Figure 3. *Confined masonry houses with failure in masonry walls and connections between tie columns and bond beams, Kec. Airnapal (North Bengkulu).*

Mentawai Islands. The latest casualty figures stand at 25 killed and 100 injured (OCHA Situation Report No. 8). The Indonesian National Development Planning Agency (BAPPENAS) puts economic losses at IDR 1.5 trillion (US $164 million).

As was the case in other recent earthquakes in Indonesia, houses were hit very hard by the two earthquakes. On mainland Sumatra, 17,695 houses were destroyed, 21,035 houses were severely damaged, and 49,496 were mildly damaged (OCHA Situation Report No. 8).

Damage to Housing

On mainland Sumatra, housing damage was concentrated along the coast north from Bengkulu and south from Padang to the Pasisir Selatan District. In this area, foundations are generally shallow strip footings made of rounded river stone masonry in cement mortar. Roofs consist of timber trusses supporting lightweight CGI sheets, asbestos sheets, or clay tiles. Hipped and pitched roofs are both common; in the Bengkulu area, timber gable walls are more common than masonry gables.

Wall systems for houses affected on mainland Sumatra include the following structural types:

- Confined or partially confined masonry. Full height fired clay brick masonry wall with varying degrees and types of confinement, including unconfined (unreinforced) masonry walls, timber tie columns and bond beams; reinforced concrete tie columns with timber bond beams; and reinforced concrete tie columns and ring beams
- Timber frame with masonry skirt around the lower third of the wall, and woven, plastered bamboo or timber above
- Timber frame.

Confined or partially confined masonry: This structural type is supported by a shallow river stone

Figure 4. *Partially collapsed unreinforced masonry house with timber bond beam (North Bengkulu).*

Figure 5. *Partially collapsed brick masonry house with RC tie columns and timber bond beams. Note partial collapse of masonry gable wall and lack of inplane stiffness in front wall, Kec. Lais (North Bengkulu), S3.53217° E102.03771°.*

Figure 6. *Confined masonry house with failure in masonry walls and connections between tie columns and bond beams, Kec. Airnapal (North Bengkulu).*

Figure 7. *Partially collapsed unreinforced masonry house with timber bond beam, Lempuing (Bengkulu), S3.82799° E102.28473°.*

masonry strip footing, and may have a reinforced concrete foundation (plinth) beam. Two types and sizes of fired clay bricks were common. Traditional hand-molded and wood kiln-fired bricks are generally 9 cm wide by 19 cm long by 4 cm in height. Their quality and strength can vary considerably depending on the type of clay used, duration of firing, and placement in the kiln. Machine-mixed, molded and fired perforated bricks, more common in and around Bengkulu, are 9 by 19 by 9 cm in size. Regardless of the type of bricks, houses typically use running bond for the masonry wall, resulting in a half-brick wide wall (13 cm with plaster, 10-11 cm without).

For confined masonry houses, columns are typically cast after the masonry wall is built, flush with the wall, and thus the same width as a brick or block (10 or 11 cm). Smooth reinforcing steel is common, typically 6-8 mm in diameter with stirrups ranging from 3-6 mm in diameter. Stirrups and ties are spaced at 15-35 cm intervals.

The most common reasons for damage or collapse of confined or partially confined masonry houses are the following:

(1) Insufficient connections between confining elements. Figure 3 illustrates the importance of connections between confining elements. Note that the reinforced concrete columns and beams, despite their insufficient and inconsistent section and use of small diameter bars and stirrups or ties at large spacing, remain largely intact, with failure occurring in the masonry wall and at the connection between tie column and bond beam.

(2) Poor quality workmanship in the masonry wall. Figure 3 also illustrates the importance of good quality masonry; in this case, partial collapse was initiated in the walls.

(3) Lack of sufficient stiffness in the in-plane direction of the front wall. A common architectural preference in Indonesia is to have many large openings at the front of the house. This lack of stiffness in the in-plane direction contributed to several partial collapses (Figures 4 and 5).

(4) Insufficient connections between tie columns and masonry walls.

(5) Tall, slender wall prone to out-of-plane failure. With plaster, the common wall is only 13 cm thick, and walls tend to be 3 m in height. In the case shown in Figure 6, the wall was over 3.5 m tall with a span over 5 m without interior crosswalls or bracing.

(6) Use of timber for bond beams. Common practice is to use reinforced concrete for tie columns and timber for the bond beams. This construction practice was not sufficient to prevent collapse of walls of some houses (Figure 7).

Several confined masonry houses located in a housing development in Bengkulu were damaged for similar reasons (figures 8 and 9). This sloping subdivision of at least 60 houses was built by a developer, and the houses were subsequently purchased by owners. Although there were some variations in floor plans, most houses were identical: two bedrooms with kitchen and indoor bathroom, single story, and approximately 40 m2.

