

ROLE OF CONSTRUCTION PRACTICES FOR STONE MASONRY STRUCTURE WITH RESPECT TO SEISMIC PERFORMANCE

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Abstract— Stone masonry is a traditional form of construction that has been practiced for centuries in regions where stone is locally available. Unfortunately, these buildings show poor performance even under minor earthquake shaking. Research on the seismic behavior of masonry structures is nowadays almost entirely dedicated to existing buildings and to the issues related to assessment and reduction of their seismic vulnerability. For countries with a long story of civilization, the seismic protection of masonry buildings involves also the issue of protecting the cultural heritage of the country. There is also a rather generalized negative attitude towards the use of structural masonry for new buildings in seismic areas, since most collapses and deaths in recent earthquakes are due to inadequate performance of unreinforced masonry buildings (usually non-engineered, low-quality, old dwellings). This explains why the large majority of the current scientific and technical literature on seismic behavior of masonry is dedicated to the study of existing structures and very seldom is masonry being nowadays considered as a choice for the design of new structures. In design of new buildings the structural behavior of masonry elements is of concern mostly in the case of infilled frames, in which however the masonry panels are not meant to serve as primary resisting elements. The paper deals with the role of construction for stone masonry structure with respect to the performance of seismic effects.

Index Terms— Earthquakes, Stone Masonry Building and Construction, Seismic Performance.

I. INTRODUCTION

Stone masonry is a traditional form of construction that has been practiced for centuries in regions where stone is locally available. Buildings of this type range from cultural and historical landmarks, often built by highly skilled stonemasons, to simple dwellings built by their owners in developing countries where stone is an affordable and cost-effective building material for housing construction. Stone masonry construction is often region-specific, and it depends on economic factors, artisan skills and experience, and the type of locally available stone. With the advances in construction materials and technologies, the use of stone masonry has substantially decreased in the last few decades, however this technology is still frequently used for building construction in parts of the world where stone is locally available and affordable material. Most of the loss of life in past earthquakes has occurred due to the collapse of buildings, constructed in traditional materials like stone, brick, adobe and wood, which were not initially engineered to be earthquake resistant. In view of the continued use of such buildings in most countries of the world, it is essential to introduce earthquake resistance features in their construction.

Past earthquakes have revealed that the stone masonry dwellings are extremely vulnerable to earthquake shaking. Earthquake-induced human and economic losses are unacceptably high in areas where stone masonry has been used for housing construction. Seismic vulnerability of these buildings is due to their heavy weight and, in most cases, the manner in which the walls have been built. Both new and existing stone masonry buildings are at risk in earthquake-prone areas of the world.

Although stone is one of the most common construction materials and stone masonry construction poses high risk to human life and property. Universities, polytechnics, and vocational training institutes do not provide any training related to stone masonry construction. As a result, construction professionals are usually not familiar with this construction technology.

II. 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 multi-family residential space 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 1: Traditional stone masonry building in Jodhpur, Rajasthan

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 300 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.

III. STONE MASONRY CONSTRUCTION

The key components of a typical stone masonry building include floor/roof systems, walls, and foundations. Stones from different sources are used for wall construction, including river stones, field stones, and quarried stones. These stones are often used without additional shaping, especially when the tools, expertise, or labour required to shape these stones are either not available or not affordable. Stone masonry walls usually consist of two wythes, and the space between the wythes is filled with mud, small stones and pieces of rubble. Through-stones (long stones that extend through all wythes), which are essential for bonding the wythes and ensuring wall integrity, are usually absent. Wall thickness is usually on the order of 500 mm, but it could be excessively large, in some cases up to 2 m. This type of stone masonry construction is called random rubble stone masonry. In some cases, stones can be partially or fully shaped (dressed) to better suit construction, as shown in Figure 2a). Construction of a random rubble stone masonry wall is shown in Figure 3b). Stone masonry walls are usually constructed using low-strength mortars, such as mud or lime sand mortar. A higher - strength cement sand mortar has been used in the last few decades; however its use does not necessarily imply an increase in the wall strength. In areas where flat stones are available, walls are often built without any mortar (that is referred to as dry masonry).



