Paper N° 694

Registration Code: S-V1463261176

CASE STUDY: DESIGN AND CONSTRUCTION OF CONFINED MASONRY HOMES IN INDONESIA

T. Hart[(1)], J. Pazdon[(2)], L. Blaisdell[(3)], E. Hausler Strand[(4)]

[(1)] *Civil/Structural Engineer, Lawrence Berkeley National Laboratory, thart@lbl.gov*
[(2)] *Engineer, Cast Connex, jpazdon@gmail.com*
[(3)] *Director of Engineering, Build Change, lizzie@buildchange.org*
[(2)] *Founder and CEO, Build Change, elizabeth@buildchange.org*

Abstract

Beginning in Aceh in 2005 after the 2004 Sumatra-Andaman Earthquake and continuing after the earthquakes in West Sumatra and Padang, Build Change, an international non-profit organization, rebuilt confined masonry and timber houses in Indonesia in partnership with local builders, improved the design and construction of houses built by partner organizations, trained builders through intensive, on-the-job training programs, and trained technical high school students about the design and construction of earthquake-resistant houses.

Using confined masonry in the reconstruction was an improvement on the existing, commonly preferred systems, rather than an introduction of a new system. Minor modifications to existing design and construction practices were used to ensure these single story houses in Indonesia were affordable, easy to build with local materials, skills and tools, and earthquake-resistant.

Despite the fact that confined masonry was already common and locally sustainable in Sumatra, convincing some homeowners, engineers, government officials, and decision makers for donor agencies to build using confined masonry was a formidable challenge. For example, most engineers and decision makers working for funding agencies – both Indonesian and foreign – had never heard of confined masonry and were reluctant to use a system that they were unfamiliar with. The major hurdle was the cost of implementing earthquake-resistant design and construction improvements into the confined masonry practice already present. The improvements Build Change implemented in their Aceh house design added cost, which made it difficult to promote in West Sumatra and Padang because the construction costs there were paid by the homeowners rather than by donor agencies as was the case in Aceh. In many cases there had to be design modifications to make the construction financially viable while still maintaining safety.

There were technical challenges as well. While unofficial guidelines for confined masonry construction are available in Indonesia, there were (and still are) not provisions for confined masonry in the Indonesian building codes and the guidelines that are available are prescriptive in nature. Confined masonry provisions in the building codes for other countries could not be directly applied to buildings in Indonesia because the construction standards and practices were different from the research and experience data that the foreign code provisions were developed from. There were also challenges with obtaining good quality building materials and establishing construction quality assurance programs, in particular the latter since inspection of home construction was not common practice in Aceh or West Sumatra.

Confined masonry homes that were built to the standards developed by Build Change performed well in subsequent earthquakes in Indonesia relative to those that were not. This has demonstrated the viability of this structural system as a low-cost, locally appropriate solution for single story housing construction when designed and constructed properly. These earthquakes also illustrated how vulnerable houses can be when simple rules and good practices for configuration (wall height and length, gable walls, open terrace frames), connections (between confining elements, between walls and tie columns), and construction quality (materials and workmanship of the masonry and concrete) – the three C's – are not followed.

Keywords: Confined masonry; housing; Indonesia

1. Background

Beginning in Aceh in 2005 after the December 26, 2004 earthquake and tsunami and continuing in West Sumatra and Padang, Build Change, an international non-profit organization, rebuilt confined masonry and timber houses in partnership with local builders, improved the design and construction of houses built by partner organizations, trained builders through intensive, on-the-job training programs, and trained technical high school students about the design and construction of earthquake-resistant houses. Confined masonry was used in the post-Aceh reconstruction since it was an improvement on an existing, commonly preferred system, rather than an introduction of a new system. Minor modifications to existing design and construction practices were used to ensure these single story houses in Indonesia are affordable, easy to build with local materials, skills and tools, and earthquake-resistant.

Confined masonry houses can perform well in earthquakes, or they can cause deaths and injuries if designed and constructed poorly. The satisfactory performance of confined masonry buildings in subsequent earthquakes in Indonesia demonstrated the viability of this structural system as a low-cost, locally appropriate solution for single story housing construction. These earthquakes also illustrated how vulnerable houses can be when simple rules and good practices for configuration, connections, and construction quality – the three C's – are not followed.

2. Design Process

In March 2005 Build Change began work in Aceh with a detailed housing subsector study, including a survey of common structural systems, locally available building materials (including quality and cost), the skill level of local builders, commonly used construction tools, architectural and cultural preferences, and climate considerations and other hazards.

