# A Tutorial on Improving the Seismic Performance of Stone Masonry Dwellings: A Compendium of Worldwide Experiences

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**SUMMARY**
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. Motivated by the colossal human and property loss associated with stone masonry buildings, Editorial Board of the World Housing Encyclopedia decided to support the development of a tutorial on improving seismic safety of stone masonry building. The document, called *A Tutorial: Improving the Seismic Performance of Stone Masonry Buildings*, was developed by the authors of this paper. The tutorial is expected to fill a gap related to practical advice on how to incorporate seismic resilience into stone masonry construction. This is a challenging task, because the construction of these buildings is usually informal (non-engineered), incremental, and controlled by the availability and affordability of local construction materials. This paper describes the content of the tutorial and outlines the key recommendations.

*Keywords: Stone masonry, tutorial, non-engineered, earthquake-resistant, seismic retrofit*

## 1. DEVELOPMENT OF THE TUTORIAL

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.

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.

Considering the high seismic risk posed by this construction practice and the likelihood for its continued application in foreseeable future, Editorial Board of the World Housing Encyclopedia decided to support the development of a tutorial on stone masonry construction. The World Housing Encyclopedia (WHE), a joint project of the Earthquake Engineering Research Institute and International Association of Earthquake Engineering, is a network of professionals who are developing resources related to improving housing construction practices in the seismically active areas of the world (WHE 2000). The document, called *A Tutorial: Improving the Seismic Performance of Stone Masonry Buildings*, was developed by the authors of this paper (Bothara and Brzev, 2011); the document will be referred to as the Tutorial in this paper. A group of international experts from Canada, India, Italy, New Zealand, Nepal, Pakistan, Switzerland, and Slovenia was formed to develop and review the tutorial.

## 2. PURPOSE AND SCOPE OF THE TUTORIAL

The Tutorial explains the underlying causes for poor seismic performance of stone masonry buildings and offers techniques for improving it for both new and existing buildings. The proposed techniques have been proven in field applications, are relatively simple, and can be applied in areas with limited artisan skills and tools. The scope has been primarily focused on stone masonry construction practices in earthquake-prone countries of Asia, in particular South Asia. Nevertheless, an effort has also been made to explain relevant stone masonry construction and retrofit techniques used in other parts of the world, especially Europe.

The Tutorial was developed at an easy-to-understand level for users with limited technical skills and expertise, and it has been divided into four chapters. Chapter 1 provides an overview of stone masonry buildings, practices around the world, and the key structural components. Chapter 2 discusses seismic deficiencies and performance of stone masonry buildings in past earthquakes. Chapter 3 contains prescriptive recommendations for new construction, while Chapter 4 outlines approaches for improving seismic resilience of existing buildings.

## 3. CHAPTER 1: AN OVERVIEW OF STONE MASONRY CONSTRUCTION

Chapter 1 provides an overview of stone masonry construction practices around the world, construction technologies, and the key components of a stone masonry building. Stone masonry buildings are common in earthquake-prone regions of the world, such as Mediterranean Europe, North Africa, the Middle East, Iran, New Zealand, South and Southeast Asia. In worldwide applications, stone masonry is mostly used for construction of one- to three-storey buildings. Figure 3.1. shows typical stone masonry buildings in various countries.

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 3.2a). Construction of a random rubble stone masonry wall is shown in Figure 3.2b). 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).

a) b)

**Figure 3.1.** Stone masonry construction around the world: a) a typical stone masonry house in Turkey (photo: M. Erberik), and b) a typical rural house in Nepal (photo: M. Schildkamp)

a) b)

**Figure 3.2.** Stone masonry construction: a) semi-dressed wedged stones ready for construction in Pakistan (photo: T. Schacher), and b) stone masonry construction in Maharashtra, India, showing exterior wythes and stone rubble in mud mortar in between (photo: S. Brzev)

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.

## 4. CHAPTER 2: SEISMIC DEFICIENCIES AND DAMAGE PATTERNS

Chapter 2 discusses observed performance of stone masonry buildings in the past earthquakes, and explains the key failure mechanisms. Seismic performance of stone masonry buildings depends on several factors, including seismic hazard (earthquake intensity at the specific site), soil conditions, and the type of roof/floor system (rigid or flexible diaphragm). The quality of building materials and construction plays an extremely important role.

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 4.1. 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 2005 Kashmir earthquake, as shown in the figure.

a) b)

**Figure 4.1** Roof collapse due to a loss of the gravity load-bearing capacity of stone walls in the 2005 Kashmir, Pakistan, earthquake: a) reinforced concrete roof, and b) timber and steel roof (photos: M. Tomazevic)

*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 4.2.


a) b) c)

**Figure 4.2.** Delamination of stone masonry walls: a) delamination mechanism (Murty 2005); b) delamination of

wall wythes in the 1993 Maharashtra, India, earthquake (photo: S. Brzev), and c) delamination of a stone masonry wall in the 2000 Beni-Ouartilane, Algeria earthquake (photo: M. Farsi)

