DESIGN and CONSTRUCTION of CONFINED MASONRY HOUSES in INDONESIA: CHALLENGES, PERFORMANCE in EARTHQUAKES, and NEED FOR FUTURE RESEARCH

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BACKGROUND AND PREVALENCE OF CONFINED MASONRY IN INDONESIA

The 2004 Indian Ocean tsunami killed 130,000 people in Indonesia and left over 500,000 homeless. Over 2.5 years, Build Change, an international non-profit organization, rebuilt 33 confined masonry houses in partnership with local builders, improved the design and construction of 4,200 houses built by partner organizations, trained 130 builders through intensive, on-the-job training programs, and trained 245 technical high school students to design and build earthquake-resistant houses.

Using confined masonry in the post-Aceh reconstruction 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. Because confined masonry is the construction method of choice for owners of modest, single story homes in rural and peri-urban Sumatra and Java, Indonesia, Build Change designed and built confined masonry houses in the post-tsunami reconstruction in Aceh. In addition, almost 70% of the families Build Change is currently working with in the West Sumatra post-earthquake reconstruction program have selected to build from confined masonry.

Confined masonry houses can perform well in earthquakes, or they can cause deaths and injuries if designed and constructed poorly. Recent earthquakes in Indonesia, namely the 27 May 2006 Central Java (Yogyakarta), 6 March 2007 West Sumatra, and 12 and 13 September 2007 Bengkulu events have 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 (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.

DESIGN PROCESS

In March 2005 we 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
- Skill level of local builders, and commonly used tools
- Architectural and cultural preferences
- Climate considerations and other hazards, such as high winds and flooding.

We identified four common structural types (confined masonry, reinforced concrete block masonry, timber frame on stilts, and timber frame with a masonry skirt), established design criteria, and using teams of volunteer structural engineers from San Francisco Bay Area design firms, performed preliminary cost estimating and design analysis on the four systems.[2] Funding to build 11 houses in a pilot project was obtained from Mercy Corps, an international relief and development agency active in the reconstruction since shortly after the tsunami. We asked each of the 11 homeowners which structural system they preferred. All chose confined masonry.

The pro bono structural engineers then performed more detailed analysis of a confined masonry house.

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[2] See Hart, T.M. (2006) "Indonesia Tsunami Housing Reconstruction" SEAONC Newsletter, May 2006.

At the same time, we 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.

SEISMIC HAZARD and ANALYSIS METHOD

Building designs were checked for seismic forces in both principal directions using equivalent static analysis methods. Calculations were performed for a spectral design acceleration of 0.4g. This assumption is based on

1. Indonesian Seismic Standard (SNI 03-1726-2002) → for Zone 6 on soft soils (0.38g), which is the highest standard currently applicable in Indonesia. Although the pilot project houses are located in Zone 5 on medium soil (0.32g), the intent was to design a structural system that could be built anywhere in Aceh or Nias and assuming the worst case soil condition.
2. International Building Code (IBC) → 0.4g is the design seismic force prescribed in the International Building Code (IBC) for a building on standard soil and within 2 km of an active seismic fault that has the potential to generate earthquakes with magnitudes of 5.0 and larger. The seismic zonation in the most recent version of the Indonesian Seismic Standard (SNI 03-1726-2002) does not recognize the seismic hazard imposed by the Sumatra fault. Current research (see Peterson et al.[3]) indicates that this fault, which lies within a few km of the pilot project houses, is active and has the potential to produce earthquakes of magnitude 5.0 and higher.

APPLICABLE CODES AND GUIDELINES

A building code for confined masonry does not yet exist in Indonesia. The Indonesian Seismic Standard (SNI 03-1726-2002), which is based on UBC 1997, applies to reinforced concrete frame construction. Infill walls are assumed non-structural and are therefore not addressed in buildings designed according to the Indonesia Seismic Code. Indonesia has a concrete code, but does not have a masonry code.

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. Given that this guideline was based on the SNI, it was interpreted as applicable to RC frame construction. The guideline was prescriptive in terms of size of frame elements, diameter of reinforcing bars, spacing of stirrups and ties, and so on, but it omitted important details such as connections and anchoring.

During the design process, we reviewed several other codes and guidelines, such as a series of posters produced by Teddy Boen[4], guidance associated with Eurocode 8[5], Marcial Blondet's construction guideline[6], and the IAEE Manual[7]. All guidelines were very useful but none was sufficient and completely appropriate for the structural and architectural system common in Aceh. Most codes and guidelines assume a two or more story structure with rigid diaphragm at the floor level and thicker wall.

In addition to producing our own detailed set of design drawings, bar bending schedules, bills of quality, we drafted a design and construction guideline for earthquake-resistant confined masonry houses[8] which was shared with BRR and other organizations working in housing at a seminar in May 2006 and through personal communication and meetings with partner organizations. The guideline is now

[3] Peterson, M.D., Dewey, J. Hartzell, S., Mueller, C., Harmsen, S., Frankel, A.D. and Rukstales, K. "Probablistic seismic hazard analysis for Sumatra, Indonesia and across the Southern Malaysian Peninsula", Tectonophysics 390 (2004) 141-158.

[4] Boen, Teddy & REKAN (2005). "Syarat-Syarat Minimum Bangunan Tembokan Bata / Batako Tahan Gempa Dengan Perkuatan Beton Bertulang"

[5] City University of London
http://www.staff.city.ac.uk/earthquakes/MasonryBrick/ConfinedBrickMasonry.htm

[6] Blondet, Marcial (editor). Construction and Maintenance of Masonry Houses: For Masons and Construction Technicians, PUCP

[7] IAEE (revised edition, 2004). Guidelines for Earthquake Resistant Non-Engineered Construction.