Four common structural types were identified in the study: confined masonry, reinforced concrete block masonry, timber frame on stilts, and timber frame with a masonry skirt. A team of volunteer structural engineers from the San Francisco Bay Area developed preliminary designs and a construction cost estimate for each of the four types [1]. Using these prototype designs, funding to build 11 houses in a pilot project was obtained from Mercy Corps, an international relief and development agency active in reconstruction since shortly after the tsunami. The homeowners in the project were asked which structural system they preferred and every one of them chose confined masonry. The pro bono structural engineers then performed more detailed analysis of a confined masonry house. At the same time, Build Change hired Acehnese engineers and an architect who created bills of quantity, detailed drawings, and a suite of floor plans and roofing alternatives that were appropriate to family size, plot size and local culture.

2.1 Seismic Hazard and Analysis Method

Building designs were checked for seismic forces in both principal directions using equivalent static analysis methods. Calculations were performed using a minimum design acceleration of 0.4g. This assumption was based on the 2002 Indonesian Building Code (SNI) [2] and the 2003 International Building Code (IBC) [3, 4], which were the most current standards in 2005. The acceleration was conservatively assumed to be at allowable stress/service level and was unreduced by a Response Modification Coefficient or R-factor. Because of their importance to the seismic performance of the building, the shear walls were designed for a design level acceleration of 0.5g. This corresponded to a Design Spectral Acceleration (S_{DS}) of 1.0g. The R-factor for the shear wall design was assumed to be 2 based on the Behaviour Factor (q) specified in Eurocode 8 [5] for confined masonry structures.

The peak ground acceleration prescribed by SNI in 2002 was 0.38g. The use of a design acceleration higher than what the SNI specified was so that the structural system could be built at any site in Sumatra in any soil condition allowed by the standard. The 0.4g acceleration also corresponded to the design spectral acceleration specified in the 2003 IBC for a soft soil site in Alaska, which has a subduction zone capable of generating large magnitude earthquakes similar to the subduction zone off the coast of Sumatra.

The USGS peak ground acceleration maps indicate the highest ground accelerations experienced in the September 30th, 2009 Padang earthquake were approximately 0.6g, significantly larger than the design forces based on the SNI current at the time (SNI-2007) but less than the design accelerations used for the Build Change homes. The excellent performance of the Build Change homes in the 2009 earthquake suggests the design was adequate to sustain loads in excess of the design baseline.

2.2 Applicable Codes and Guidelines

A building code for confined masonry still does not exist in Indonesia. The 2002 SNI [2], which was based on UBC 1997, has provisions for reinforced concrete frame construction that assumes that the concrete frames are the primary lateral force resisting system and thus are to be designed to resist the entire seismic force. Masonry walls within a concrete frame are assumed to be non-structural infill that do not contribute to the lateral force resistance. In a confined masonry system, however, the masonry wall is the primary lateral force resisting system rather than the concrete frame. Thus the SNI provisions for concrete frame construction could not be applied to the design of the confined masonry walls or the concrete confining elements.

The Badan Rehabilitasi dan Rekonstruksi (BRR), the Indonesian governmental agency charged with overseeing the Aceh recovery program, produced a building guideline for houses in mid-2005 [6]. The guideline was prescriptive in terms of size of frame elements, diameter of reinforcing bars, spacing of stirrups and ties, etc., but it omitted important details such as connections and anchoring.

During the design process, several other codes and guidelines were reviewed, including a series of posters produced by Indonesian structural engineer Teddy Boen [7], Marcial Blondet's construction guideline originally developed for confined masonry construction in Peru [8], and the IAEE Manual [9]. Teddy Boen's posters were a valuable resource that provided a starting point for the design and were the only resource available at the time that incorporated common construction practices in Indonesia. All of the other guidelines provided useful information about confined masonry construction. However, they could not be used for design because of the significant differences in the structural and architectural systems described in these guidelines compared with what was being built in Aceh. For example, the codes and guidelines typically specified minimum height to thickness ratios ranging between 20 and 25, but in Indonesia ratios exceeding 30 are common because of the standard clay brick sizes used there and the custom of using half-brick thick walls. Also, most guidelines specify concrete slabs for floors and roofs, whereas in Indonesia the roofs are typically framed out of wood or light gauge steel.

