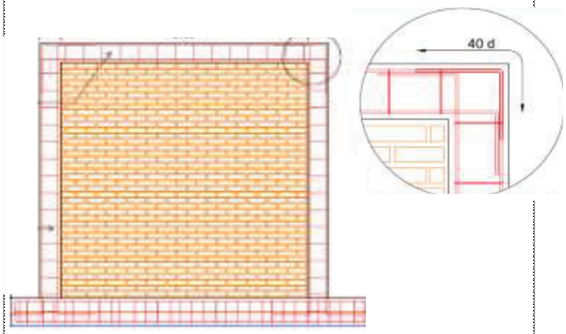
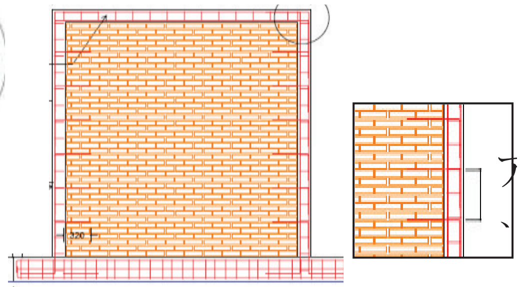
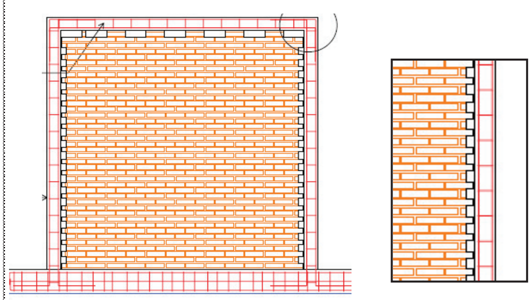
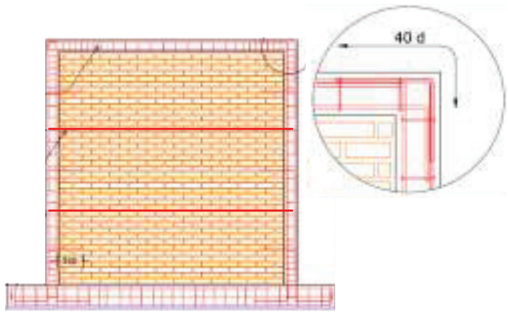
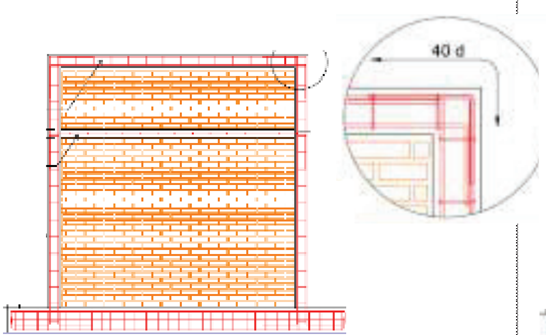
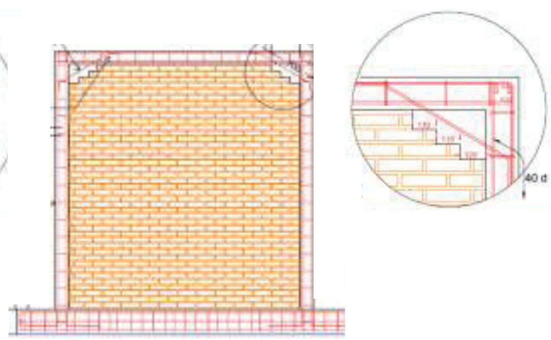
3.3.5 Proposed design 5 (Model G: lintel beams)

This is a model on the similar idea with Model F to install horizontal reinforcement in the wall. The reinforcement of this model is an RC beam of section dimension of 10cmx10cm with longitudinal rebar of two round bar of ϕ 10mm and stirrups of ϕ 8mm @200mm. The position of the beam is at lintel level.

