STONE MASONRY CONSTRUCTION

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BACKGROUND

Stone masonry is a traditional form of construction practiced for centuries in the regions where stone is locally available. It is still found in old historic centers, often in buildings of cultural and historical significance, and in developing countries where it represents affordable and cost-effective housing construction. This construction type is present in earthquake-prone regions of the world, such as Mediterranean Europe and North Africa, the Middle East, India, Nepal, and other parts of Asia. The World Housing Encyclopedia contains nine reports describing stone masonry housing construction practices in Greece (WHE Report 16), Italy (WHE Report 28), India (WHE Report 18 and 80), Nepal (WHE Report 47 and 74), Palestinian Territories (WHE Report 49), Slovenia (WHE Report 58), and Algeria (WHE Report 75).

The typical cost of a new stone masonry house is between 50 and 90 US$ /m^2 in India, and between 150 and 200 US$/$m^2$ in Algeria.

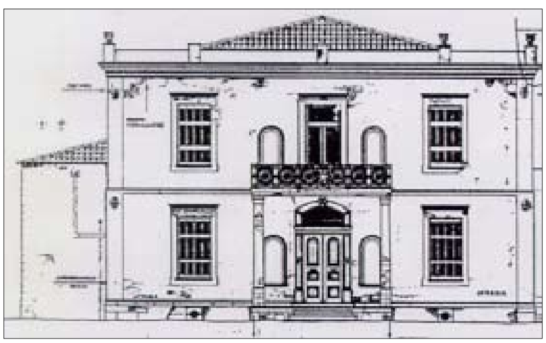

Figure 1: Stone masonry building in Greece (WHE Report 16)

Figure 2: Single-family stone masonry house in Italy (WHE Report 28)

Figure 3: Unreinforced concrete and stone masonry building in the Palestinian Territories (WHE Report 49)

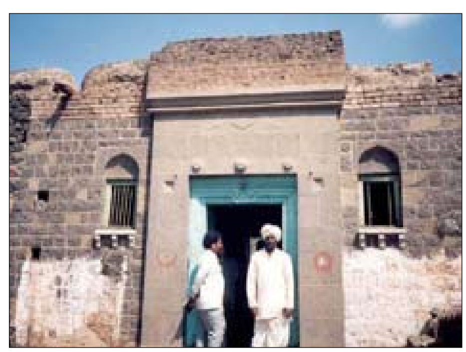

Figure 4: Typical Maharastra, India village (WHE Report 18, India)

STONE MASONRY BUILDINGS

Houses of this construction type are found both in urban and rural areas. There are broad variations in their shape and the number of stories. Houses in rural areas are generally smaller in size and have smaller openings since they are typically used by a single family. Buildings in urban areas are often of mixed use, that is, with a commercial ground floor and multifamily residential area above. Houses in the countryside are built as stand-alone structures, while the neighboring houses in old town centers often share a common wall.

Rural one-story stone masonry houses with timber frames and thick flat roofs for thermal insulation ("khan") are widely spread throughout India. In the mountainous and hilly regions of Nepal there are two types of stone masonry houses: a traditional oval-shaped house and a rectangular-shaped house, both typically two stories high. In hilly Mediterranean countries the number of stories varies between two in rural areas and five in towns. Typically, stone masonry houses are used by the lower and middle classes, however in historical urban centers they are often inhabited by the upper classes. Urban masonry buildings are characterized with several internal renovations and updates in the course of their useful life.

Figure 5: Traditional oval-shaped rural stone house in Nepal (WHE Report 74)

The main lateral and gravity load-resisting system consists of stone masonry structural walls. The walls are generally uniformly distributed in both orthogonal directions with a wall thickness ranging from 400 mm to 700 mm. The wall density (area of walls in one direction versus total plan area) ranges from 5% to 25%. Stone masonry apartment buildings in Algeria have an extremely low level of wall density (5% to 6%) despite having up to five stories with a story height of 3.5 m.

Structural walls are made of the following:

- Rubble stone in mud/lime mortar or even without mortar (Greece, WHE Report 16; Italy, WHE Report 28; Nepal, WHE Reports 47 and 74)
- Massive stone masonry in lime/cement mortar (Algeria, WHE Report 75; India, WHE Report 80)
- Two exterior wythes of larger stones with rubble infill in mud/lime mortar, often without through stones that should connect the exterior wythes (India, Italy, Nepal, Slovenia)
- Two-wythe stone masonry walls filled with plain concrete (Palestinian Territories, WHE Report 49)

The houses are built by local builders or by owners themselves, without any formal training. The quality of construction in urban areas is generally superior to that found in rural areas.

Structural walls are supported either by stone masonry strip footings or there are no footings at all. Floor structures in towns and historic centers are vaulted brick masonry at the ground floor level and timber joists at the upper floor levels. Timber joists are usually placed on walls without any physical connection. The original floor structures in historic buildings have typically been replaced either by a precast joist system or by solid reinforced concrete slabs especially in Italy (WHE Report 28) and Slovenia (WHE Report 58). Reinforced concrete (RC) slabs are used for floor structures in the multistory stone masonry buildings that are still being built in India. In the Palestinian Territories (WHE Report 49), floor and flat-roof structures in the newer composite (stone and concrete) masonry construction are solid RC slabs.