[8] Build Change (2006) "Earthquake-Resistant Design and Construction Guideline for Single Story Reinforced Concrete Confined Masonry Houses Built in the Aceh Permanent Housing Reconstruction Program"

available on the Build Change website. A simple step-by-step construction guideline for homeowners and builders is in press.

BRR hired a consultant to check drawings for completeness starting in 2006. Even though we had already completed building our pilot project houses, we submitted our drawings for approval in order to gain additional validation and support for promoting confined masonry with partner organizations. Approval was granted in late 2006.

Our design for Aceh received a 2006 Excellence in Structural Engineering Award from the Structural Engineers Association of Northern California and a Certificate of Merit in the statewide competition. An independent review of one of our designs was done by a structural engineering company in Jakarta. With the exception of recommending deeper anchorage between the foundation and the foundation beam, the design was endorsed by the structural engineering firm. Our house design was called "best in Aceh" in 2006 by a team of Indonesian seismic experts. ARUP, an international design engineering firm, commented in a review of one of our client's projects, that the Build Change "design…combines seismic resilience with a high degree of buildability."

ARCHITECTURAL, CULTURAL and CLIMATE CONSIDERATIONS

Single Story. All houses designed and built by Build Change were single story. Typical two or more story construction in Indonesia is a hybrid system between RC frame with masonry infill and confined masonry.

Fig. 1. Build Change Pilot Project House, Hipped Roof (Owner: Rusdi Razali).

Tall, Slender Wall. Because of the hot climate, there is a preference for a tall wall, up to 3m in height from floor to ceiling. Masonry is built using running bond, in which the bricks are laid end to end, resulting in a half-brick wide wall. This tall, slender wall has an aspect ratio that is higher than what is typically recommended for confined masonry buildings.

Large Openings. Similarly, there is a preference for tall doors and windows with vents above over the doors and windows, especially at the front of the house.

Lightweight, Timber Truss Roof. Pitched or hipped roofs are preferred because of the significant amount of rainfall.

Other Criteria. The BRR building guideline included additional architectural criteria which we followed, such as minimum 36m^2 in plan, at least two bedrooms, at least two entrances and exits, orientation appropriate for sun, wind, and Islamic culture, and toilet, septic tank, soakaway.

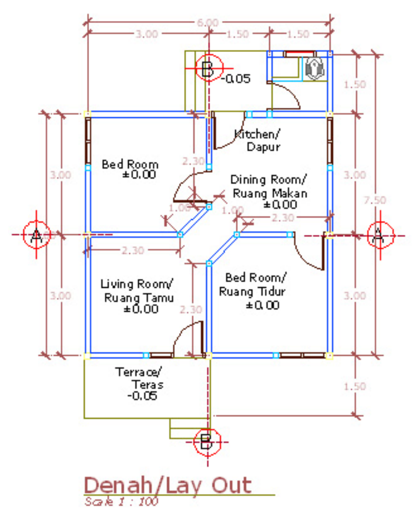


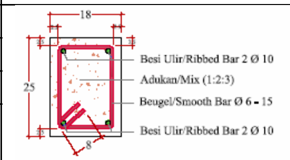
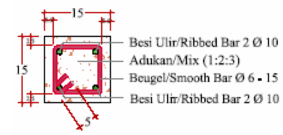
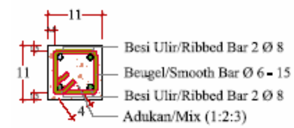
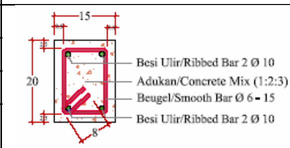
Fig. 2. Build Change Pilot Project House, 2 bedroom, 2 living room, toilet outside.

DESIGN DETAILS

Foundation and Floor: Trapezoidal-shaped stone masonry strip footing. S-shaped, 50 cm steel anchors were used every 1m, as recommended by the BRR Guideline. These anchors are 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 finished floor height at least 60 cm above ground surface.

Reinforced Concrete Confining Elements: Reinforced concrete bond beams at the foundation/plinth and roof level, and reinforced concrete major tie columns at all corners, and wall intersections, minor tie columns at changes in contour and adjacent to all openings except the small bathroom vent window. See table 1 for details.

Table 1. Confining Element Section and Bar Details (dimensions in cm)

	BRR Guideline	Build Change Design	
PLINTH BEAM			
--Section	15 x 20	18 x 25	
--Longitudinal Bars	4-12mm dia smooth	4-10mm dia ribbed	
--Stirrups	8mm dia at 15 cm	6mm at 15 cm	
MAJOR COLUMNS			
--Section	15 x 15	15 x 15	
--Longitudinal Bars	4-12mm dia smooth	4-10mm dia ribbed	
--Ties	8mm dia at 15 cm	6mm at 7.5 cm for the first 7 ties at top and bottom, elsewhere 15 cm	
MINOR COLUMNS			
--Section	11 x 11	11 x 11	
--Longitudinal Bars	4-12mm dia smooth	4-8mm dia ribbed	
--Ties	8mm dia at 15 cm	6mm at 7.5 cm for the first 7 ties at top and bottom, elsewhere 15 cm	
RING BEAM			
--Section	15 x 20	15 x 20	
--Longitudinal Bars	4-12mm dia smooth	4-10mm dia ribbed	
--Stirrups	8mm dia at 15 cm	6mm at 15 cm	