3.3.6 Proposed design 6 (Model H:haunched beams)

This is a model to strengthen connection of columns and beams by installing additional triangular RC portions. The connections are often found separated in damaged buildings, which often causes total collapse of the buildings. (Figure 1,2) In order to prevent the separation, anchorage of longitudinal

Table 3 Designs of specimens of proposal designs

Model	Model C	Model D
Design No	Proposed design 1	Proposed design 2
Type	easier form work for concrete placing	anchor between columns and walls
Design features	Columns and beams: 100mmx225mm ovelapping splice of rebar: 40d RC members: different dimension, same section area	Columns and beams: 150mmx150mm ovelapping splice of rebar: 40d anchor between columns and beams: φ 8mm l=40d at 6 lay
Figures of design		
Model	**Model E**	**Model F**
Design No	Proposed design 3	Proposed design 4
Type	teething of wall ends	continuouse anchor
Design features	Columns and beams: 150mmx150mm ovelapping splice of rebar: 40d teething of wall edges	Columns and beams: 150mmx150mm ovelapping splice of rebar: 40d reinforcement: two anchor steel bar are extended
Figures of design		
Model	**Model G**	**Model H**
Design No	Proposed design 5	Proposed design 6
Type	Intel beam	haunch corners
Design features	Columns and beams: 150mmx150mm ovelapping splice of rebar: 40d reinforcement: lintel beam (100mmx100mm) is addded	Columns and beams: 150mmx150mm splice of rebar: none (end of rebar just hooked) RC members: corners are reinforced with haunches
Figures of design		

rebar (overlapping splice) is usually employed like the Bench mark Model (Model B). But this detailing is difficult to be implemented on site as explained in 3.2. Specimens of usual construction practice. It
may also cause insufficient compaction of concrete because of congestion of rebar at the connection. The additional triangular RC portion is expected to allow easier construction works and better placing of concrete.

4. RESULS, ANALYSIS AND CONSIDERTATION

Table 4 shows outline of the results of cyclic loading tests of each to specimens. Fig.9 is envelope of hysteretic curve. These data leads us to following analyses.

Table 4 Outline of results of cyclic loading tests

Model	Type	Maximum loads			eformation at Max load		Behavior
		+ (pushing)	− (pulling)	Average	deformation	ratio	
A	Usual construction practice 2	3.54	4.69	4.12	16.09	1/200(0.5%)	1)Cracks appeared in upper part of the wall, 2) Maximum load was recorded at deformation 0.5%, 3)Cracks extended into joint of column and beam
B	Bench mark	5.09	5.61	5.35	30.20	1/100(1.0%)	1)Diagonal cracks appeared in all the wall, 2)Deformation increased, 3)Maximum load was recorded at deformatin 1.0%
C	Proposed design 1:easier form work	6.05	5.85	5.95	30.02	1/100(1.0%)	Similar behavior to Model B (Bench mark) Maximum load was larger than the bench mark
D	Proposed design 2:anchor between columns and walls	6.05	5.44	5.75	30.04	1/100(1.0%)	1)Vertical cracks appeared in early stage, 2)Diagonal cracks appeared in all the wall, 3) Maxmum load incresed
E	Proposed design 3:teething of wall ends	4.28	4.26	4.27	41.72	1/70(1.4%)	Similar behavior to Model D. Maximum load did not incress as Model D
F	Proposed design 4:continuous anchor	6.93	6.70	6.82	30.04	1/100(1.0%)	Similar behavior to Model B (Bench mark) Maximum load was larger than the bench mark
G	Proposed design 5: lintel beams	7.4	7.32	7.36	42.10	1/70(1.4%)	1)Diagoanal cracks appeared in each of upper and lower part of the lintel beam, 2)Deformation increased, 3)Maximum load at about 1.4%, 4) Finally cracks extended beyond the lintel beam
H	Proposed design 6:haunched beams	4.96	4.29	4.63	10.54	1/300(03%)	1)Many cracks appered in lower part of the wall, 2)Maximum load was small at small deformtion at deformation 0.3%, 3)The cracks extended into columns
I	Usual construction practice 1	5.06	4.62	4.84	15.60	1/200(0.5%)	Similar behavior to Model A