Build Change and its team of volunteer engineers utilized these resources and other documents to develop a detailed set of design drawings for the pilot project. These drawings were then used by Build Change to develop a design and construction guideline for earthquake-resistant confined masonry houses [10], which was first shared with BRR and other organizations working in housing at a seminar in May 2006 and later through personal communication and meetings with partner organizations.

2.3 Architectural, Cultural, and Climate Considerations

2.3.1 Tall, Slender Wall

Because of the hot climate, there was a preference for a tall wall, up to 3m in height from floor to ceiling. Masonry walls were customarily built using running bond, in which the bricks are laid end to end, resulting in a half-brick thick wall. This tall, slender wall has an aspect ratio that is higher than what is typically recommended for confined masonry buildings but it was the familiar and preferred method of construction in Indonesia at the time.

2.3.2 Large Openings

Because of the hot climate, there was a preference for tall doors and windows with vents above over the doors and windows, especially at the front of the house.

2.3.3 Lightweight, Timber Truss Roof

Pitched or hipped roofs were preferred because of the significant amount of rainfall that annually occurs in Indonesia.

2.3.4 Other Criteria

The BRR building guideline for the Aceh reconstruction [6] included additional architectural criteria, including a minimum 36m^2 plan footprint; at least two bedrooms; at least two entrances and exits; orientation appropriate for sun, wind, and Islamic culture; and toilet with a septic tank.

2.4 Design Details

2.4.1 Foundation and Floor

A trapezoidal-shaped stone masonry strip footing with steel dowels into the concrete plinth beam was used per the recommendation of the BRR Guideline. The dowels were intended to prevent uplift and to function as shear keys between the stone masonry foundation and the plinth beam. The floor was unreinforced concrete on compacted fill, with a finished floor height at least 60 cm above ground surface.

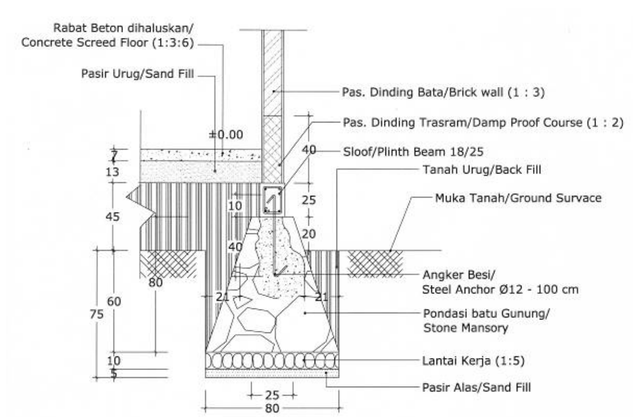

Fig. 1 - Wall Footing

2.4.2 Reinforced Concrete Confining Elements

Reinforced concrete bond beams were used at the foundation/plinth and roof levels. Reinforced concrete major tie columns were placed at all corners and wall intersections and minor tie columns were located at changes in contour and adjacent to all openings except the small bathroom vent window.

The initial design used the bar detailing and section sizes that were specified in the BRR guidelines, but construction challenges led to revisions to the design. The section size of the plinth beam was increased to increase the strength of the foundation beam in light of variable soil conditions and to make it easier to fit the column reinforcing inside the beam reinforcing at the column-beam connections. The longitudinal bar diameter was reduced by using deformed bars instead of smooth to make it easier for builders to cut and bend the bars properly by hand. The stirrup and tie bar diameters and spacing were modified for workability reasons and to provide increased strength in shear at the top and bottom of the columns. The spacing of stirrups in the bond beams was increased to save cost because the design calculations indicated that greater stirrup spacing was possible. The rebar hook length, hook rotation, and joint detailing were shown on the drawings whereas it was not common practice to call out these details on engineering drawings used in Aceh.

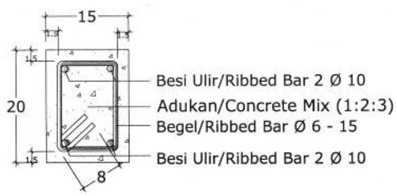

Fig. 2 - Ring Beam

Fig. 3 - Tie Column

2.4.3 Walls

Fired clay brick masonry walls were built prior to casting the columns, with Durowall-type steel reinforcement placed in the bed joint and tied into the columns at every seven courses of masonry and above and below openings,. All walls were finished with cement-based plaster and painted.