We started building our first house with the bar detailing and section size specified by BRR, however, quickly encountered construction challenges. We pulled our first foundation beam out and rebuilt it. How and why we deviated from the BRR Guideline:

- Increased the section size of the plinth beam: To increase the strength of the foundation beam in light of variable soil conditions, and to make it easier to connect beams with columns. With a 15 x 20 foundation (plinth) beam and a 15 x 15 column, it is very difficult to fit column steel inside beam steel, maintain sufficient cover over the concrete in the plinth beam, while also maintaining sufficient space between the long bars in the column, so as to be able to bend a stirrup that is square, not round.
- Reduced longitudinal bar diameter and used ribbed instead of smooth: 12mm long bars and 8mm bars for stirrups and ties were too difficult for builders to cut and bend properly.
- Reduced the stirrup and tie bar diameter and reduced the spacing of stirrups at the top and bottom of the columns: again for workability reasons, and to provide increased strength in shear at the top and bottoms of the columns.
- Considered increasing the spacing of stirrups in the bond beams, all of which were resting on a masonry wall or foundation. Our design calculations indicated that greater stirrup spacing was allowed.
- Specified hook length, hook rotation, and joint detailing on the drawings. It was not common practice to call out these details on engineering drawings used in Aceh. See Figs. 3 and 4.

Fig. 3. Bond Beam-Tie Column Connection Model. Note it has been suggested that to strengthen the interior corner, the interior long bars should pass through the joint and tie to the external long bars.

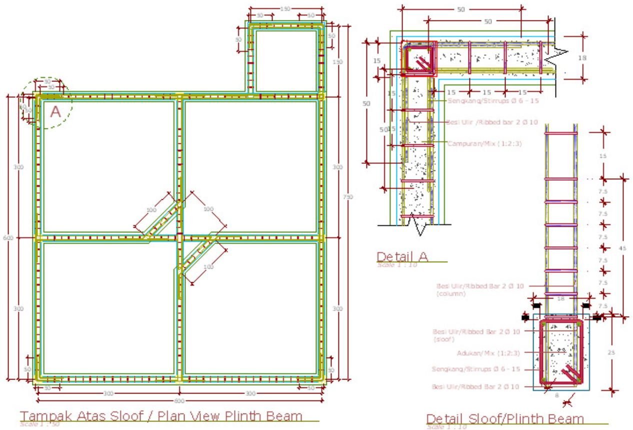


Fig. 4. Bond Beam Layout and Connection Detailing

Walls: Fired clay brick masonry walls built prior to casting the columns, with Durowall-type steel reinforcement placed in the bed joint every seven courses of masonry, above and below openings, and tied into the columns.

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 against out-of-plane failure:

(1) increase the number and length of shear walls in both directions, and add cross walls or bracing. All floor plans had cross walls every 4m or less,

(2) increase the wall thickness by changing the masonry bond to English or Flemish bond, as is common for confined masonry structures in other countries, such as India, Peru, and Iran. To use full-brick wide bonding, the length of the brick must be twice as long as it’s 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 adds cost and requires a higher skill level from the masons, therefore this was not a feasible option,

(3) reinforce or restrain the wall by using additional confining elements such as extra tie columns, a lintel beam, or reinforcement in the wall. We considered wrapping wire mesh around the wall, tied into the foundation and ring beams, but we thought this might be difficult to build, and although the mesh would be covered in plaster, we had concerns that the mesh would delaminate over time.[9] A lintel beam would add little value at high cost because the top of the frames were already so close to the top of the wall.

We opted for the combined solution of additional vertical confining elements adjacent to all large openings, and horizontal steel reinforcement in the wall. The reinforcement detail (Fig. 5 and 6) was also assumed to increase the in-plane strength of the wall. We shifted the openings to the corners to and locations of major columns so that only one additional tie column would be needed (rather than two, if the openings remain centered). All walls were finished with cement-based plaster and painted.

Fig. 6. Wall with Horizontal Reinforcement.

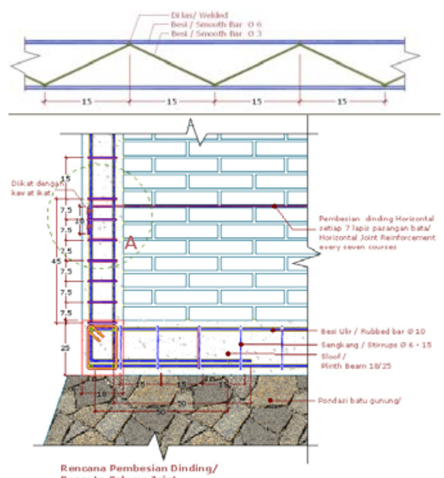


Fig. 5. Horizontal Wall Reinforcement.

[9] Inspired by Prof. Ken Elwood, UBC

Fig. 7. Build Change Pilot Project House, Pitched Roof. Owner: Ruslan AB.

Roof. Roof was made of timber trusses covered by corrugated galvanized sheeting. Both hipped (Fig. 1) and pitched (Fig. 7) roofs covers with CGI sheets were already common. Timber gables were used for pitched roofs. Trusses were tied down with U-shaped steel plates. The tie downs were needed to prevent uplift in strong winds, and intended as an alternative the common practice of wrapping the tie column bars around the trusses, leaving them exposed to corrosion.

