



Tenth U.S. National Conference on Earthquake Engineering
Frontiers of Earthquake Engineering
July 21-25, 2014
Anchorage, Alaska

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

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ABSTRACT

Beginning in Aceh in 2005 and continuing in West Sumatra and Padang, Build Change, an international non-profit organization, rebuilt confined masonry 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 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 were affordable, easy to build with local materials, skills and tools, and earthquake-resistant.

The recent earthquakes in Indonesia 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.

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Background and Prevalence of Confined Masonry in Indonesia

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 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 to design and build 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

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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 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.

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 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 performed preliminary cost estimating and design analysis on 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 the reconstruction since shortly after the tsunami. The homeowners in the project were each asked which structural system they preferred. All chose confined masonry.

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 was based on the 2002 Indonesian Seismic Standard [2] and the 2003 International Building Code [3, 4]. The highest standard applicable in Indonesia was used since the intent was to design a structural system that could be built anywhere in Aceh or Nias and assuming the worst case soil condition.

Applicable Codes and Guidelines

A building code for confined masonry did not exist in Indonesia. The 2002 Indonesian Seismic Standard [2], which was based on UBC 1997, applied to reinforced concrete frame construction. Indonesia had a concrete code but did 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 [5]. Since 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, several other codes and guidelines were reviewed, including a series of posters produced by Teddy Boen [6], Marcial Blondet's construction guideline [7], and the IAEE Manual [8]. All of these guidelines were very useful but none was sufficient and completely appropriate for the structural and architectural system common in Aceh. Most codes and guidelines assumed a two or more story structure with rigid floor diaphragms and thicker walls.

Lacking a definitive code or guideline to use as a basis of design, 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 [9], 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.

Architectural, Cultural and Climate Considerations

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 was 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: 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.

Lightweight, Timber Truss Roof: Pitched or hipped roofs were preferred because of the significant amount of rainfall that annually occurs in Indonesia.

Other Criteria. The BRR building guideline for the Aceh reconstruction [5] included additional architectural criteria, including a minimum 36m² 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.

Design Details

Foundation and Floor: Trapezoidal-shaped stone masonry strip footing with steel dowels, as recommended by 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.

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. 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. The stirrup and tie bar diameters and spacing was modified for workability reasons and to provide increased strength in shear at the tops and bottoms of the columns. The spacing of stirrups in the bond beams was increased to save cost, as the design calculations indicated that greater stirrup spacing was possible. The rebar hook length, hook rotation, and joint detailing were shown on the drawings. It was not common practice to call out these details on engineering drawings used in Aceh.

Walls: Fired clay brick masonry walls were 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. 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 shifted 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).

Roof. The roof was made of timber trusses covered by corrugated galvanized sheeting. Both hipped and pitched roofs covers with CGI sheets were already common in Indonesia. The trusses were tied down with U-shaped steel plates. The tie downs were needed to prevent uplift in strong winds and were intended as an alternative to the common practice of wrapping the tie column bars around the trusses, which were susceptible to corrosion and pullout during high wind events.

Building Materials and Properties

Bricks: Fired clay bricks were widely available in Sumatra. The bricks were hand-molded and fired in open kilns using wood or rice husks as fuel. The brick quality (strength, consistency of size and shape) was variable. 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. Simple three-point bending tests and visual checks were used to evaluate the brick strength in the field.

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.

Rebar: Both ribbed and smooth bar were available in Aceh. Ribbed bar is more expensive. Ribbed bars were used for longitudinal bars and smooth bars were used for stirrups and ties. Scientific Construction Labs performed pro bono tensile tests on 22 random samples of steel reinforcement obtained from local shops in Aceh, including both ribbed and smooth steel in diameter between 4 and 13mm. The yield strength was found to be in the range of 57 to 81 ksi.

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. This process was time consuming, and consistent separation between the long bars was difficult to maintain due to flexibility of the binding wire. The detail was changed to welded bars with 3mm bars as the diagonals. The welding was initially performed by welders in a local welding school. When the welding school could not meet the demand, private sector local welding shops were used.

U-Shaped Steel Plates: The U-shaped steel plates for the ring beam – truss connection were manufactured by local shops. 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 weak, weathered clayey sandstone. The stronger red stone was used for construction.

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.

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

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. It was very difficult to reuse formwork made with such soft, easily warped timber. Thus in later projects, plywood formwork that could be reused was utilized.

Lightweight Steel: Later in the Aceh reconstruction lightweight steel channels were used for the roof trusses instead of wood. This shift away from timber was made due to the increasing cost and difficulty in obtaining good quality structural timber and concerns over authenticity of the timber source.

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.

Configuration

Masonry Gable Walls: 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.

Large Openings: 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. Vertical confining elements were added to all openings with area greater than 2.5m². Horizontal bed joint reinforcement was added to the wall at every seven courses and above and below openings. On later projects lintel and sill beams

were used instead of horizontal reinforcement.

Tall Walls and Long Walls: 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.

Covered Terraces: Covered terraces are en vogue in Indonesia. 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.

Connections

Between Confining Elements: 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.

Between the Masonry Wall and Tie Column: 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.

Between the Ring Beam and Truss: 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.

Construction Process & Quality

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.

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.

Concrete Mixing and Pouring: Concrete was mixed at 1:2:3 by volume on the ground or on a paved surface. The builders had a tendency to add too much water to the mix, 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.

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.

During the pilot project, a team of researchers from the Institute of Technology – Bandung (ITB) performed handheld concrete hammer testing on a random sample of concrete elements in the houses designed by Build Change. The foundation beams and column strengths at 28 days or older tested in the range of 175-200 kg/cm², which exceeded the BRR building guideline requirement.

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.

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.

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 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. Build Change wanted to use a homeowner-driven model in Aceh, but when the homeowners were given the option of building their houses themselves or hiring Build Change to build 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 the cost of the standard 36m² house was within the budget allotted to the pilot project.

Despite the fact that confined masonry was already common and locally sustainable in Aceh, convincing engineers and decision makers 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 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 RC 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, since the 1980s there have been guidelines available for confined masonry houses in Indonesia [6]. 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 has been the cost of implementing earthquake-resistant design and construction into the confined masonry practice already present. The improvements Build Change implemented in their Aceh house design added cost. 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 were used in West Sumatra because of the cost, for example the horizontal bed joint reinforcement in the walls.

Conclusions

Confined masonry was used in the post-Aceh reconstruction since it was a common construction method in Aceh 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.

Acknowledgments

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 Cassidy, Matt Eatherton, Jeff Falero, Andy Fennel, Tim Hart, David Kirschenbaum, Forrest Lanning, Andrew Mole, Jay Pisano, Rafael Sabelli, Tom Voss, and Carl Wilford.

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