Out of plane failure of the tall, slender wall was a primary concern in the design process. Several alternatives were considered in order to mitigate out-of-plane failure, including adding cross walls and bracing to reduce the wall span. Wrapping wire mesh around the wall was considered but ruled out because of concerns about constructability and possible delamination of the mesh. Increasing the wall thickness by changing the masonry bond to English or Flemish bond, as is common for confined masonry structures in other countries, was also considered. However, to use full-brick wide bonding the length of the brick must be twice as long as its width plus the thickness of a head joint. Most of the bricks in Aceh are the wrong proportion for this bonding (too wide and short). Plus, this type of bond added cost and required a higher skill level from the masons; therefore this was not a feasible option. The final solution was to add vertical confining elements adjacent to all large openings and horizontal steel reinforcement within the wall bed joints. The openings were placed at the corners adjacent to major columns so that only one additional tie column would be needed.

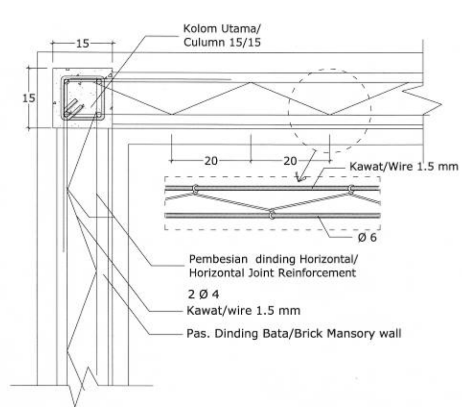

Fig. 4 - Horizontal Bed Joint Reinforcement

Build Change engineers observed fewer than expected out of plane wall collapses of CM walls without bed joint reinforcement after earthquakes in Yogyakarta and West Sumatra beginning in 2006. Out of plane weakness of the wall itself did not appear to be a factor because the collapses that were observed appeared to be the result of failure of the concrete tie elements or an orthogonal wall which resulted in the loss of confinement of the masonry walls. Testing conducted by Japanese researchers on confined masonry walls built using common Indonesian construction also did not show out of plane failure of the wall as the controlling failure mechanism. [11] In light of these observations, and because the cost of the horizontal steel reinforcement was prohibitive, Build Change engineers reconsidered the need for the horizontal bed joint reinforcement that was designed to mitigate the out of plane weakness that was assumed to be present. It was decided to allow the homeowners to omit the bed joint reinforcement with the condition that the other design and construction guidelines for the walls were followed.

2.4.4 Roof

The roof was initially made of timber trusses covered by corrugated galvanized sheeting. Later in the Aceh reconstruction, light gauge steel channels were used for the roof trusses instead of wood due to the increasing cost and difficulty in obtaining good quality structural timber and concerns over authenticity of the timber source. Both hipped and pitched roofs covers with CGI sheets were already common in Indonesia. The timber trusses were tied down with U-shaped steel plates while the steel trusses were tied down with bent steel C-channels that were screwed to the truss and bolted to the ring beam. The tie downs were needed to prevent uplift in strong winds and were used in lieu of the common practice of wrapping the tie column bars around the trusses, a detail that was susceptible to corrosion and pullout during high wind events.

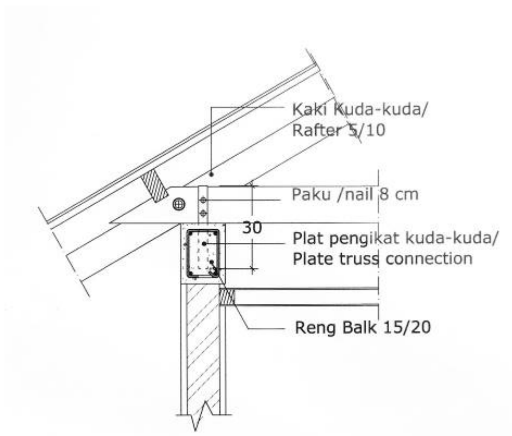

Fig. 5 - Truss to Ring Beam Connection

2.5 Building Materials and Properties

2.5.1 Bricks

Fired clay bricks were widely available in Sumatra but of variable quality (strength, consistency of size and shape) Simple three-point bending tests and visual checks were used to evaluate the brick strength in the field.

2.5.2 Cement

Two types of cement were common in Sumatra: Type 1 Portland Cement and Portland Pozzolan Cement (PPC). Type 1 was used for the structural concrete and PPC was used for the masonry wall and plaster because of the increased workability and lower price. Lime was not available from local shops in Indonesia and thus was not used as an additive.

