UNREINFORCED BRICK MASONRY CONSTRUCTION

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BACKGROUND

Bricks were first fired around 3500 BC, in Mesopotamia, present-day Iraq, one of the high-risk seismic areas of the world. The ziggurat temples at Eridu, possibly the world's first city, have withstood not only earthquakes but also wars and invasions. From Roman aqueducts and public buildings to the Great Wall of China, from the domes of Islamic architecture to the early railway arch bridges, from the first 19th century American tall buildings to the 20th century nuclear power plants, bricks have been used as structural material in all applications of building and civil engineering.

The most commonplace use of bricks worldwide throughout time is in residential dwellings. The shape and size of bricks can vary considerably, and similarly the mortars used depend on local material availability, but the basic form of construction for houses has minor geographical variations and has changed relatively little over time.

The worst death toll from an earthquake in the past century occurred in 1976 in China (T'ang Shan Province), where it is estimated that 240,000 people were killed. Most of the deaths were due to the collapse of brick masonry buildings.

In more recent times, seismic codes place substantial constraints on unreinforced brick masonry construction in earthquake-prone areas, limiting the allowed number of stories,

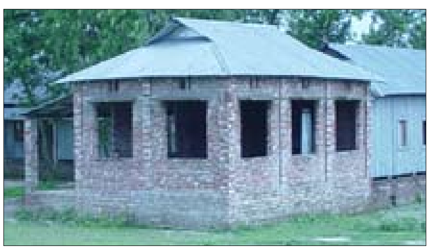

Figure 1: One-story brickwork construction in Bangladesh (WHE Report 91)

Figure 3: Unreinforced brick masonry building with reinforced concrete roof slab (WHE Report 21, India)

Figure 2: Two-story brick masonry building with wooden floors (WHE Report 41, Kyrgyzstan)

Figure 4: Six-story unreinforced brick masonry apartment building (WHE Report 73, Slovenia)

Figure 5: Four-story building with strengthened spandrels in Offida (WHE Report 29, Italy)

the minimum thickness of walls, and the number and position of openings. As a result, construction of load-bearing unreinforced brick masonry structures has dwindled in these countries, and alternative forms of construction such as confined masonry or reinforced masonry, considered less vulnerable, have been developed instead. The present section describes only unreinforced, fired-brick masonry structures, while other forms of masonry construction, from stone and sun-dried brick to reinforced and confined masonry, are treated in other sections of this volume.

In the World Housing Encyclopedia, examples of this construction typology range from Colombia to Kyrgyzstan and from India to Italy.

MASONRY FABRIC

Brickwork is an assembly of brick units bonded together with mortar. While brick size can vary considerably depending on the quality of the clay and the manufacturing tradition, the basic firing technology is common worldwide. Variations in kiln typology are very limited. The major factors influencing the strength of the bricks are the purity of the clay and the firing temperature. Mortars are subject to greater variation, but the basic materials used in mortar mixes are sand, water, and one or more of the bonding agents, mud, clay, or cement, depending on local availability. The proportion of bonding agent/s to sand determines the compressive and bonding strength of the mortar. In earthquake-prone areas, the development of an effective level of bonding between mortar and bricks is essential to resist shear-cracking. Bricks might be frogged or specially shaped to create mechanical interlocking and improve bonding. Brick construction is relatively simple and cheap. In certain cases bricklaying may require highly skilled labor; however, this type of construction is usually performed by small to very small building contractors or as self-built construction.

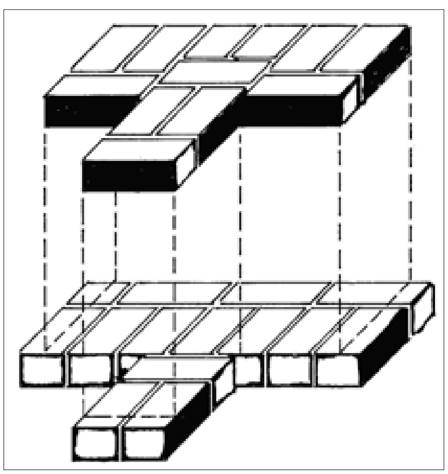

Figure 6: Details of bonding arrangement for masonry units at wall junction (WHE Report 73, Slovenia)

From an ***architectural*** point of view, brick construction is rather flexible, allowing substantial freedom in the layout of internal spaces and the distribution of openings, making it quite adaptable to different climatic conditions.

From an ***environmental*** and ***structural*** point of view, masonry performance depends on the performance of mortar and brick units, and their composite behavior.

Modern building codes provide guidelines for the preferred combinations of mortar mixes and brick units in order to optimize both the strength and the environmental performance of the wall assemblages made of these components.