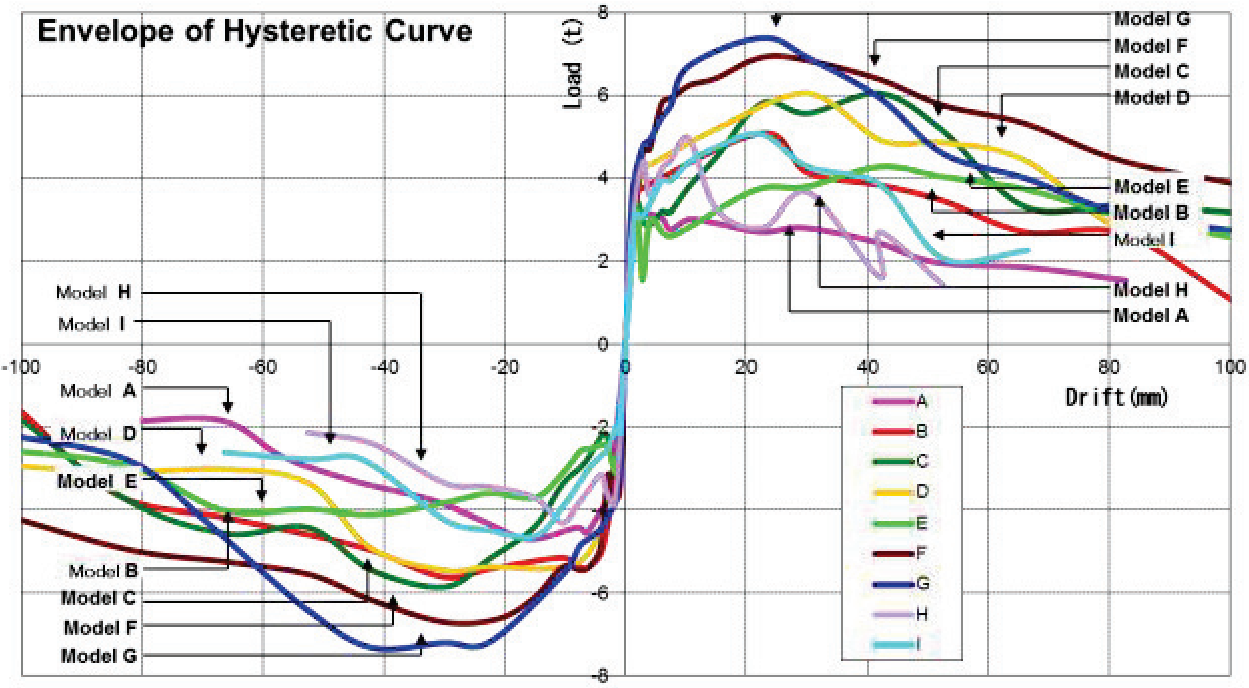


Fig. 9 Envelope of hysteretic curves

4.1. Connection of RC members (Comparison analysis between Bench mark (Model B) and Model A,H, and I)

4.1.1 Result and analysis

The authors expected that failures at connection like Fig. 1 and 2 would occur in Model A and I because improper connection of longitudinal rebar would be the main cause of this types of failures, but actually did not. We notice there is difference of concrete placing between specimen and construction practice on site. The specimens have well compacted concrete using vibrators. On the other hand RC members on site do not, and have cold joints at the connection. Furthermore improper construction practice like filling scratched paper like Fig. 4 also could occur. These facts lead us to conclusion that failures at connection of RC members which often lead to collapse of total structures are caused by both improper connection of rebar and poor concrete placing.

Regarding maximum loads and deformation the bench mark model (Model B) has larger maximum load and drift than Model A and I. Both specimens of A and I have several shear cracks in the uppermost part of columns, which seemed to hinder the development of further strength and ductility. In case of the bench mark, this part has no shear cracks perhaps because of additional number of longitudinal rebar by overlapping splices and has larger strength and deformation capacity. This is additional effect of overlapping splices and should be taken into consideration in structural design.

Model H is designed mainly to strengthen the connection to prevent dangerous failures like Fig. 1 or 2. However it has far smaller strength and drift than the benchmark (Model B). Judging from crack patterns, another type of failure occurred in Model H that several shear cracks occurred in lower part of columns perhaps because haunch portion increased rigidity of upper part of columns and deformation concentrated in less rigid part of lower one, which caused the shear cracks. This can be summarized imbalanced reinforcement of specific part may cause change of total failure mechanism and bring another problem.

4.1.2 Consideration

One of the most fatal failures is one at connection of RC members and the authors unsuccessfully tried to reproduce it in the tests. One of the reasons that this failure could not be reproduced was the good compaction of concrete of specimens by vibrators. It gives lessons that concrete placing should be conducted well and that border surface of concrete placing (cold joints) should not be located near connection where the bending moment is larger. This needs to be further discussed from the viewpoint of feasibility and acceptability on site. Compaction of concrete is usually conducted by sticking with bars, not by vibrators. It is not easy to realize good compaction without vibrators. In order to avoid border surface of concrete placing from near the connection, drastic change of formwork and concrete placing has to be done. This issue should be further discussed with possible change of construction procedures.

Model H designed to prevent the fatal failure showed the poor performance. It does not mean this type of approach is bad in general, however in this case another failure mode was induced because of the presence of the haunches. The key idea of this design to give 1) easier detailing of installing additional rebar instead of bending of longitudinal rebar, 2) additional space at the corner for congested rebar, could be a possible solution. Better design based of the lessons such as appropriate design of haunches or reinforcement of weak part should be explored.