Although not considered in the analysis, it is likely that this connection between the roof truss and ring beam provides some bracing against out of plane failure. The benefits of having lower mass (and thus lower inertia force) at the roof level by using an already common and appropriate timber truss roof were considered to outweigh the lack of rigidity at the ring beam level. Replacing the roof system with a more rigid system, such as a reinforced concrete slab, was not considered because such a system is ill-suited to the climate and can be very dangerous if constructed poorly.

BUILDING MATERIALS AND PROPERTIES

Fig. 8. Three point bending test for brick strength, use average size Indonesian male, no bouncing

Bricks. Fired clay bricks are widely available in Sumatra. Soil is mixed by buffalo, machine, or by hand; bricks are hand-molded and fired in open kilns using wood or rice husks as fuel. Brick quality (strength, consistency of size and shape) was variable. We did a quick review of the brick manufacturing process at several kilns to determine which vendors to purchase from. The type of clay and the firing process had the biggest impact on brick quality. Many brick producers had access only to a source of clay that was prone to warping and shrinking during firing. The length of burn, fuel used in burning, and the location of the brick in the kiln also strongly influenced its properties. Bricks at the top of the kiln were rarely completely fired, and would erode or crumble in the rain. We used simple three-point bending tests[10] (see Fig. 8) and the following checks to evaluate brick strength in the field.

- No cracks or chips
- No visible unmixed portions or divits
- Brick is square, not warped or curved
- Dimensions are consistent among a sample of 10-20 bricks; they do not vary by more than 1 cm in the long direction and 5 mm in width and height
- When two bricks are hit together, the sound is a metallic clink, not a dull thud
- When left out in the rain or soaked in water for 24 hours, bricks do not crumble.

Cement. Two types of cement are common in Sumatra: Type 1 Portland Cement (SNI 15-2049-2004 or ASTM C-150) and Portland Pozzolan Cement, PPC (SNI 15-0302-2004 or ASTM C-595 M95). We used Type 1 for the concrete, foundation and floor, and PPC for the masonry wall and plaster, because of the increased workability and lower price. We have not found lime in local shops in Indonesia.

Rebar. Both ribbed and smooth bar is available in Aceh. Ribbed bar is more expensive. We used ribbed bars for longitudinal bars and smooth for stirrups and ties. SCL performed pro bono tensile tests

[10] Inspired by the work of Sir Roger Bonner and Dr. Martin Fisher building schools in Africa in the mid-1980's. The forces in three-point bending are more realistic than those imposed on the brick by holding it out at arm's length and dropping it, a common practice for testing brick strength.

on 22 random samples of steel reinforcement obtained from local shops, including both ribbed and smooth steel in diameter between 4 and 13mm. Yield strength was in the range of 57 to 81 ksi for bars in 7 to 13mm diameter range, and 40 ksi was assumed in design.

Durowall-Type Reinforcement. This truss type reinforcement was initially assembled on-site by the builders using two 6mm diameter bars tied together with binding wire in a truss pattern (Fig. 9, top). This process was time consuming, and consistent separation between the long bars was difficult to maintain due to flexibility of the binding wire. We switched to a welding school to prefabricate the reinforcement using 3mm bars as the diagonals (Fig. 9 bottom). When the welding school could not meet our demand, we used private sector local welding shops.

Fig. 9. Horizontal reinforcement fabricated on-site with binding wire (top) and prefabricated at welding shop (bottom).

Fig. 10. U-Plate for ring beam-truss connection.

U-Shaped Steel Plates. The U-shaped steel plates for the ring beam – truss connection were manufactured by local shops (Fig. 10). The 4mm thick, 4cm wide plates were embedded in the ring beam and bolted to trusses.

Stone. Angular mountain stone for the stone masonry strip footing was available in yellow, red, and black varieties. The least expensive yellow stone was a weak, weathered clayey sandstone. We used red, which is also sandstone, but stronger.

Gravel. Crushed gravel was expensive and not easily found in Aceh. As such, we used rounded gravel with diameter up to 3 cm. Quality of gravel varied in that depending on the source, some gravel was coated with fine clay and required rinsing prior to use.

Sand. Like gravel, depending on the source, the sand was often mixed with fine clay particles. To evaluate sand in the field, we put a handful of sand in a plastic cup or bottle, filled it with water, and shook it up. If the water was clear, the sand was accepted. If it was cloudy, it was rejected.

Timber. Timber was loosely divided into three classes. Class 1 is tropical hardwood, which was largely unavailable. Type 2 is a less dense, tropical softwood that is strong enough for structural timber. We used Class 2 for structural roofing elements and window and door frames. Class 3 includes other softwoods of lower quality and appropriate only for batterboard and formwork. It was very difficult to reuse formwork made with such soft, easily warped timber. In later projects, we fabricated formwork out of plywood that could be used two to three times.

Lightweight Steel. All new houses designed and/or built by Build Change following the 11 pilot project houses used lightweight steel channels for the roof trusses. This shift away from timber was made due to the increasing cost and difficulty in obtaining good quality structural timber, and concerns over legality of the timber source. Although all timber purchased in the pilot project came with documentation certifying legality, we had concerns about the authenticity of these certificates.

CONSTRUCTION PROCESS

Soils: The pilot project houses were built on coastal alluvium. We screened for soil hazards by

(1) inspecting other nearby masonry houses to check for cracks associated with differential settlement,
(2) digging the pits for the septic tanks first so we 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, we dug it out and replaced it with compacted fill. And,

(3) testing the soil strength every 1m along the length of the foundation excavation by pushing a 12mm diameter steel rod into the ground. If the rod could be pushed more than 20cm into the ground, we kept digging.