Figure 2: Stone masonry construction in Rajasthan: a) a typical stone masonry house in Jodhpur, and b) a typical rural house in a village of Jodhpur



Figure 3: Stone masonry construction: a) Un-dressed stones for construction, and b) Stone masonry construction in Jodhpur, Rajasthan, India

Floors and roofs in stone masonry buildings utilize a variety of construction materials and systems. The choice is often governed by the regional availability and cost of materials, and local artisan skills and experience. Common floor and roof systems include timber joists or trusses, masonry vaults, and reinforced concrete slabs.

IV. SEISMIC PERFORMANCE OF STONE MASONRY

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.

Seismic Deficiencies and Damage Patterns

Stone masonry buildings are vulnerable to the effects of even moderate earthquakes. The excessive thickness of stone walls, often compounded by heavy floors or roof, result in the heavy weight of these buildings and induces significant inertia forces during an earthquake. The key seismic deficiencies characteristic of stone masonry buildings subjected to earthquake ground shaking are discussed below.

Lack of structural integrity is one of the key reasons for collapse of stone masonry buildings. Seismic performance of an unreinforced masonry building depends on how well the walls are tied together and anchored to the floor and the roof (Tomazevic 1999). For example, when wall-to-floor anchors fail, the building loses integrity and it may experience a sudden collapse. Wall connections are usually the "weakest link" in a stone masonry building. Typical damage patterns associated with the lack of structural integrity include corner collapse, separation of walls at intersection, and floor/ roof collapse.

Roof collapse is one of the major causes of fatalities in masonry buildings during earthquakes. It can take place when either the walls lose the ability to resist gravity loads and collapse, or when the roof structure collapses. Roof collapse is often caused by inadequate wall-to-roof anchorage. The roof structure can simply "walk away" from the walls and cave into the building. Roof collapse can also be caused by the collapse of supporting walls, as shown in Figure 4. Some stone masonry buildings have heavy roofs that contribute to their seismic vulnerability. Heavy RC roof slabs contributed to the collapse of buildings in the Rajasthan earthquake, as shown in the figure 4.



Figure 4: Roof collapse due to a loss of the gravity load-bearing capacity of stone walls in the Rajasthan

Delamination of wall wythes is a common failure mechanism in stone masonry buildings. As discussed earlier, stone masonry walls comprise two exterior wythes, and the space between the wythes is usually filled with small stones and pieces of rubble bonded together with mud mortar. These wythes are usually constructed using large stone boulders (either round stones or partially dressed stones) which are not tied together. Once the shaking starts, unstable stone blocks start to move sideways, and the internal core move downwards leading to delamination of wythes. Delamination mechanism is illustrated in Figure 5.

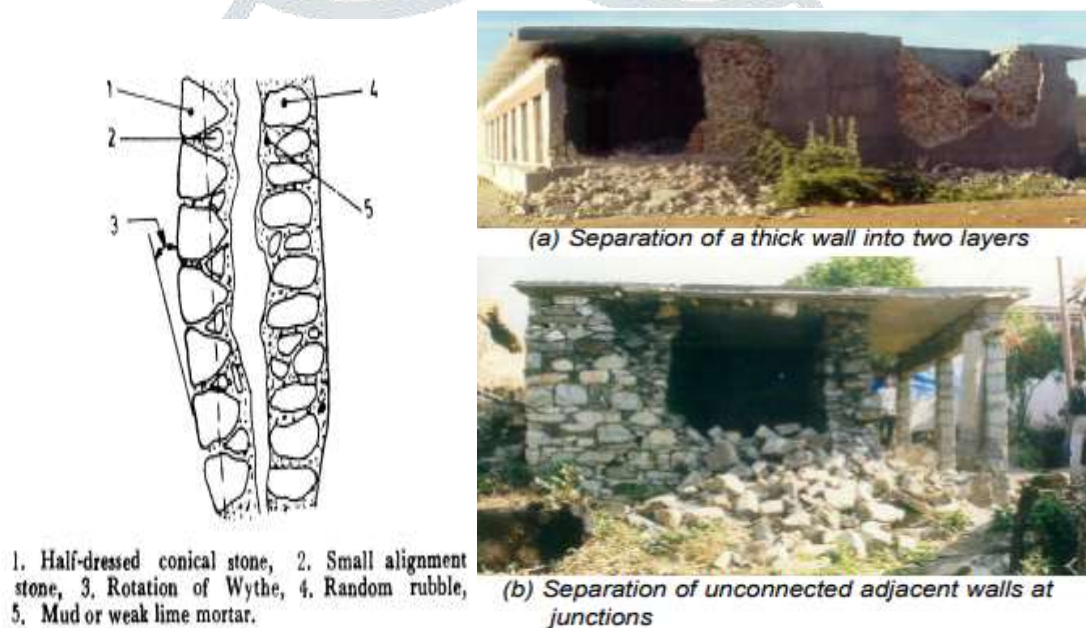


Figure 5: Wall delaminated with buckled wythes and Delamination of stone masonry walls