The structural performance of brick masonry buildings depends on the following four types of connections within masonry elements:

1. Integrity and shear resistance of brick masonry walls is influenced by the extent and quality of bond between mortar and bricks. It is essential for the brickwork to be properly constructed to allow for the best possible level of bonding to develop. It is also important to ensure repointing of bed and head joints at regular time intervals so as to ensure the maximum possible surface of contact.

2. The second level of connection is among the wythes of brick walls. Modern masonry construction standards require regularly spaced ties between the wythes of a cavity wall to ensure monolithic behavior and redistribution between the wall wythes. In historic masonry construction it is common for the walls to be either one- or two-brick-wide solid brick, or to consist of two external wythes with a cavity filled with rubble (to improve the thermal capacity of the wall). The connection between the two wythes was ensured by headers, (bricks placed through the wall at regular intervals).

3. The third level of connection is among the walls at the corners and junctions and depends on the specific fabric of corner returns. Such connections ensure 3-D behavior of the masonry box-like structure and the redistribution of lateral forces among walls.

4. The forth level of connection is between the walls and the horizontal structures (floors and roof); this connection highly influences the seismic performance of the building.

PERFORMANCE IN PAST EARTHQUAKES

In proportion to its widespread presence worldwide, there are many examples of brick masonry performance in past earthquakes. The extent of damage depends on the seismic hazard and the earthquake intensity at a particular site.

Common damage patterns found in WHE reports include the following:

- Collapse of chimneys and plaster cracks (MMI intensity VII)
- Shear cracks in the walls, mainly starting from corners of openings (MMI intensity VIII)
- Partial or complete out-of-plane wall collapse due to lack of wall-to-wall anchorage and wall-to-roof anchorage. In extreme cases this is accompanied by partial or total collapse of floor and roof structures (MMI intensity VIII-IX)
- Total collapse of walls and entire buildings in some cases (MMI intensity X), for example, 2001 Bhuj (India) earthquake

Evidence from recent earthquakes has confirmed that the overall performance of brick masonry buildings is dependent on the type of roof system: buildings with lightweight roofs suffered relatively less damage while buildings with reinforced concrete roofs suffered much greater damage. This performance was observed after the 2001 Bhuj (India) earthquake (M7.7), where brick buildings in the epicentral area (MMI intensity X) were surveyed (IIT Powai 2001). This is in line with the evidence collected after the 1997 Umbria-Marche (Italy) earthquake (MMI VIII), where many buildings with heavy reinforced concrete roofs suffered substantial structural damage and partial collapse. (Note that the total number of collapsed buildings was significantly less than the Bhuj earthquake.)

It can be observed from the WHE reports that the seismic performance rating for brick masonry buildings is fairly homogenous worldwide. According to the EMS scale, brick buildings fall generally in Class B, except for the examples of modern design or buildings with seismic strengthening, which have been classified as Class C.

Figure 7: Shear cracks in an unreinforced brick masonry building from the 1993 Killari earthquake (WHE Report 21, India)

Figure 8: Collapse of brick masonry buildings in the 1988 Spitak earthquake (WHE Report 4, Armenia)

Figure 9: Severe damage to an unreinforced brick masonry building due to inadequate wall density in the 1963 Skopje, Macedonia earthquake (WHE Report 73, Slovenia)

SEISMIC STRENGTHENING

Due to the large presence of existing brick masonry buildings in residential building stock worldwide, substantial research and implementation have gone into the development of strengthening techniques during the past 30 years, as the most effective way to reduce human and monetary losses in earthquakes. Some of the techniques are adaptations of traditional devices found in vernacular architecture.

Typical strengthening techniques widely applied include the following:

- Installation of a new RC ring beam (or band) at the roof level. It is very important to achieve a good level of connection between the new RC ring beam and the existing masonry, if further seismic damage is to be avoided.

Figure 10: Construction of a RC ring beam/lintel band (WHE Report 21, India)

- Stitching and grouting. Wall cracks are stitched with reinforcement and grouted with mortar to restore the wall integrity. This technique consists of drilling holes through the walls and installing steel bars; subsequently, the holes are grouted with cement grout. For historic buildings it is essential that the grout is lime-based and the bars are stainless steel or another non-corroding material.

Figure 11: Grouting to improve capacity of spandrel walls (WHE Report 29, Italy)

- Installation of metallic ties. These ties can anchor a wall to the floor and roof diaphragms or to an opposite wall. Roof and floor slabs are anchored to the walls to ensure the inertia force transfer to the walls. When a wall is anchored directly to an opposite wall, the metallic ties will pass under the floor structure. It is very important to accomplish a regular distribution of ties for both approaches because irregular tie distribution may be a cause of earthquake damage. Installation of ties may also require that new boundary members (chords and collectors) are added to the floor and roof to ensure the integrity and diaphragm action.