Stone Masonry Strip Footing Construction: At the base of the excavation, we used a weak screed layer 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. See Fig.11 for an example of a poorly built strip footing.

Fig. 11. Poorly built stone masonry strip footing. Note gaps between stones, stones standing on end.

Bar Bending and Assembly: In addition to detailed design drawings, we produced bar bending schedules that showed the cut length of each bar so as to facilitate the overlaps as detailed in the drawings and reduce waste.

Concrete Mixing and Pouring: Concrete was mixed at 1:2:3 by volume on the ground or on a paved surface. Builders had a tendency to add too much water to the mix, especially when using a mechanical mixer on one of our later projects. We used different methods to illustrate the importance of too much water, from slump tests, and simply picking up a handful of mixed concrete and if the water (and cement) ran out through one's fingers, it was too wet.[11]

Concrete spacers were used to separate the steel from the formwork. Concrete spacers were known about but not common; if the builders used spacers, they used small stones rather than squares of concrete with binding wire we used in our projects. Formwork was wetted prior to pouring concrete. In the pilot project, we rammed the concrete with a rod and tapped the formwork with a hammer in order to compact the concrete. In a later project, we used vibrators, however, the builders had a tendency to overvibrate and liquefy the concrete. We required builders to cast the entire bond beam all in one day. Concrete was cured by sprinkling water on it for five to seven days.

During the pilot project, a team of researchers from Institute of Technology – Bandung (ITB) performed handheld concrete hammer testing on a random sample of concrete elements in our houses. Foundation beams and column strengths at 28 days or older were in the range of 175-200 kg/cm^2, which meets or exceeds the requirement in the BRR building guideline. According to the researchers, this was significantly higher than they were finding in houses built by other organizations, which were in the range of 60-100kg/cm^2 at 28 days. One of our ring beams tested at 7 days was 125 kg/cm^2.

Fig. 12. Typical Build Change foundation beam, Build Change-designed house for CRS

Fig. 13. Typical Build Change ring beam, Build Change-designed house for CRS

Fig. 14. Bad practice, connections and concrete quality, other organizations

[11] Inspired by Teddy Boen.

Bricklaying: 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 are so porous, they have a tendency to absorb water from the mortar before the cement has time to hydrate and create a strong bond. We promoted wetting or soaking the bricks prior to building the wall.[12] In addition, we stressed uniform joint thickness no greater than 15mm, filling the joints completely with mortar, staggering the vertical joints, and ensuring the wall remained plumb. Some examples of masonry produced by Build Change-trained masons, vs. that produced by other organizations, is shown in Figs. 15 through 20.

Fig. 16. Typical wall built by Build Change-trained mason

Fig. 17. Typical wall built by Build Change-trained mason

Fig. 18. Typical wall built by other mason

Fig. 19. Typical wall built by other mason

Fig. 20. Typical wall built by other mason

Carpentry: Carpentry was the least challenging aspect of the construction process; we found many skilled carpenters, some of whom suggested changes to our truss details that made them simpler to build (Fig. 21). 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 we accepted the order from the vendor, but a few days in the tropical sun, and some of them would warp or split.

Fig. 21. Builder, homeowner, Build Change architect, and Build Change engineer discuss ring beam-truss connection

[12] Following a visit from Prof. John Nichols, we began a series of bond strength tests. In the first series, we built six brick tall prisms, varying things like wetting vs. not wetting the bricks, type of cement, type of sand. After 7 days we laid the prisms down and loaded in three point bending so the prisms failed in flexure. The wetted models could carry over twice the load prior to failure than the one with the bricks laid dry. The bricks are porous, the weather is often quite hot, so bricks laid dry will absorb water out of the mortar before the cement has time to hydrate and create a good bond. In our test series, all failures took place at the interface between the top of the mortar bed and the bottom of the brick above. There wasn't much of a difference between all of the wetted models, so it was difficult to tell how the type of cement and type of sand influenced the load carrying capacity. This may have been due to our simple test setup. Additional tests are planned.

PERFORMANCE IN RECENT EARTHQUAKES

Since the tsunami, there have been at least six earthquakes of significant strength to cause housing collapses, deaths, and injuries in other parts of Indonesia. Build Change sent reconnaissance teams to three of the affected regions: Central Java, M6.3 on 27 May 2006; West Sumatra, M6.4 and 6.3 on 6 March 2007; and Bengkulu and the Mentawai Islands, M8.5, 7.9 and 7.0 on 12 and 13 September 2007.[13] Strong ground motion recordings are not available for any of the events. The Central Java event was the most deadly (killing 5,782 people), had the most devastating effect on housing stock, damaging or destroying 135,000 houses, and yielded compelling examples of good performance of confined masonry houses in villages where 70-90% of the other buildings were destroyed or heavily damaged.

Many newly built confined masonry houses with reinforced concrete tie columns and bond beams at the plinth and roof levels performed well in these earthquakes. See Figs. 22 and 23 for a well-built confined masonry house with no evidence of damage, on the edge of heavily damaged Pleret. In typical confined masonry practice, the tie columns are cast after the masonry wall was built, flush with the wall, and thus the same width as a brick or block (10 or 11 cm). Smooth reinforcing steel is common in both Central Java and West Sumatra, typically 6 or 8mm in diameter with stirrups ranging from 3 to 6mm in diameter. Stirrups were often spaced at 15 to 25 cm intervals.