2.5.3 Rebar

Both ribbed and smooth bar were available in Aceh with ribbed bar being more expensive. Ribbed bars were used for longitudinal bars and smooth bars were used for stirrups and ties. Pro-bono tensile tests performed by Scientific Construction Labs found yield strengths in the range of 57 to 81 ksi.

2.5.4 Durowall-Type Reinforcement

The truss type reinforcement used in the initial constructions was assembled at local welding shops using two 6mm diameter bars tied together with 3mm bars as the diagonals.

2.5.5 U-Shaped Steel Plates

The U-shaped steel plates used to connect the ring beam to the timber trusses were manufactured by local shops. The 4mm thick, 3cm wide plates were embedded in the ring beam and bolted to trusses.

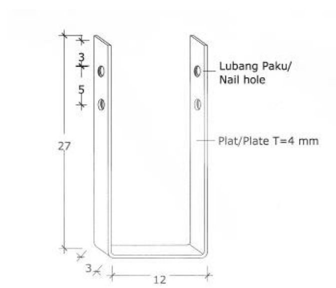

Fig. 6 - U-shaped plates used at trusses

2.5.6 Stone

Angular mountain stone for the stone masonry strip footing was available in yellow, red, and black varieties. The least expensive yellow stone was weak, weathered clayey sandstone. The stronger red stone was specified for construction.

2.5.7 Gravel

Crushed gravel was expensive and not easily found in Aceh. Thus rounded gravel with diameter up to 3 cm was used instead. The quality of gravel varied depending on the source; some gravel was coated with fine clay and required rinsing prior to use.

2.5.8 Sand

River sand was specified and beach sand was not used because of its high chlorine content. To evaluate the presence of fines in sand in the field, a handful of sand was placed in a plastic cup or bottle filled with water, and shaken. If the water was clear, the sand was accepted. If it was cloudy, it was rejected.

2.5.9 Timber

Tropical hardwood was largely unavailable. Thus a less dense tropical softwood that was still strong enough for structural timber was used for the structural roofing elements and the window and door frames. Other softwoods of lower quality were only used for batter board and formwork. In later projects, stiffer plywood formwork that could be reused was utilized.

2.5.10 Light Gauge Steel

The availability of light gauge steel members was initially very limited in Aceh and what was available was not of acceptable strength and quality. During the reconstruction an Australian steel framing manufacturer constructed a steel fabrication plant in Aceh and was able to locally produce light gauge steel sections of acceptable quality.

3. The "Three C's": Configuration, Connections, and Construction Quality

Since the 2004 earthquake and tsunami in Aceh, there have been several M6.0 and above earthquakes in Indonesia that have caused housing collapses, deaths, and injuries, including in Central Java, West Sumatra, and Padang. Because of the high number of houses constructed with confined masonry in Indonesia, these earthquakes yielded compelling examples of good performance of confined masonry houses in villages where other buildings were destroyed or heavily damaged.

Many newly built confined masonry houses performed well in these earthquakes. However, confined masonry houses that were poorly designed and/or constructed did suffer damage and in some cases collapse. Build Change sent survey teams to the affected villages and studied the performance, both good and bad, of confined masonry houses in Indonesia and developed a database of common flaws that likely contributed to the bad performance. These flaws, and how Build Change addressed them, are described in the following sections. The problems and solutions are grouped according to the three C's – configuration, connections, and construction quality.

3.1 Configuration

Masonry gables are notoriously poor performers in earthquakes. Damage and failure to masonry gable walls was widespread and plagued both new and older houses with and without reinforced concrete ring beams. In most cases, the gable masonry was neither properly confined nor properly connected to the roof. Cross-bracing between gables was not common. In theory, it should be possible to properly detail and build a masonry gable wall. However, there were many construction challenges, including but not limited to: locating the gable beam reinforcing correctly, bending the reinforcing at the ends at the proper angle, and embedding the gable beam reinforcement into the columns or ring beams below. Most builders had difficulty constructing these elements correctly. The solution was to remove the masonry above the ring beam by placing a light frame truss on the wall and using a timber or other lightweight cover. Alternatively, a hipped roof was used rather than a gable roof.