Damage was common at the upper column-beam connection in the open frame supporting the gable wall above the covered terrace (Figure 8). The gable wall and the side walls collapsed completely in several cases. The most significantly damaged structure was the only one that was not yet plastered (Figure 9); in Indonesia, cement-based plaster adds significant strength to the masonry wall. It is

Figure 8. *Subdivision of confined masonry houses, damage to covered terrace, Bengkulu, S3.83218° E102.29287°.*

Figure 9. *Subdivision of confined masonry houses, collapse of masonry wall exacerbated by insufficient connections, Bengkulu, S3.83218° E102.29287°.*

likely that some houses were more damaged than others because of 1) variations in construction quality and workmanship, and 2) location on the hillslope. These failures should be studied for the purpose of improving guidelines for new confined masonry construction. The causes of these failures, particularly workmanship and poor connections, should be emphasized in the guidelines.

Timber frame with masonry skirt: Many timber frame houses with 40 cm to 1 m of masonry around the base of the wall performed well in the earthquake. Like confined masonry, this type of house is supported by a shallow stone masonry strip footing; however, there is rarely any connection between the timber posts and the footing, or the timber posts and the masonry panel. The damage to these structures, considered "semi-permanent" in Indonesia, consisted of cracking of the masonry panel, failure of the masonry panel as a rigid block, and shifting and damage to the timber frame (Figure 10).

The Mentawai Islands: These islands are a predominantly rural, sparsely populated chain of four major and many small islands approximately 9 hours by boat from mainland Sumatra. In many villages on the southernmost of the Mentawai Islands — North Pagai and South Pagai — 25%-90% of the houses were destroyed or uninhabitable. There are three primary structural housing types in the villages: 1) timber frame houses on stilts or shallow stub footings;

Figure 10. *Timber frames with masonry skirt, Kec. Lais (North Bengkulu). Left: Superstructure has shifted off, although the relatively heavy roof structure remains largely intact, and the masonry panel is partially collapsed, Kota Agung, S3.55841° E102.08951°.*

Figure 11. *Timber frame with posts resting directly on soft ground, Barimanua, Pulau Sipora, Mentawai Islands.*

Figure 12. *Confined concrete block masonry, partial collapse due to lack of sufficient connections between confining elements, Barimanua, Pulau Sipora, Mentawai Islands.*

2) timber structures with a concrete block masonry skirt up to 1 m; and 3) confined or unreinforced hollow or cellular block masonry structures with timber truss roofs. In all cases, roof cover is lightweight, consisting of CGI sheets, asbestos sheets or locally made thatch (rumbia). Concrete block structures were damaged more significantly and in greater numbers than the timber houses.

Damage to the timber houses resulted from a few causes. First, timber posts rest directly on the ground, which caused the posts to sink in the ground at soft soil sites and sites inundated by tsunami; this foundation system is vulnerable to weathering of the timber due to the lack of isolation from water uptake from the ground (Figure 11). Some houses with a stone or concrete stub foundation slid off the foundation. Superstructures lack bracing in the in-plane direction, and members are connected with nails only. Timber is not maintained or treated; newer houses with treated or painted timber performed better than those with older, weathered timber.

Confined concrete block masonry structures had similar problems to the confined masonry structures on the mainland, including lack of sufficient connections between confining elements, and poor quality block masonry (Figure 12). Most concrete blocks are cellular. There was a wide variation in the strength of the blocks used, some of them crushing easily under hand pressure. This lack of strength results from low cement content, use of beach sand, and production by hand (without mechanical vibration).

Liquefaction effects on houses: Effects of liquefaction, in the form of differential settlement and foundation cracking (Figure 13), vertical cracks in masonry walls, heave and cracking of interior floors, and reports of water and sand coming up

Figure 13. *Cracks in foundation and walls associated with settlement and tilt on liquefiable soils, Lempuing (Bengkulu), S3.82799° E102.28473°*

Figure 14. *Temporary houses, Barimanua Village (Mentawai Islands).*

Figure 15. *Hyundai Shop, Padang.*

through the cracks in the floors, were found in at least six houses in Lempuing, a village on the edge of Bengkulu city. This low-elevation site consists of clean, fine to medium sand near the surface, on top of high groundwater. Floor slabs generally consist of thin (5-10 cm) unreinforced concrete.

Transitional Housing and Reconstruction

The Indonesian government has promised IDR 15 million (approximately US $1,700) for each family with a destroyed house, IDR 10 million for severely damaged houses, and IDR 5 million for mildly damaged houses. However, it is unlikely that this funding will be disbursed to the families until 2008. Homeowners are staying in temporary shelters consisting of recycled timber, thatch, tents and tarps (Figure 14) and starting to rebuild using recycled materials and their own resources. The Indonesian Red Cross and some international aid agencies are providing some basic materials, such as nails and tarps. In fear of a tsunami, some villages in the Mentawai Islands have asked to relocate to inland or higher ground.