Fig. 22. Well designed and built confined brick masonry house, edge of heavily damaged Pleret (Bantul), S7.83686° E110.41552°, IMG_6636

Fig. 23. Well built confined masonry wall, house on edge of heavily damaged Pleret (Bantul), S7.83686° E110.41552°, IMG_6640

In contrast, the house shown in Fig. 24 illustrates many of the shortcoming common to poorly designed and built confined masonry houses in Indonesia – tall slender wall with tendency to overturn, insufficient connections between confining elements, no reinforcement in the wall especially above openings. These flaws, and how Build Change has addressed the flaw in design, are described in the following sections. The problems and solutions are grouped according to the three C's – configuration, connections, and construction quality.

Fig. 24. Confined masonry house under construction, insufficient connections, Pleret (Bantul). S7.87574°, E110.40703°, IMG_6575

[13] See EERI Newsletter Inserts from August 2006 and November 2007.

CONFIGURATION

(1) MASONRY GABLE WALLS

Problem: Masonry gables are notoriously poor performers in earthquakes (see Figs. 1 and 2) and should be avoided. Damage and failure to masonry gable walls was widespread throughout all three earthquake-affected regions, and plagued both new and older houses with and without reinforced concrete ring beams. In most cases, gable masonry was neither properly confined nor properly connected to the roof. Cross-bracing between gables was not common.

Figure 1. Masonry gable wall overturning in 27 May 2006 Central Java Earthquake, Keputren, Pleret (Bantul) S7.86905° E110.40272°, IMG 6721

Figure 2. Masonry gable wall overturning in 27 May 2006 Central Java Earthquake, (Bantul) S7.89468°, E110.37341°, IMG 6542

Build Change Solution: REMOVE THE MASONRY ABOVE THE RING BEAM: Shift the truss over to rest on the wall and use a timber or other lightweight cover (Fig. 3). Alternatively, use a hipped roof (Fig. 4) which is the lowest cost alternative, and also performs better in high winds.

Figure 3. Papan Gable (Maimunah's house designed and built by Build Change, Keunue ue, Peukan Bada, Aceh Besar)

Figure 4. Rabung Empat Roof (Rusdi Razali's house designed and built by Build Change, Keunue ue, Peukan Bada, Aceh Besar)

Other Options: In theory, it should be possible to properly detail and build a masonry gable wall. However, there are so 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 have difficulty constructing these elements correctly. We have seen examples in which the steel cage is assembled, laid to rest on the wall for show, and just prior to pouring concrete, it is removed and used for the next house. This results in dangerously insufficient construction.

(2) LARGE OPENINGS

Problem: Large openings at the front of the house are common. There are many examples from all three earthquakes in which the front of the house has collapsed, while the back of the house remained intact (see Figs (5 and 6). The problem associated with this lack of stiffness in the in-plane direction of walls with large openings and lack of confining elements to restrain masonry panels from failing outwards is exacerbated by the heavy mass of the masonry gable wall.

Figure 5. Collapse of front wall in confined masonry house , Padang Panjang, IMG_8831

Figure 6. Partially collapsed brick masonry house with RC tie columns and timber bond beams, note partial collapse of masonry gable wall, and lack of in-plane stiffness in front wall, Kec. Lais (North Bengkulu) S3.53217° E102.03771°

Build Change Solution (Fig. 7):

(1) Reduce the weight above the openings by following the previous recommendation about gable walls,
(2) Reduce the number and area of windows, and consolidate them to provide longer, continuous shear walls,
(3) Add vertical confining elements to all openings with area greater than $2.5m^2$. To reduce cost, shift openings from the middle of the panel to the corner, and
(4) Add horizontal reinforcement to the wall every seven courses and above and below openings.

Figure 7. Rabung Empat Roof (Rusdi Razali's house designed and built by Build Change, Keunue ue, Peukan Bada, Aceh Besar)

Other Options:
Instead of the horizontal reinforcement every seven courses, consider using a lintel beam and sill beam.

(3) TALL WALLS and LONG WALLS

Problem: Walls upwards of 4m in height and longer than 6m without crosswalls and bracing are common and prone to out-of-plane failure, as illustrated in Fig. 8 for a tall wall and Fig. 9 for a long wall.

Figure 8. Confined masonry building with overturning failure of tall, unsupported wall, Kec. Airnapal (North Bengkulu)

Figure 9. Confined masonry warehouse with overturning failure of long walls without cross-bracing, X. X (X) SX° EX°. IMG_8891

Build Change Solution: Reduce the wall height to a maximum of 3m, and add crosswalls or bracing at the ring-beam level for spans longer than 4m. Tie the walls into the columns using horizontal reinforcement.

(4) COVERED TERRACES

Problem: Covered terraces are en vogue in Indonesia. These open frame elements often have heavy, unreinforced and unconfined masonry gable walls above them. The frame elements are poorly detailed and connected to each other and to the main walls of the house. See Figs. 10 and 11.

Figure 10. Subdivision of confined masonry houses, damage to covered terrace, Bengkulu. S3.83218° E102.29287°

Figure 11. Subdivision of confined masonry houses, damage to covered terrace, Bengkulu. S3.83218° E102.29287°

Build Change Solution: (1) Avoid the covered terrace by using a simple extended overhang, as shown in Fig. 7. Note that this requires good quality timber, or bracketing to support the overhang. Or, (2) Reduce the mass above the open frame by replacing the masonry, and ensure the connectins are detailed properly (Fig. 12).