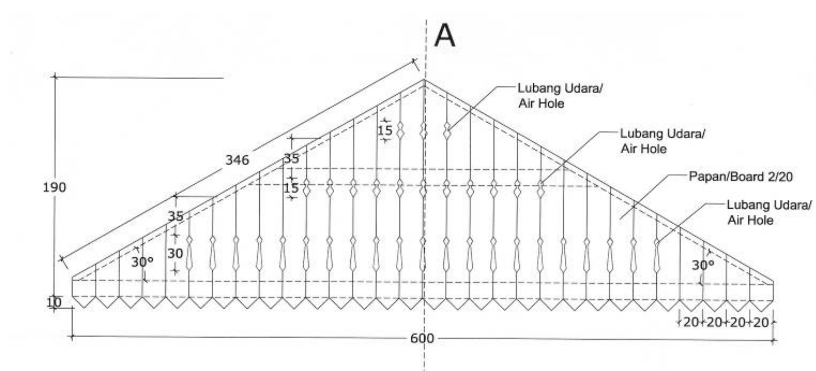

Fig. 7 - Gable Trusses

Large openings at the front of the house were common. There were many examples where the front of the house has collapsed while the back of the house remained intact. These large openings resulted in a reduction of stiffness in the in-plane direction of walls and in a lack of confining elements to restrain masonry panels from failing in the out-of-plane direction. The solution was multi-faceted: the weight above the openings was reduced by changing the gable walls from masonry to light frame, the window openings were reduced and consolidated to provide longer, continuous shear walls, and vertical confining elements were added to all openings with area greater than 2.5m^2. Initially, horizontal bed joint reinforcement was added to the wall at every seven courses and above and below openings but, as discussed above, in later projects lintel and sill beams were used instead of horizontal reinforcement.

Masonry walls upwards of 4m in height and longer than 6m without crosswalls and bracing were common and prone to out-of-plane failure. The solution was to limit the wall height to a maximum of 3m, and adding crosswalls or bracing at the ring beam level for spans longer than 4m.

A roofed terrace at the entry was a feature common to the homes observed. These open frame elements often had heavy, unreinforced and unconfined masonry gable walls above them. The frame elements were poorly detailed and poorly connected to each other and to the main walls of the house. The solution was to use a simple light frame extended roof overhang instead of a covered terrace. Another solution was to reduce the mass of the covered terrace by using light framing instead of masonry.

3.2 Connections

Insufficient connections between reinforced concrete tie columns and bond beams in confined masonry structures contributed to a majority of failures. The common practice of terminating the bond beam and tie column bars in the joint, while providing a small hook at the end, did not provide sufficient development or anchoring. This problem was widespread in both confined masonry and RC framed structures, including newly-built confined masonry houses. The solution was to bend the column reinforcement into the beams and overlap them with the beam reinforcement. The plinth and ring beam reinforcing was also bent and lapped around all intersections rather than terminated with small hooks.

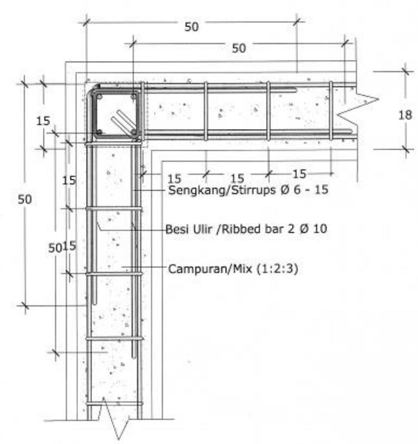

Fig. 8 - Beam/Column Intersection

Separation between wall and confining elements occurred in many houses. Toothing, which creates a mechanical bond between the wall panel and column and is recommended for confined masonry buildings in other countries, is not commonly practiced in Indonesia. Homeowners and builders there were unwilling to spend the extra money and time on the additional formwork required to accommodate a toothed wall. The solution was to use either steel dowels or horizontal bed joint reinforcement embedded in the masonry and tied into the columns.

Roof trusses were typically connected to the ring beams by simply wrapping the reinforcement from the columns around the truss chord. As noted earlier, these dowels were susceptible to corrosion and pullout during high wind events. The solution was to strengthen this connection by using a U-shaped steel plate.

3.3 Construction Quality

3.3.1 Soils

The pilot project houses were built on coastal alluvium. A three step process was used to assess soil hazards. First, nearby masonry houses were inspected for cracks associated with differential settlement. Second, the septic tanks were dug first so that the engineers could take a look at the soil profile and screen for liquefaction hazards and soft, expansive clays or peats. Although the water table was within 2-4m of the ground surface, the soil was clayey so liquefaction was not considered a hazard. Expansive clay was a bigger concern. Expansive clays were identified by touch and shrinkage tests. When it was encountered, these clays were dug out and replaced with compacted fill. Finally, the soil strength was tested at regular intervals by pushing a 12mm diameter steel rod into the ground. If the rod could be pushed more than 20cm into the ground, digging continued.