EARTHQUAKE PERFORMANCE

The most important factors affecting the seismic performance of these buildings are:

- The strength of the stone and mortar
- The quality of construction
- The density and distribution of structural walls
- Wall intersections and floor/roof-wall connections

Stone masonry construction generally shows very poor seismic performance. Poor quality of mortar is the main reason for the low tensile strength of rubble stone masonry. Timber floor and roof structures are usually not heavy and therefore do not induce large seismic forces. However, typical timber floor structures are made of timber joists that are not properly connected to structural walls. These structures are rather flexible and are not able to act as rigid diaphragms. Due to their large thickness, stone masonry walls are rather heavy and induce significant seismic forces.

Delamination and disintegration of the masonry are damage patterns typical for walls built with two exterior wythes and rubble infill in weak mud mortar with many air voids. Out-of-plane failure can occur when the connections between the exterior and interior walls are inadequate. When the connections between the perpendicular walls are strong, the wall shear capacity can be exhausted, thus causing typical shear cracks to develop.

The key seismic deficiencies of the two-wythe stone masonry buildings in the Palestinian Territories (WHE Report 49) are poor connections between the walls and slabs, as well as a very poor bond between the concrete and stones in masonry walls. These deficiencies result in the disintegration of wall wythes and collapse of the walls.

In the case of a one-story house in India with exterior masonry walls and an inner timber frame supporting a heavy mud overlay, the structure could be unstable due to poor post-to-beam connections. The presence of frames may be beneficial, however, if it prevents the exterior walls from collapsing inwards (India, WHE Report 18).

Most vulnerable stone masonry houses in Nepal (WHE Reports 47 and 74) suffered severe damage and the loss of integrity during past earthquakes even when the buildings were located at a large distance from the epicenter.

The percentage of stone masonry buildings that collapsed or were damaged beyond repair in recent earthquakes depends on the general quality of construction and the earthquake intensity.

The percentage of collapsed masonry buildings in a few recent earthquakes is listed below:

- 8% in the 1999 Athens earthquake (M5.9) (Greece, WHE Report 16)
- 12% in the 1998 Bovec earthquake (M5.6) (Slovenia, WHE Report 58)
- 15% in the 1993 Maharastra earthquake (M6.5) (India, WHE Report 18)

Figure 6: Typical collapse of a corner (WHE Report 16, Greece)

Figure 7: Typical damage during the 1998 Bovec earthquake in Slovenia (WHE Report 58)

IMPROVED SEISMIC RESISTANCE OF NEW CONSTRUCTION

The main provisions to improve seismic resistance of stone masonry building are:

- Enhancing the building integrity by tying the walls together and ensuring that the floor-to-wall connections are sound
- Achieving increased masonry strength by using cement mortar and through-stones

The integrity of a building can be increased by providing ring beams at the floor and roof levels and by installing knee-braces to reinforce post-to-beam frame connections. This is particularly true in the case of stone masonry houses in India (WHE Report 18).

SEISMIC STRENGTHENING OF EXISTING STONE MASONRY BUILDINGS

In order to increase the seismic resistance of structural walls, the basic building material has to be strengthened. Stone masonry can be strengthened by means of deep repointing and/or by systematically filling the voids with injected cement-based grout (practiced in Greece and Slovenia). The installation of through-stones, the pointing of exterior walls with cement mortar and the strengthening of wall corners using wire mesh and cement overlay is practiced in Algeria, India, and Nepal.

Figure 8: The application of through-stones as practiced in India (WHE Report 18)

The actual shear resistance of structural walls can be enhanced if they are properly tied and connected to floor and roof structures. In the case of existing buildings, this is achieved by means of steel, timber, or reinforced concrete ties at floor levels. Vertical ties of the same material are inserted at the corners and between openings to prevent instability. The timber joists of floor structures are connected to the walls by means of steel anchors and plates. Ties are placed symmetrically on both wall sides; alternatively, RC are placed at the exterior and steel ties are placed at the interior wall surface. (This technique is practiced in Algeria, WHE Report 75.)

An RC ring beam provided at the roof level is one of the most effective measures to prevent the out-of-plane collapse of gable walls. Dislocation of the roof structure is prevented by anchoring its elements into the ring beam.

Increased lateral load resistance can be additionally achieved by constructing new stone walls in one or both directions and/or by decreasing the dead load. The new walls are much more effective if they are subjected to compressive stresses due to dead loads. This measure is recommended in combination with the replacement of existing timber floors with RC slabs, which are also then capable of acting as rigid diaphragms.

There is a long history of strengthening and/or repairing these buildings after past earthquakes. To date, these retrofit applications have either confirmed the effectiveness of certain strengthening or repair techniques or exposed mistakes.

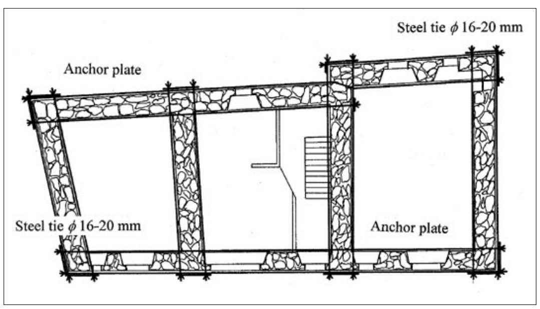

Figure 9: Tying walls with steel ties at each floor level as practiced in Slovenia (WHE Report 58)

Figure 10: Seismic-strengthening techniques in Italy: installation of new steel wall ties (WHE Report 28)

Figure 11: An example of a strengthened building with vertical and horizontal reinforced concrete ties at the first floor level as practiced in Algeria (WHE Report 75)