Figure 12. Covered terrace with lightweight wall, Build Change designed house for Catholic Relief Services (Aceh Besar)

CONNECTIONS
(5) BETWEEN CONFINING ELEMENTS

Insufficient connections between reinforced concrete tie columns and bond beams in confined masonry structures contributed to a majority of failures in all three events. The common practice of terminating the bond beam and tie column bars in the joint, while providing a small hook at the end, does not provide sufficient development or anchoring. This problem was widespread in all earthquakes, and a dominant cause of failure for newly-built confined masonry houses in which both tie columns and bond beams were present. In Indonesia, insufficient connections are a problem that plagues both confined masonry and RC frame construction. See Figs 13 through 15 for examples.

Figure 13. Zoom-in view of ring beam – column connection. IMG_6577

Figure 14. Confined masonry house with failure in masonry walls and connections between tie columns and bond beams, Kec. Airnapal (North Bengkulu)

Figure 15. Connection failure, RC frame building, Central Java

Build Change Solution: Bend the column reinforcement into the beams and overlap by 50 times the diameter of the bar. Similarly, bend the plinth and ring beam reinforcing around corners. Tie with double binding wire.

(6) BETWEEN MASONRY WALL and TIE COLUMN

Problem: Critical to good performance of confined masonry buildings is the connection between the wall and tie columns. Separation between wall and confining elements occurred in many houses in all earthquakes. See Figs. 16 and 17.

Figure 16. Insufficient connection between wall and tie column and between tie column and bond beam, Pleret (Bantul) S7.88174° E100.40869°, IMG_6746

Figure 17. Insufficient connection between wall and tie column and between tie column and bond beam, Segoroyoso, Pleret (Bantul) S7.88174° E100.40869°, IMG 6749

Build Change Solution: Toothing, which is recommended for confined masonry buildings, is not commonly practiced in Indonesia. Homeowners and builders are unwilling to spend the extra money and time (respectively) on additional formwork required to accommodate a toothed wall. Further, our experience has been that it is difficult to get the concrete to flow completely into the toothed area. Instead, we used Durowall-type horizontal steel reinforcement in the bed joint of the masonry, every seven courses and above and below openings, and tied into the columns and beams. *See Figs in other Sections.*

(7) BETWEEN RING BEAM and TRUSS

Roof trusses are typically connected to the walls by simply and wrapping the bars from the columns around the truss chord. Improving this connection can provide some bracing against out-of-plane failure.

Build Change Solution: Strengthen this connection by using a U-shaped steel plate. *See Figs in other Sections.*

CONSTRUCTION QUALITY

(8) MASONRY WALL QUALITY

The first line of defense in a confined masonry structure in earthquake strong shaking is a well-built masonry wall. Typical single story confined masonry houses in Indonesia have been shown to perform well in earthquakes, even when the tie columns are small in section and use smooth bars of small diameter, provided the masonry wall is well constructed, with adequate bonding between bricks and mortar. See Figs. 19 and 20 for examples of wall collapses with columns and roof intact. Weak bonding is clearly a contributor to failure (Fig. 21); bricks were not soaked in water before building wall, and/or the mortar mix was too dry.

Fig. 19. Subdivision of confined masonry houses, collapse of masonry wall exacerbated by insufficient connections, Bengkulu. S3.83218° E102.29287°

Fig. 20. Confined masonry house with failure in masonry walls and connections between tie columns and bond beams, Kec. Airnapal (North Bengkulu)

Fig. 21. Close up view of collapsed ring beam and wall, same as Fig. 20. Failure plane between top of mortar bed and bottom of brick above it.

Build Change Solution: Follow the suggestions in previous sections on construction quality, and finish the wall with cement-based plaster.

Fig. 22. Homeowner standing in front of her collapsed wall, note quality of concrete, Padang Panjang, S (X) SX° EX°, IMG_8840

(9) CONCRETE QUALITY

Problem: Poor quality concrete also contributed to failures. See Fig. 22. Same solutions apply: follow suggestions in previous sections on construction quality.

(10) FOUNDATION, SOIL and DRAINAGE

We have seen very little earthquake-induced damage to confined masonry houses in Indonesia that could be attributed to a soil or foundation problem. In the Central Java event, we found one example of sliding along the wall-foundation interface; in this case, there was no foundation beam. Effects of liquefaction were observed in one village in the Bengkulu event (Fig. 24).

Fig. 23. Displacement along wall/foundation interface, Tegal Kebong Agung, Imogiri (Bantul) S7.93434° E110.36667°, CIMG1769

Fig. 24. Cracks in foundation and walls associated with settlement and tilt on liquefiable soils, Lempuing (Bengkulu), S3.82799° E102.28473°

COST

The cost of the 36m^2 house, plastered, painted, and finished with electrical wiring, toilet, and septic and soakaway was approximately US$4,500 at the start of our pilot project. Two years later, due to escalating cost of materials, labor, and the switch to lightweight steel for the roof, the price had climbed to US$7,000. This is a materials and labor only cost; it does not include design engineering, drafting, plot layout, cost estimating, materials warehousing and transport, and construction supervision.

The following is the relative cost of confined masonry as compared with other common structural systems in use in Aceh and West Sumatra, from least expensive to most expensive:[14]

- Timber or timber with masonry skirt using recycled timber and recycled bricks (least expensive)
- Poorly designed and built confined concrete block masonry
- Poorly designed and built confined fired brick masonry
- Timber or timber with masonry skirt using all new materials
- Poorly designed and built RC frame with masonry infill
- Well designed and built confined fired brick masonry
- Well designed and built RC frame with masonry infill (most expensive).