3.3.2 Stone Masonry Strip Footing Construction

At the base of the excavation, a weak screed layer was used instead of the more common layer of loose cobbles. The challenge with the stone masonry strip footing was to ensure the builders filled all the gaps between the stones with mortar, laid the stones down rather than standing them up, and used long stones at corners and T-junctions.

3.3.3 Concrete Mixing and Pouring

Concrete was mixed at a ratio of 1:2:3 by volume on the ground or on a paved surface. Builders had a tendency to add too much water to the concrete during mixing, especially when using a mechanical mixer. Slump tests and simply picking up a handful of mixed concrete were used to illustrate the importance of too much water in the mix.

To address the need to maintain adequate concrete cover on reinforcing steel, concrete spacers were used to separate the steel from the formwork. Concrete spacers were known about but not common in Aceh; if the builders used spacers, they used small stones rather than squares of concrete with binding wire. Initially, the concrete was rammed with a rod and the formwork was tapped with a hammer in order to compact the concrete. Later on vibrators were used. However, the builders had a tendency to over-vibrate and liquefy the concrete. The builders were instructed to cast the entire bond beam all in one day.

3.3.4 Bricklaying

Typical single story confined masonry houses in Indonesia have been shown to perform well in earthquakes provided the masonry wall is well constructed. Where the masonry failed, the primary contributors were weak quality of the bricks and weak bonding between the bricks and the mortar.

Mortar was mixed at 1:3 in the same manner as concrete. A mix of 1:2 was used for the damp proof course and the walls in the bathroom. Because the bricks were so porous, they had a tendency to absorb water from the mortar before the cement has time to hydrate and create a strong bond. Build Change's solution was to require the builders to wet or soak the bricks prior to building the wall. Prism tests verified that the brick wetting increased the strength of the prisms. In addition, it was stressed to the builders to use a uniform joint thickness no greater than 15mm, fill the joints completely with mortar, stagger the vertical joints, and ensure that the wall remained plumb.

3.3.5 Carpentry

Carpentry was the least challenging aspect of the construction process; there were many skilled carpenters in Aceh, some of whom suggested changes to the truss details that made them simpler to build. The primary challenge with the timber elements was that some of the window and door frames were produced with timber that wasn't totally dry. The frames would look straight and square when they first arrived on site, but after a few days in the tropical sun some of them would warp or split.

4. Obstacles to Adoption

Post-disaster housing reconstruction models range from top-down donor-driven approaches, in which the funding agencies or governments make the decisions about structural systems, architecture, and layout with little or no input from the homeowners and hire contractors to build, to bottom-up homeowner-driven approaches, in which the homeowners are provided cash and/or materials and allowed to select the structural system and architecture and purchase materials and hire builders themselves. A reflection of the relative merits and challenges inherent in each of these approaches is beyond the scope of this paper. However, a brief mention is given here because the obstacles to adoption are different depending on who is in the decision-making position.

The Aceh reconstruction was primarily donor-driven, while Build Change's program in West Sumatra was homeowner-driven. In Aceh, BRR and most funding and implementing agencies designed and built the same house for all of their beneficiaries, with some organizations offering different floor plan options. Build Change wanted to use a homeowner-driven model in Aceh, but when the homeowners were given the option of hiring builders themselves or hiring Build Change to procure builders for them with their inputs, they all chose the latter. The homeowners wanted to choose the construction type, layout, architecture, roof type, and paint color, but they did not want to purchase materials and hire builders themselves. There were no obstacles to adoption of confined masonry by the homeowners, as all of them preferred this system and the cost of the standard 36m^2 house was within the 28.8M Rupiah (3000 US Dollar) budget initially allotted to the pilot project by the BRR.

Despite the fact that confined masonry was already common and locally sustainable in Indonesia, convincing engineers and decision makers in some of the other donor agencies working in Aceh and West Sumatra to build confined masonry was a formidable challenge. Although some organizations bought into this structural system because it was already common, low-cost, culturally preferred, and locally sustainable, others who had little experience with confined masonry construction opted for an infilled reinforced concrete frame. This was primarily because of:

Lack of familiarity with confined masonry: Most engineers and decision makers working for funding agencies (both Indonesian and foreign) had never heard of confined masonry. Those with familiarity with multi-story reinforced concrete frame with masonry infill design would apply the same thinking to confined masonry. They were reluctant to accept the small columns and presence of cold joints within the columns.

