APPENDIX 2: HOUSING SUBSECTOR STUDY AND DESIGN OF CONFINED MASONRY HOUSES IN INDONESIA

HOUSING SUBSECTOR STUDY

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 production capacity, 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.[1] 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. 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

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

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 assuming the worst case soil condition.

2. International Building Code (IBC) -- 0.4g is the design seismic force prescribed in the 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 SNI does not recognize the seismic hazard imposed by the Sumatra fault. Current research (see Peterson et al.[2]) 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 SNI, which is based on a now-outdated American standard, the 1997 Universal Building Code (UBC), 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[3], guidance associated with Eurocode 8[4], Marcial Blondet's construction guideline,[5] and the IAEE Manual.[6] All guidelines were very useful but none was sufficient and

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[2] 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.

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

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

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

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

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 walls.

In addition to producing our own detailed set of design drawings, bar bending schedules, and bills of quantity, we drafted a design and construction guideline for earthquake-resistant confined masonry houses[7] 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. This guideline has been published as a simple step-by-step construction guideline for homeowners and builders is available on the Build Change website[8].

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."

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

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.

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.

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[7] 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"

[8] www.buildchange.org/USAIDPrimers.html

Large Openings. Similarly, there is a preference for tall doors and windows with vents above, 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 36m2 in plan, at least two bedrooms, at least two entrances/exits, orientation appropriate for sun, wind, and Islamic culture, and toilet, septic tank, soakaway.

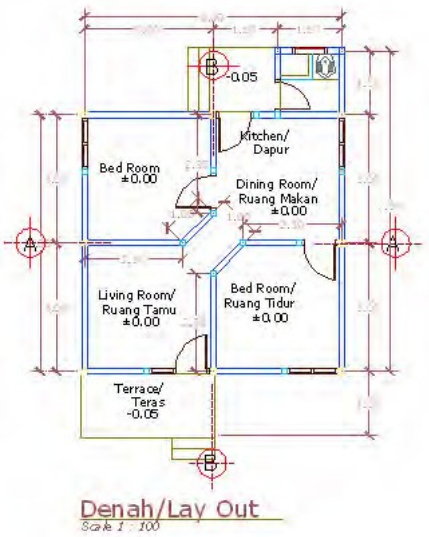

Figure 2. Build Change Pilot Project House, 2 bedroom, living room, dining room, with toilet outside.

DESIGN DETAILS

Foundation and Floor: Trapezoidal-shaped stone masonry foundation wall. 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 unless noted otherwise)

	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
--Ties	8mm dia at 15 cm	6mm, at 7.5 cm for the first 7 ties at column intersections, elsewhere 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,

Figure 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.

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 connections of columns and beams.
- 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.

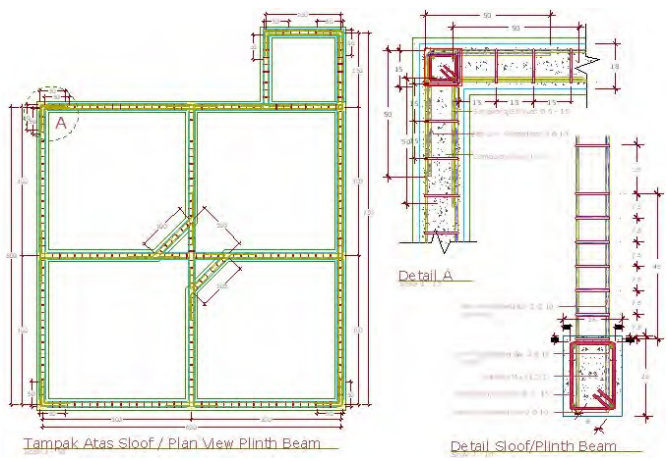

Figure 4. Bond Beam Layout and Connection Detailing

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 overturning and out-of-plane failure:

(1) increase the number and length of shear walls in both directions and 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.

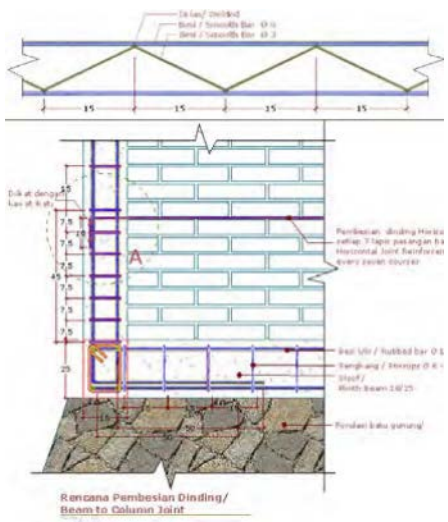

Figure 5.Horizontal Wall Reinforcement.

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

Roof. Roof was made of timber trusses covered by corrugated galvanized sheeting. Both hipped (Figure 1) and pitched (Figure 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 embedded in the ring beam and bolted to the trusses. 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.


Figure 6. Wall with Horizontal Reinforcement.


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

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 seismic inertial 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

Bricks. Fired clay bricks are widely available in Sumatra.

Soil is mixed by buffalo, machine, or by hand; bricks are hand-molded in forms 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


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

[9] Inspired by Prof. Ken Elwood, University of British Columbia

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 (see Figure 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.

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

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 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 (Figure 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 (Figure 9 bottom). When the welding school could not meet our demand, we used private sector local welding shops.

Figure 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 (Figure 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 roof 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 encountered, we dug them out and replaced them with compacted fill.
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.

Figure 11. Poorly built stone masonry foundation. Note gaps between stones, stones standing on end.

Stone Masonry Foundation Wall 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 foundation 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 Figure 11 for an example of a poorly built strip foundation.

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 to reduce waste.

Concrete Mixing and Pouring: Concrete was mixed at 1:2:3 (cement : sand : aggregate) 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 correct water/cement ratio, from slump tests to simply picking up a handful of mixed concrete and if the water (and cement) ran out through one's fingers, it was too wet.

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 the 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 consolidate the concrete. On a later project we used mechanical vibrators. However, the builders had a tendency to overvibrate and liquefy the concrete. We required builders to cast the entire bond beam 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/cm2.

Figure 12. Typical Build Change foundation (plinth) beam, Build Change-designed house for CRS

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

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

Bricklaying: Mortar was mixed at 1:3 (cement : sand) 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.11 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, are shown in Figs. 15 through 20.

Figure 15.Typical wall built by Build Change-trained mason

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

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

Figure 18. Typical wall built by other mason

Figure 19. Typical wall built by other mason

Figure 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 (Figure 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.

Figure 21. Builder, homeowner, Build Change architect, and Build Change engineer discuss ring beam-truss detail