ADVANTAGES

The advantages of using confined masonry over RC frame construction for single story houses in Indonesia are both technical and economic in nature. For example,

- VULNERABILITY: An RC frame structure with masonry infill is more likely to cause deaths and injuries in a strong earthquake than a confined masonry structure. The masonry infill panel in an RC frame structure is vulnerable to collapse in an earthquake. In a confined masonry structure, the masonry infill can be not only properly restrained from failure, but also leveraged to add strength to the structural system.
- SKILL LEVEL of BUILDERS: A lower degree of skill, construction supervision, and tools are needed to build confined masonry houses than RC frame with masonry infill.

[14] Please note that this is approximate; we are in the process of updating unit costs and cost estimates.

- COST: It is potentially less expensive to build a confined masonry structure than RC frame. As mentioned previously, smaller diameter bars and fewer stirrups can be used in the bond beams and tie columns which are confining masonry walls.
- LONG-TERM IMPACTS: It is more common (and sustainable) in Indonesia to build single story, simple houses as confined masonry. Working together with tukangs and homeowners to build with skills, materials, and tools they are likely to use in the future will have a longer-term impact on reducing deaths and injuries during earthquakes.

VULNERABILITIES

Poor Construction Quality. Poorly designed or built confined masonry houses are vulnerable to collapse or heavy damage, as described in the Performance in Recent Earthquakes section.

Two-Story Construction. Our houses for Aceh were not designed for a second story, nor was a soil investigation done to determine if the soil could support the additional load of a second story. The addition of a second story is unlikely for the majority of the families; as such, designing for a second story would have made the houses even more cost prohibitive.

Adding a second story to the existing slender walled system is not recommended. However, second story expansion in the West Sumatra program is equally as unlikely and/or addressed as follows:

- The affected areas are primarily rural, and most homeowners are more likely (and able) to expand horizontally prior to expanding vertically.
- Most homeowners affected by the earthquakes in West Sumatra are barely able to afford a single story confined masonry house, and are unlikely to afford to build a second story during the lifetime of their house.
- Families who are wealthy enough to build a second story now or in the near future are building RC frame with masonry infill, even though we have recommended to them to use confined masonry with full-brick wide bonding. One commercial building in Padang has been built in this manner.
- Several (middle income) families who are building second stories now are building the second story from timber.

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 decisionmaking position.

The Aceh reconstruction was primarily donor-driven, while Build Change's new program in West Sumatra is homeowner-driven. In Aceh, BRR and most funding and implementing agencies designed and built the same house for all of their beneficiaries. Some organizations gave different floor plan options. We wanted to use a homeowner-driven model in Aceh, but when we gave the homeowners the option of building themselves or us building for them with their inputs, they all chose the latter. The homeowners wanted to choose the structural system, 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, as all homeowners selected this system, and cost of the standard 36m2 house was within the budget we were allotted by Mercy Corps.

Despite the fact that confined masonry was already common and locally sustainable in Aceh, convincing engineers and decisionmakers in some of the other donor agencies working in Aceh 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 because of

(1) Lack of familiarity with confined masonry: Most engineers and decisionmakers working for funding agencies – both Indonesian and expatriate – had never heard of confined masonry. Those with familiarity with multi-story RC frame with masonry infill design would apply the same thinking to confined masonry. They would not be able to accept the small columns and presence of cold joints within the columns.

(2) Lack of a building code for confined masonry in Indonesia: Thanks to the pioneering work of Teddy Boen, since the 1980's there have been guidelines available for confined masonry houses in Indonesia. There is not yet a building code.[15] Many decisionmakers 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.

In Build Change's new program in West Sumatra, which is entirely homeowner-driven, there are no obstacles to adoption of confined masonry as the structural system. The major hurdle is the cost for earthquake-resistant design and construction. The improvements we implemented in our Aceh house design – larger diameter ribbed bars, longer overlaps at connections, steel reinforcement in the wall – add cost. Although all families we are working with in West Sumatra are rebuilding better – especially regarding masonry quality and joint detailing – none of the families are including reinforcement in the wall every seven courses, as we did in Aceh.

RESEARCH NEEDS

There is still a role for technology and engineering in bridging the gap between conservative, code-based engineering design, and affordable and locally sustainable but sufficiently earthquake-resistant construction. This experimental research agenda is proposed in order to bridge that gap, and bring us closer to sustainable, low-cost earthquake-resistant building solutions. Materials testing and full-scale shaking table testing of a minimum 3m by 3m plan models with roof are needed.

Out-of-Plane Performance and Wall Reinforcement. Is horizontal reinforcement needed in the wall, and if so, how much and how should it be attached to the columns? How does the need for, type, and minimum amount of reinforcement change when there are openings in the wall?

Joint Detailing. What is the easiest, least expensive way of detailing the joints between tie columns and bond beams, and between orthogonal sections of bond beams? How does this change if smooth bars are used?

Tie Column and Bond Beam Section and Bar Size. What is the minimum section size for the confining elements, bar diameter, and stirrup and tie spacing? How does this change if smooth bars are used? Can the element size and steel detailing be reduced/increased depending on the quality of the masonry wall?

Masonry Wall Quality. How do we easily quantify and define the quality of the masonry wall? What factors influence the wall strength the most, and what simple measures can we take in the field to illustrate these points, and improve the construction?

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[15] For another example of an Indonesian guideline for simple houses, see Departemen Pekerjaan Umum, 2006. PEDOMAN TEKNIS: Rumah dan Bangunan Gedung Tahan Gempa

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