Lack of a building code for confined masonry in Indonesia: Thanks to the pioneering work of Teddy Boen, there have been guidelines available for confined masonry houses in Indonesia since the 1980's [7]. However, there is not yet building code provisions for confined masonry. Many decision makers in funding agencies, especially those lacking a technical background, were reticent to deviate at all from the BRR reconstruction guideline because of fear over liability.

Construction cost in West Sumatra: The major hurdle in implementing earthquake-resistant design and construction into the confined masonry practice already present in West Sumatra was cost. The improvements to typical confined masonry construction that Build Change implemented in their Aceh house design added to the construction cost of the homes. Reconstruction funds that were available in West Sumatra after the earthquakes there were less than half of what was available to rebuild the houses in Aceh, so the individual homeowners were required to contribute more money to rebuild their homes. Most homeowners had limited financial resources, so although all families Build Change worked with in West Sumatra rebuilt better, especially regarding masonry quality and joint detailing, not all of the details used in Aceh could be used in West Sumatra because of the cost. For example, the horizontal bed joint reinforcement in the walls was omitted as explained earlier. Other homeowners did not use confined masonry at all, instead building their homes with timber with or without masonry skirt walls that could be constructed with high quality but for less cost than confined masonry.

5. Conclusions

Confined masonry was used in post-earthquake reconstruction in-Aceh and West Sumatra since it was a common construction method in these regions and has a history of good performance in earthquakes. Minor modifications to existing design and construction practices were used to ensure that these houses would be affordable, easy to build with local materials, skills and tools, and earthquake-resistant. Since there was no building code for confined masonry in Indonesia, Build Change and its team of volunteer engineers developed design criteria based on confined masonry standards developed from numerous sources and construction guidelines developed in Indonesia. These criteria were also based on observations of confined masonry performance in subsequent Indonesian earthquakes, which were grouped together according to the three C's – configuration, connections, and construction quality. Obstacles to adoption included lack of familiarity among decision-makers for relief agencies, the lack of code provisions for confined masonry, and cost.

6. Acknowledgements

The authors gratefully acknowledge the group of San Francisco Bay Area volunteer engineers who worked with Build Change on the Aceh pilot project: Kevin Moore, Evan Reis, Margarite Bello, Lisa Cassedy, Matt Eatherton, Jeff Falero, Andy Fennel, Tim Hart, David Kirschenbaum, Forrest Lanning, Andrew Mole, Jay Pisano, Rafael Sabelli, Tom Voss, and Carl Wilford.

7. References

[1] Hart T. Indonesia Tsunami Housing Reconstruction. *Structural Engineering Association of Northern California News* 2006; **62** (5): 5.

[2] Badan Standardisasi Nasional (BSN). *Indonesian National Standard, Design Method of Earthquake Resistance for Buildings, SNI 03-1729-2002*. Jakarta, 2001.

[3] International Code Council. 2003 International Building Code. Country Club Hills, IL, 2002.

[4] Masonry Standards Joint Committee (MSJC). *Building Code Requirements for Masonry Structures, ACI 530-02/ASCE 5-02/TMS 402-02*. American Concrete Institute, Structural Engineering Institute of the American Society of Civil Engineers, and The Masonry Society: Farmington Hills, MI, 2002.

[5] European Committee for Standardization. *Eurocode 8: Design of Structures for Earthquake Resistance*, EN1998-1:2004. Brussels. 2004.

[6] BRR. *Guidelines on Housing Repair and Reconstruction, Book 3*. Jakarta, 2005.

[7] Boen T. *Constructing Seismic Resistant Masonry Houses in Indonesia*. United Nations Centre for Regional Development: New York, 2005.

[8] Blondet M. *Construction and Maintenance of Masonry Houses for Masons and Craftsmen*. Pontificia Universidad Católica del Perú: Lima, 2005 (www.world-housing.net/tutorials).

[9] International Association of Earthquake Engineering (IAEE). *Guidelines for Earthquake Resistant Non-Engineered Construction*. Tokyo, 2004.

[10] Build Change. *Earthquake Resistant Design and Construction Guideline*. Denver, CO, 2006.

[11] Narafu T, Imai H, Ishiyama Y, Kusumastuti D, Wuryanti W, Shirakawa K, Kinoshita M. Experimental Study of Confined Brick Masonry in Indonesia. *Proceedings of the 15th World Conference on Earthquake Engineering*: Lisbon, Portugal, 2012.