*Out-of-plane wall collapse* is one of the major causes of destruction in stone masonry buildings. This is particularly pronounced in buildings with flexible floors and roofs, large distance between transverse (cross) walls, and weak connections between the structural components. As a result, each wall vibrates on its own when subjected to earthquake ground shaking, an ultimately collapses (topples), as shown in Figure 4.3a). Out-of-plane toppling of gable walls in stone masonry buildings with pitched roofs is common, because these walls are taller than other walls and tend to vibrate as free-standing cantilevers (see Figure 4.3b).

a) b)

**Figure 4.3.** Out-of-plane collapse of stone masonry walls: a) the 2009 Padang, Indonesia, earthquake (Bothara et al. 2010), and b) collapse of gable walls in the 2011 Christchurch, New Zealand, earthquake (photo: J. Bothara)

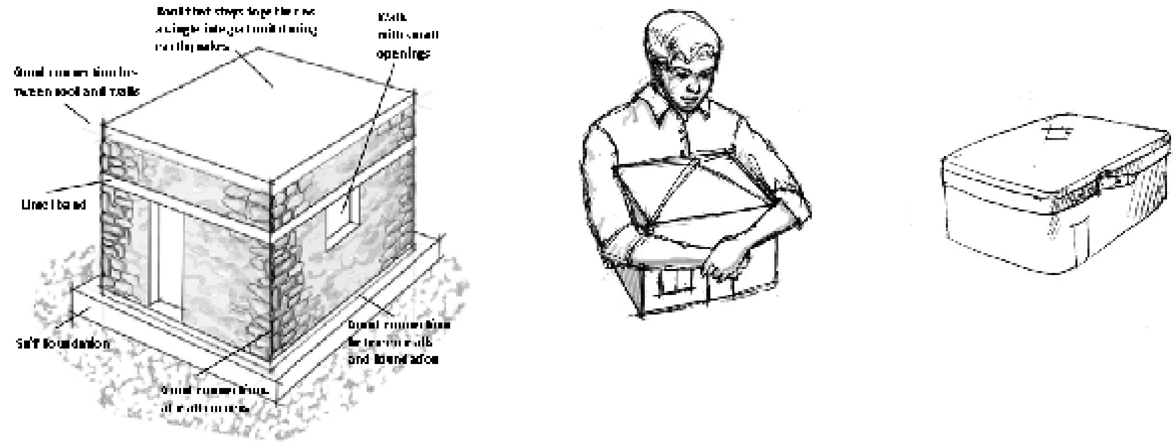
In addition to the above discussed deficiencies, stone masonry buildings are vulnerable to earthquake effects due to the use of round, unshaped stones and low-strength mortar, and low level of artisan skills. Reports from past earthquakes have confirmed that the use of low quality building materials and poor construction practices often result in significant earthquake damage or destruction. For example, evidence from the 2001 Bhuj earthquake in India indicates that semi-dressed/dressed stone masonry in cement mortar generally suffered less damage than random rubble stone masonry in mud mortar (Jain et al. 2002).

## 5. CHAPTER 3: CONSTRUCTION OF NEW BUILDINGS WITH IMPROVED EARTHQUAKE PERFORMANCE

Chapter 3 outlines important considerations to be taken into account before and during the construction of a new stone masonry house to ensure its satisfactory seismic performance. General requirements related to the construction of new stone masonry buildings have been outlined, including site selection, building configuration, opening size and location, elements for improved seismic performance, and improved construction techniques and materials.

Evidence from past earthquakes has confirmed that the overall shape, size and dimensions of a building play a critical role for its satisfactory performance during an earthquake. The tutorial emphasises regular building plan and uniform elevation as one of the key requirements for satisfactory earthquake performance.

Past earthquakes have also shown that damage to unreinforced masonry buildings is significantly reduced when building components are well connected and the building vibrates like a monolithic box. In many cases, unreinforced masonry buildings have flexible floors, so there is a need to provide additional elements to tie the walls together and ensure acceptable seismic performance. Structural integrity of a building can be achieved by developing a box action by ensuring good connections between all building components—foundations, walls, floors, and roof. Key requirements for the structural integrity in a masonry building are illustrated in Figure 5.1a). A seismic band (ring beam) is one of the critical provisions for ensuring structural integrity. Usually provided at lintel, floor, and/or roof level in a building, the band acts like a ring or belt, as shown in Figure 5.1b). Seismic bands may be constructed using either RC or timber. Proper placement and continuity of bands and proper use of materials and workmanship are essential for their effectiveness.



a) b)

**Figure 5.1.** Key requirements for ensuring box action in a stone masonry building: a) a summary (adapted from Murty 2005), and b) a seismic band acts like a belt (GOM 1998)

Key recommendations regarding the construction of stone masonry walls are summarized below:

1. The maximum thickness of a stone masonry wall should be limited to 450 mm. Seismic forces are proportional to building mass (i.e., a wall of a larger thickness attracts higher seismic loads); therefore the construction of thicker walls is both uneconomical and unsafe.
2. Through-stones, that is, long stones placed through the wall to tie wall wythes together and prevent delamination, are one of the most important earthquake-resistant features of a stone masonry wall. Through-stones make the wall wythes perform like hands with interlaced fingers, as shown in Figure 5.2.