Damage to Reinforced Concrete Buildings

In the urban areas of Bengkulu and Padang, RC frame with masonry infill is still the most common structural type for multistory commercial buildings and hospitals, although a few steel frame structures are under construction in Padang. In the cities, many multistory RC frame with masonry infill buildings had cracks; however, little structural damage was observed. In Padang, two buildings collapsed completely, both RC frame buildings with RC slab roof and floors. One of them, the Hyundai shop, is shown in Figure 15.

Major structural damage to RC frame buildings in Bengkulu was similarly limited, observed at only two buildings, both “ruko” buildings — combination house (rumah) on upper floors, and shop (toko) on ground floor. The ground floor is an open frame at the front, with a brick infill wall at the back and possibly a brick infill wall halfway back with a door. Both damaged rukos were located on sites that slope downward away from the road or parking area, and thus the ground floor is supported by a frame on spread footings bearing at different elevations. Due to safety concerns, it was not possible to do a detailed inspection of settlement and deformation of the foundation elements.

Figure 16. *Two-story ruko, 3° tilt in first floor column, Bengkulu, S3.80362° E102.27617°.*

Figure 17. *Three-story ruko, Bengkulu, S3.80581° E102.27953°.*

Figure 18. *SMAK SNT Carolus School, pre-2000 earthquake building on right, post-2000 earthquake building on left, Bengkulu, S3.82846° E102.29587°.*

The ground floor of the five-bay, two-story ruko shown in Figure 16 dropped by approximately 1 m due to failure at the column-slab interface. The structure is tilting back by approximately 4º, and the first floor columns are leaning to the left at 3º. Ribbed, 14 mm diameter steel was used in the columns and beams, with ties of 6 mm diameter spaced at 4 cm near the joint. Similar failure at the column-ground floor-beam interface occurred at a three-story, two-bay ruko (Figure 17). In this case, the failure was clearly exacerbated by slope failure towards the building. The columns were 32 cm x 32 cm and used up to eight smooth 15 mm diameter longitudinal bars.

Nonstructural damage, primarily in the form of cracks in masonry infill walls, was common in multistory commercial buildings. Falling hazards existed at many frame structures in which the column was not located at the corner, and unreinforced masonry walls were used to extend the plan area.

Schools: UN OCHA reports that 260 educational facilities were destroyed, and 450 severely damaged. The SMAK-SNT Carolus School in Bengkulu consists of two separate two-story RC frame buildings, one of which was a new building constructed after the previous building collapsed in an earthquake in 2000. The other building was repaired after the 2000 earthquake. Only hairline cracks were found at the edges of masonry infill walls in the new building; however, the timber truss roof collapsed where it was joined to or battered by the older building (Figure 18). The repaired building had new, hairline cracks in the same pattern as those that were plastered and painted after the last earthquake. The tops of the first floor columns were also cracked. It appeared that they had been previously repaired by a sealant or adhesive. Some masonry interior walls were partially collapsed.

Confined masonry interior and end walls collapsed at a rural single-story school complex in Lais Sub-district (Figure 19), leaving the long walls standing and supported against out-of-plane failure primarily through column steel tied around the roof trusses. Without strong-motion recordings, it is difficult to

Figure 19. *Sekolah Dasar Negeri No. 04, note steel splice location, use of rounded cobbles in concrete, Kec. Lais (Bengkulu), S3.52958° E102.04525°.*

Figure 20. *Collapsed confined masonry building, note lack of plinth beam and connection between column and plinth, Pal 30, Kec. Lais, (North Bengkulu), S3.53490° E102.05996°.*

say how much directionality contributed to the end and interior wall collapses. The ring beams were not capable of spanning these wide classrooms. Ring beams were approximately 15 cm x 11 cm in section and used four 8 mm diameter longitudinal bars, with 4-5 mm diameter stirrups spaced at distances of 20-30 cm. Similar to the problems observed for confined masonry houses, connections between tie columns and bond beams were insufficient. Coarse gravel to cobble-size aggregate was used in the concrete, which was broken easily by hand pressure.

A second school compound with significant damage in Lais Subdistrict consisted of two buildings. A single-story confined masonry building collapsed (Figure 20). The plinth was built of rounded river stone masonry, without a plinth beam for the columns to tie into. Failure at these and the upper column-beam joints likely led to collapse. The columns themselves appeared to be largely intact. A newer single-story building, rectangular in plan with a covered terrace on one side, experienced cracking and tilt of the columns on the terrace. Cracking from deformation in the out-of-plane direction (perpendicular to the long axis of the building) was observed.

Hospitals: Nonstructural damage to hospital buildings in Bengkulu and Padang resulted in cracked masonry infill walls, chipped plaster, and dust (Figure 21); patients were evacuated to tents (Figure 22). The M. Yunus hospital in Bengkulu was not operational right after the earthquake due to repair work needed. The building code considers masonry infill walls to be nonstructural elements, which has important implications for critical facilities that need to remain operational after earthquakes.

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Figure 21. *Nonstructural damage at M. Yunus hospital in Bengkulu (photo: Boen).*

Figure 22. *Patients were evacuated to tents (photo: Boen).*