4.2. Dimension of section of RC members (Comparison analysis between the benchmark (Model B) and Model A and C)

4.2.1 Result and analysis

The maximum lateral loads of Model A, B and C are observed in order described below. It is exactly same as size of inertia moment of RC members of each specimen.

Model C > Model B > Model A

4.2.2 Consideration

The idea of model C requires no additional cost of concrete and steel and has possibility to reduce cost of formworks. This could be a good proposal which consists of appropriate designs. Careful consideration should be made in 1) section design like Model C has different inertia moment in each of different directions (X or Y), 2) balance of strength in direction of X and Y in configuration of RC members is necessary, 3) well detailing designs are necessary at crossings of walls.

4.3. Connection between RC members and walls (Comparison analysis between Bench mark (Model B) and Model D and E)

4.3.1 Result and analysis

Model D and E are designed to improve connection between RC members and walls. Model D shows a little better behaviour than the bench mark in pushing and similar in pulling. Failure mechanism of the bench mark is that vertical cracks appeared in connection of columns and walls in early stage but then diagonal cracks appeared and bearing load was keep increasing. On the other hand Model D got vertical cracks around ends of anchors and bearing load is not increasing. Model E has similar behaviour to Model D just like vertical cracks in parts of teething of bricks and concrete at far lower bearing load. The authors noticed crack in Model D and E occurred in bricks, not in mortar. This implies the one of the reasons of vertical cracks in early stage at low bearing load is poor strength of bricks (average: 4.16Mpa). This suggests strength of brick has to be taken into consideration in designing of connection improvements.

4.3.2 Consideration

The connection between RC members and walls is very critical as separation of them leads to out-of plane collapse of walls shown in the shaking table test (Figure 6). The vertical cracks in early stage are dangerous behaviour from this view points. Both Model D and E do not show enough performance we expected. Further improvement is necessary such as better detail designs of anchors and teething and combination with other improvement such as reinforcing walls.

4.4. Reinforcing walls (Comparison analysis between Bench mark (Model B) and Model F and G)

4.4.1 Result and analysis

Both Model F and G showed well improved behaviour in comparison with the bench mark with remarkably larger maximum loads. It can be concluded that the idea of reinforcing walls is effective in improving performance in shaking motion is verified.

4.4.2 Consideration

Both of Model F and G could be a good proposal for the final goal of appropriate designs. Especially Model F has higher possibility as it costs less and does not need additional works such as form work and concrete placing.

5. CONCLUSION

Seismic designs for non-engineered houses are needed to be affordable for people and feasible in conditions on site so as to be widely accepted and adopted in developing countries. The specimens in this experimental study are designed to meet these requirements and verified by the full scale specimens. Judging from the results of the experiments, several proposal designs are proved to be appropriate such as 1) rectangular dimension of columns and beams in Model C, 2) continuous anchor in Model F and lintel beams in Model G. On the other hand, the unsuccessful results of proposal designs stated in the section 4.1.and the section 4.3. were unexpected. Another type of findings seem to be common in all kinds of models such 1) parts of members with large bending moment like near top and bottom of columns should be reinforced with smaller spacing hoops or other ways, 2) reinforcing of specific part leads the total structure to behave in different ways (reinforcing of specific parts causes different types failure mechanism) .

The authors have a basic policy to propose designs which will be welcomed to be adopted in construction sites. The structural designs need to consider various aspects of vulnerability such as connection between structural members, connection between structural members and walls, improving resilience of walls and others. Therefore they must have combination of effective proposals. In the context the authors conducted the series of experiments in a methodology of comparison with the benchmark and each of proposed idea of improvement and obtained the findings stated above. This study is a basic study leading to the target of appropriate designs and further efforts are needed.

6. WAY FORWARD TO NEXT STEPS

The experiments of the study were conducted under conditions of 1) without vertical load such as roofs, 2) lateral force is loaded only to beams, which are not precisely same as loading of actual earthquakes. Also all the wall specimens do not have windows and door openings. Further the experiments are cyclic loading in in-plane and out-of plane loading is another very important issue. All these need to be further investigated.

Another key issue to appropriate designs is workability/feasibility of construction works on site. Appropriate designs need to be implemented without difficulties with limited availability of tools and facilities in constructing non-engineered houses. They also need to be acceptable to local workers with limited technical knowledge and skills. In order to verify these aspects, pilot construction and monitoring under actual situation should be conducted. The authors will make ways forward with these challenges and expects collaboration with people of same desire.

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