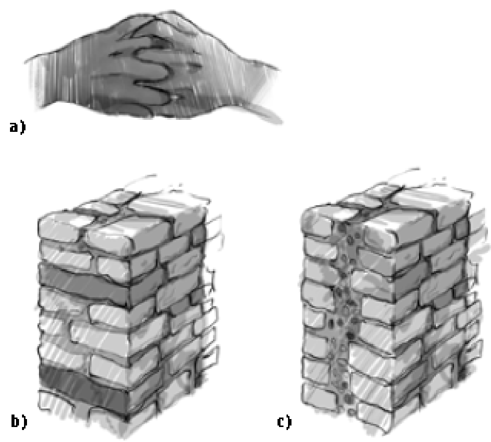



**Figure 5.2.** Through-stones in a stone masonry wall: a) through-stones act like interlaced fingers; b) a wall with through-stones, and c) a wall without through-stones (GOM 1998)

## 6. CHAPTER 4: RETROFITTING OF EXISTING STONE MASONRY BUILDINGS

Chapter 4 provides an overview of established seismic retrofitting strategies for stone masonry buildings that have been used in post-earthquake rehabilitation efforts around the world, and proposes approaches for improving seismic resilience of existing stone masonry buildings.

The following retrofit strategies have shown the highest cost/benefit ratio in terms of improved seismic safety of stone masonry buildings: i) enhancing integrity of the entire building by ensuring a box-like seismic response, ii) enhancing the wall strength for in-plane and out-of-plane effects of seismic loads, and iii) improving floor and roof diaphragm action.

Building integrity is the most important prerequisite for its survival during earthquake ground shaking. The following provisions for improving integrity of an existing building have been discussed in this chapter:

- Tying the walls by means of external steel tie-rods, RC bands, or bandages,
- Connecting the walls at corners and/or intersections,
- Improving floor and roof integrity, and
- Strengthening wall-to-floor and wall-to-roof connections.

It is important to ensure that the new or retrofitted floor/roof structure is adequately anchored to the existing walls. A typical detail used to retrofit stone masonry buildings in Italy after the 2002 Molise earthquake is shown in Figure 6.1. (Maffei et al. 2006).

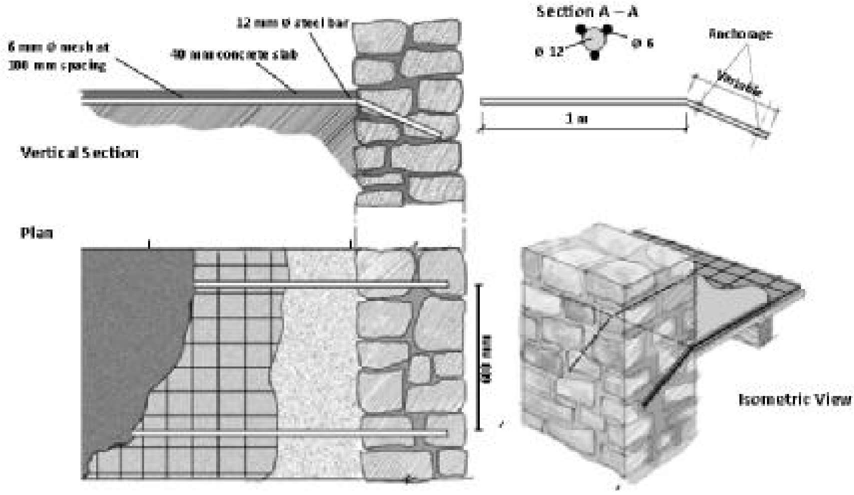



**Figure 6.1.** Wall-to-floor anchorage with steel dowels embedded into the wall (Maffei et al. 2006)

Another important retrofit strategy is to enhance the seismic resistance of existing masonry walls. That can be achieved using one of the commonly used wall retrofit techniques, such as the installation of through-stones or jacketing. Jacketing consists of covering the wall surface with a thin overlay of reinforced mortar, micro-concrete, or shotcrete. Jacketed wall surfaces must be interconnected by means of through-wall anchors. An adequate bond between the new jacket and the existing wall surface must be ensured. When properly implemented, jacketing provides confinement and ensures wall integrity for in-plane and out-of-plane seismic effects. Jacketing was used to retrofit stone masonry buildings in Pakistan after the 2005 Kashmir earthquake, as shown in Figure 6.2.

a) b)

**Figure 6.2.** Jacketing of stone masonry walls in Pakistan after the 2005 Kashmir earthquake: a) a wall surface showing reinforcement and anchors in place before the plaster application (photo: Q. Ali), and b) a detail of steel mesh reinforcement and through-wall anchors (photo: T. Schacher).

## 7. CONCLUSIONS

The tutorial 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.

The authors of this paper believe that by implementing the recommendations suggested in the Tutorial, the risk to the occupants of stone masonry building can be significantly reduced in future earthquakes. The Tutorial is expected to be useful both for the seismic risk mitigation and post-earthquake reconstruction, and potential users include field level technicians, academics and students, government officials and non-governmental organizations.

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