

APPENDIX I: UNDERSTANDING CAUSES OF COLLAPSE OF CONFINED MASONRY HOUSES IN INDONESIA

Since the 2004 Indian Ocean tsunami, there have been at least seven earthquakes of significant strength to cause housing collapses, deaths, and injuries in other parts of Indonesia: Central Java, M6.3 on May 27, 2006; West Sumatra, M6.4 and 6.3 on March 6, 2007; Bengkulu and the Mentawai Islands, M8.5, 7.9 and 7.0 on September 12 and 13, 2007, and Padang, West Sumatra M7.6 on September 30, 2009. 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 while confined masonry homes that did not follow minimum design and construction standards were damaged. See Figures 1 and 2 for a well-built confined masonry house with no evidence of damage, on the edge of heavily damaged Pleret (2006 Central Java earthquake). 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.



Figure 1. Well designed and built confined brick masonry house, edge of heavily damaged Pleret (Bantul), S7.83686° E110.41552°, IMG_6636



Figure 2. 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 Figure 3 illustrates many of the shortcomings 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 the flaws can be addressed 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. 3. Confined masonry house under construction, insufficient connections, Pleret (Bantul). S7.87574°, E110.40703°, IMG_6575

THE FIRST C: CONFIGURATION

(1) MASONRY GABLE WALLS

Problem: Masonry gables are notoriously poor performers in earthquakes (see Figures 4 and 5) 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 4. Masonry gable wall out-of-plane failure in 27 May 2006 Central Java Earthquake, Keputren, Pleret (Bantul) S7.86905° E110.40272°, IMG_6721



Figure 5. Masonry gable wall out-of-plane failure in 27 May 2006 Central Java Earthquake, (Bantul) S7.89468°, E110.37341°, IMG_6542

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 (Figure 6). Alternatively, use a hipped roof (Figure 7) which is the lowest cost alternative, and also performs better in high winds.



Figure 6. Papan Gable (Maimunah's house designed and built by Build Change, Keunue ue, Peukan Bada, Aceh Besar)



Figure 7. 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. In Aceh, cases were observed 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 earthquakes in which the front of the house has collapsed, while the back of the house remained intact (see Figures 8 and 9). 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 8. Collapse of front wall in confined masonry house , Padang Panjang, IMG_8831



Figure 9. Partially collapsed brick masonry house with reinforced concrete (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



Figure 10. Rabung Empat Roof (Rusdi Razali's house designed and built by Build Change, Keunue ue, Peukan Bada, Aceh Besar)

Solution (Figure 10):

- (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.

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 Figure 11 for a tall wall and Figure 12 for a long wall.



Figure 11. Confined masonry building with overturning failure of tall, unsupported wall, Kec. Airnapal (North Bengkulu)



Figure 12. Confined masonry warehouse with out-of-plane failure of long walls without cross-bracing, , IMG 8891

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 for connection to each other and to the main walls of the house. See Figures 13 and 14.



Figure 13. Subdivision of confined masonry houses, damage to covered terrace, Bengkulu. S3.83218° E102.29287



Figure 14. Subdivision of confined masonry houses, damage to covered terrace, Bengkulu. S3.83218° E102.29287

Solution:

- (1) Avoid the covered terrace by using a simple extended overhang, as shown in Figure 10. 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 connections are detailed properly (Figure 15).

THE SECOND C: 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 use of smooth rebar and the common practice of terminating the bond beam and tie column bars in the joint with a small hook does not provide sufficient rebar development or confinement. 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 Figures 16 through 18 for examples.



Figure 15. Covered terrace with lightweight wall, Build Change designed house for Catholic Relief Services (Aceh Besar)

Solution: Use deformed bars. Bend the column reinforcement into the beams and overlap by 40 times the diameter of the bar. Similarly, bend the plinth and ring beam reinforcing around corners. Tie with double binding wire to maintain proper placement in the poured RC element.



Figure 16. Zoomed in view of ring beam column connection. IMG_6577



Figure 17. Confined masonry house with failure in masonry walls and connections between tie columns and bond beams, Kec. Airnapal (North Bengkulu)



Figure 18. Connection failure, RC frame building, Central Java

(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 and allowed the walls to fail out-of-plane. See Figures 19 and 20.



Figure 19. Insufficient connection between wall and tie column and between tie column and bond beam, Pleret (Bantul) S7.88174° E100.40869°, IMG_6746



Figure 20. Insufficient connection between wall and tie column and between tie column and bond beam, Segoroyoso, Pleret (Bantul) S7.88174° E100.40869°, IMG_6749

Solution: Toothing, or staggering the bricks/blocks at the column interface so that the concrete pours into the wall every other course, is recommended for confined masonry buildings. The practice is not common in Indonesia. Homeowners and builders are unwilling to spend the extra money and time (respectively) on additional formwork required to accommodate a toothed wall or concrete to pour it. Further, our experience has been that it is difficult to get the concrete to flow completely into the toothed area. Instead, truss-type horizontal steel reinforcement can be used in the bed joint of the masonry, every seven courses of bricks and above and below openings, and tied into the columns and beams.

Other Options: Instead of running ladder reinforcement column-to-column, a single bar can be laid in the bed joint for 50cm and tied into the column every seven courses of bricks. This adds less out-of-plane capacity to the center of the wall panel, but solves the wall panel-to-column problem sufficiently.

(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.

Solution: Strengthen this connection by using a U-shaped steel plate with bolts.

THE THIRD C: CONSTRUCTION QUALITY

(8) MASONRY WALL QUALITY AND USE OF PLASTER

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 bars of small diameter, provided the masonry wall is well constructed, with adequate bonding between bricks and mortar. See Figures 21 and 22 for examples of wall collapses with columns and roof intact. Weak bonding is clearly a contributor to failure (Figure 23); bricks were not soaked in water before building wall, and/or the mortar mix was too dry.



Figure 21. Subdivision of confined masonry houses, collapse of masonry wall exacerbated by insufficient connections, Bengkulu. S3.83218° E102.29287



Figure 22. Confined masonry house with failure in masonry walls and connections between tie columns and bond beams, Kec. Airnapal (North Bengkulu)

Plaster is often ignored in structural engineering analysis; however, for a simple confined masonry building with a relatively weak wall, high quality cement-based plaster can add significant strength. The house in Figure 21 is the only house in which wall collapse occurred in a subdivision of similar houses affected by the 2007 earthquakes near Bengkulu. It is the only house that hadn't been plastered yet.

Solution: Insist on good construction quality, and finish the wall with cement-based plaster.



Figure 23. 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.



Figure 24. Homeowner standing in front of her collapsed wall, note quality of concrete, Padang Panjang, IMG_8840.

(9) CONCRETE QUALITY

Problem. Poor quality concrete also contributed to failures. See Figure 24. Same solutions apply: ensure good quality materials and workmanship are used.

(10) FOUNDATION, SOIL and DRAINAGE

Very little earthquake-induced damage to confined masonry houses in Indonesia in recent earthquakes can be attributed to a soil or foundation problem. In the Central Java event, one example of sliding along the wall-foundation interface was found; in this case, there was no foundation beam. Effects of liquefaction were observed in one village in the Bengkulu event (Figure 26).



Figure 25. Displacement along wall/foundation interface, Tegal Kebong Agung, Imogir (Bantul) S7.93434° E110.36667°, CIMG1769



Figure 26. Cracks in foundation and walls associated with settlement and tilt on liquefiable soils, Lempuing (Bengkulu), S3.82799° E102.28473