Consider a hipped roof building with two window openings and one door opening in a wall (Figure 6a). It has lintel and plinth bands. Since the roof is a hipped one, a roof band is also provided. When the ground shakes, the inertia force causes the small-sized masonry wall piers to disconnect from the masonry above and below. These masonry sub-units rock back and forth, developing contact only at the opposite diagonals (Figure 6b). The rocking of a masonry pier can crush the masonry at the corners. Rocking is possible when masonry piers are slender, and when weight of the structure above is small. Otherwise, the piers are more likely to develop diagonal (X-type) shear cracking (Figure 6c); this is the most common failure type in masonry buildings.

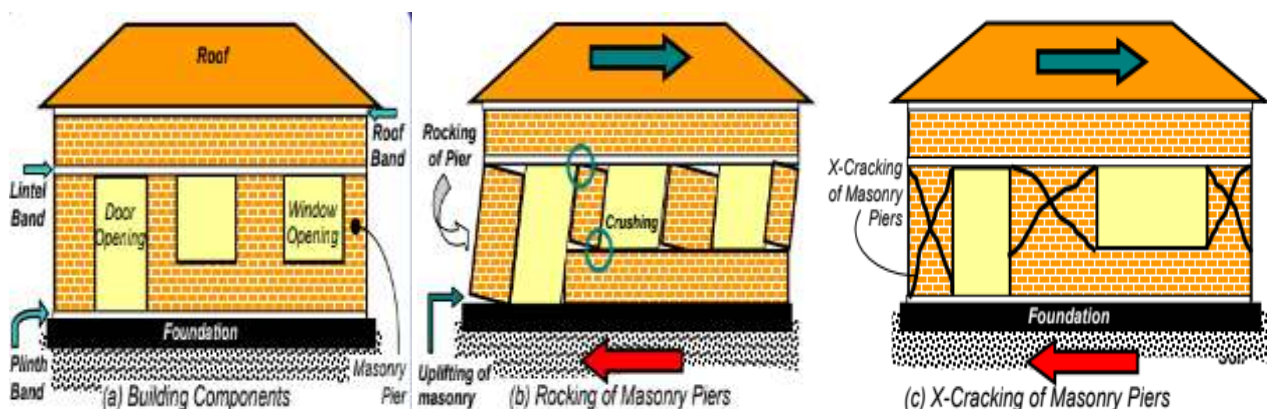


Figure 6: Earthquake response of a hipped roof masonry building – no vertical reinforcement is provided in walls.

V. IMPROVED SEISMIC RESISTANCE

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 deeper pointing 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.

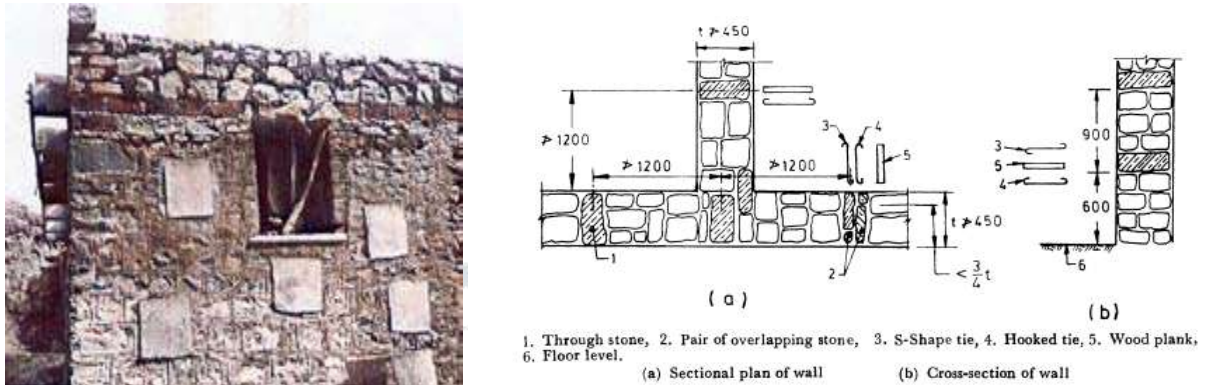


Figure 7: The application of through-stones and bond elements as practiced in India

Door and window openings in walls reduce their lateral load resistance and hence should preferably be small and more centrally located and overall arrangement of reinforcing low strength masonry buildings as shown in figure 8.