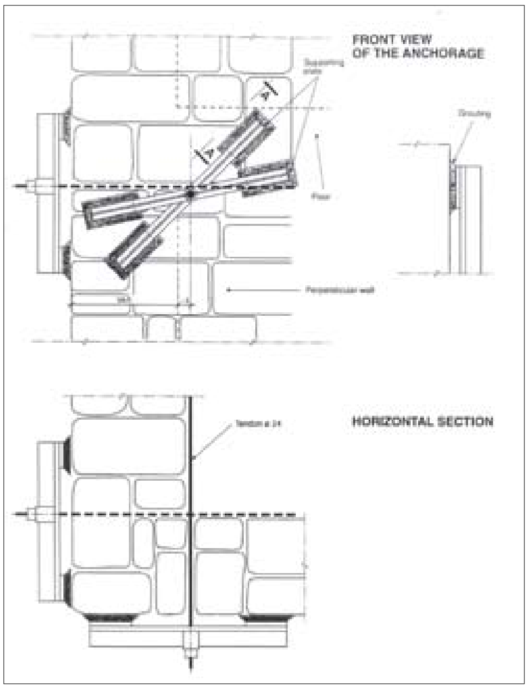

Figure 12: Modern tie re-habilitation (WHE Report 29, Italy)

Figure 13: Tie-anchorage construction detail (WHE Report 29, Italy)

- Reinforced cement coating or reinforced concrete overlay. These methods help the lateral load resistance of walls similar to shotcreting. Reinforcement is usually a steel mesh or perhaps a polymer grid developed from a newer technology. These methods can have detrimental effects on the condition of the bricks

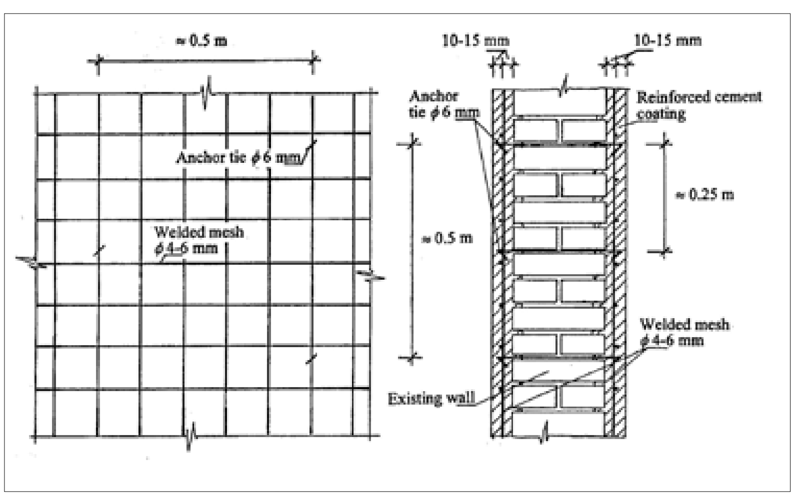

Figure 14: Seismic-strengthening by reinforced cement coating (WHE Report 73, Slovenia)

as well as the architectural character of the building similar to the shotcreting approach.

- Crack injection with cement paste or epoxy. For small to moderate cracking, cracks can be filled with anti-shrinking grout to reestablish wall integrity.
- Repointing. In the case of poor mortar quality and good quality bricks, the existing mortar can be partially replaced with a cement or lime/cement mortar of significantly better quality.
- Shotcreting: strengthening of walls with shotcrete jackets. This technique consists of installing new steel wire mesh and attaching it to the existing wall with through-wall ties or strips spaced at 500 mm on center both horizontally and vertically. The limitation of this intervention is the fact that it needs to have a proper independent footing in order to be effective. Also, it severely limits the "breathing" of the wall and this may produce severe decay of both bricks and lime mortar in older masonry buildings. This method also alters the architectural character of the building which may be disadvantageous.
- Installation of vertical columns. These columns are anchored to the wall by metallic anchors to prevent the out-of-plane buckling of the wall. Columns, generally steel sections, are spaced such that the brick can easily span the distance between them without failing. The columns are attached to the floor and roof diaphragms. This is particularly helpful for tall, thin walls.

The importance and effectiveness of seismic provisions was confirmed both in the 1993 Killari earthquake (M 6.4) and the 2001 Bhuj earthquake in India. A building with a RC lintel band located in the Killari village only a few kilometers from the epicenter suffered only minor damage in the earthquake, while a large majority of the buildings in the same village collapsed, causing over 1,400 deaths. (WHE Report 21, India). Similarly, unreinforced masonry buildings with RC bands survived the 2001 Bhuj earthquake with moderate damage while the neighboring buildings of similar construction without seismic provisions collapsed.