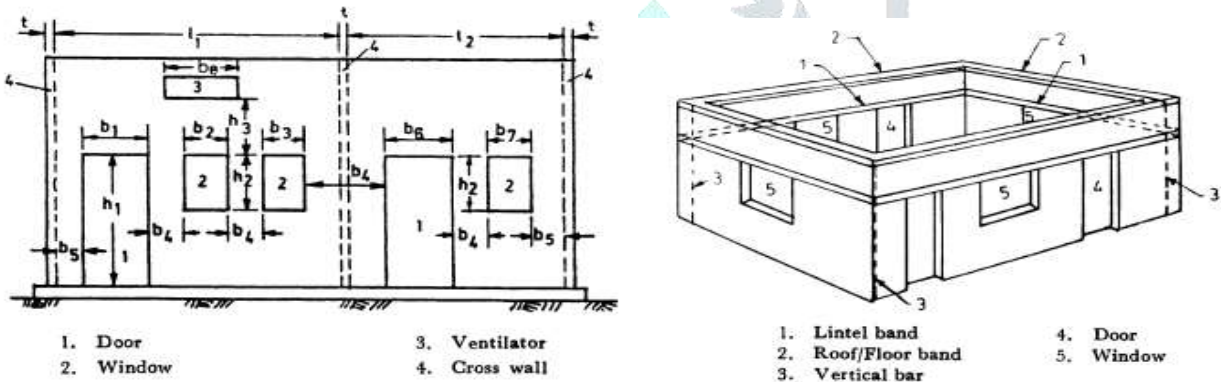


Figure 8: Dimensions of openings overall arrangement of reinforcing low strength masonry buildings

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.

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.



Figure 9: Seismic-strengthening techniques in Italy: installation of new steel wall ties

Horizontal bands are also the most important earthquake-resistant feature in masonry buildings. The bands are provided to hold a masonry building as a single unit by tying all the walls together, and are similar to a closed belt provided around cardboard boxes.

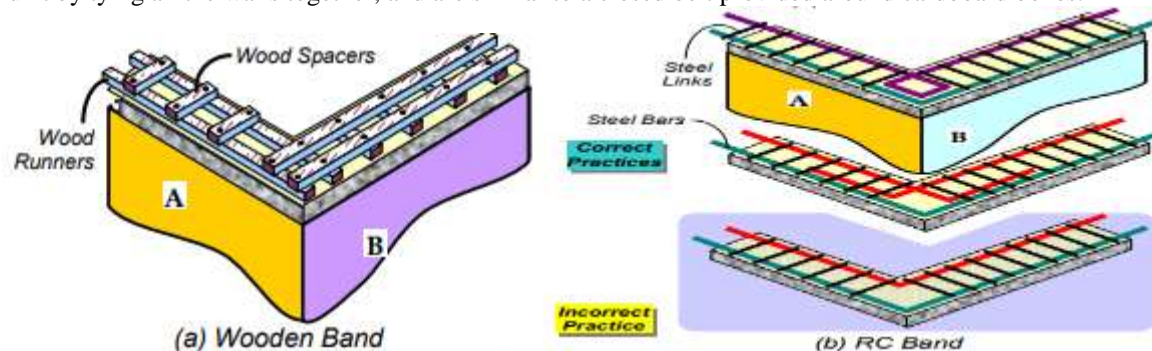


Figure 10: Horizontal Bands in masonry buildings



(a) Building with no horizontal lintel band: collapse of roof and walls

(b) A building with horizontal lintel band in Killari village: no damage

Figure 11: The 1993 Latur Earthquake (Central India) - one masonry house in Killari village had horizontal lintel band and sustained the shaking without damage.

VI. CONCLUSION

The study described in this paper offers recommendations for improving seismic resilience of stone masonry buildings in regions of high seismic hazard. The satisfactory seismic performance of stone masonry buildings can be ensured by keeping in mind the following guidelines:

- Improve the quality of building materials and construction practices,
- Ensure the integrity of building components to create a box-like effect during earthquake shaking, and
- Use the recommended effective seismic provisions, such as seismic bands.

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