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State-of-the-Art Review on Masonry Structure: *Identification Behaviour and Seismic Retrofitting Techniques for Structures*

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Abstract: ***Masonry structures are commonly constructed and are popular in developing countries due to its low cost and easiness on construction. It has been studied from different experiment that these buildings are vulnerable to strong external loading such as earthquake, strong wind, blast etc. because of lack of strength, ductility and inappropriate configuration of building. In this paper, the behaviour of masonry structure during earthquake and the previous studies on the strengthening techniques for masonry buildings are reviewed and summarized. It is expected that this paper will provide some additional information and guidance for household and engineers in selecting an appropriate retrofitting technique for masonry structures.***

Keywords: In-Plane Failure, Mesh Retrofitting Technique, Out-of-Plane wall, Strengthening, structural integrity

1. Introduction

Masonry is one of the commonly used construction material around the world due to its low cost and construction easiness. For the developing countries like Nepal, it covers almost 85% in the sector of building construction. More than 30% of the world's population lives in a house of unbaked earth, which is one type of unreinforced masonry [1]. During the last century, human casualties during earthquakes were mainly caused by structural damage, being the failure of unreinforced masonry structures responsible of more than 60% of them [2]. According to Hima et al. [3] with the introduction of new construction materials and techniques, the use of these materials has substantially decreased in the last few decades, however it is still used abundantly for residential buildings in rural and remote areas of Nepal. In areas which are accessible by road and in the plain terrains of the south, brick is widely used, and in other northern hilly and mountainous remote areas where alternate materials are unaffordable; abundantly available stone is used [3]. Those masonry buildings are laid in weak cement sand, mud mortar, or even dry in some cases. The quality of mortar and masonry units and the level of workmanship are poor, due to lack of awareness and economic restraints on the people [3]. The collapse is more likely to occur in the out-of-plane direction or in the partially infilled RC frame, which has led to the idea that this type of structure possesses some poor seismic performance [4]. Normally, the masonry infill is not taken as a structural element but as secondary. However, it should be noted that the masonry infills can contribute in causing casualties if the buildings are subjected to strong external loadings, especially out-of-plane loading [5].

Seismic retrofit or Strengthening is to enhance the structural capacities (strength, stiffness, ductility, stability and integrity) of structure, so that the performance level of the building can be raised to withstand the design earthquake consideration. In the context of Nepal, most of the houses are unreinforced masonry structure by considering and followed the traditional techniques. The performance level of building reducing along with its life time. These structure behaves normally during its life time but after meeting with design period, it cannot capable to take the existing loads and obviously it will not be possible to take the extra loads on it. Enhancement of structural behaviour or performance level of such a deficient building can be done by increasing strength of structural element through the process of retrofitting.

2. Identification Failure Modes of Masonry Structure

After massive earthquake in 2015 in Nepal, huge numbers of masonry structure were damaged. The main reason behind such type of failure is due to some characteristic of masonry structure like heavy mass of structure attract large seismic force, good in compression but cannot take tension and lack of strength, ductility and inappropriate configuration of building.

2.1 Lack of structural integrity

In 2015 earthquake, most of the masonry structures of Nepal were damaged due to lack of structural integrity. Structural integrity is one of the key parameter to reduce damage on progressive collapse. Lack of structural integrity of structure is one of the principle sources of weakness responsible for severe damage leading to collapse. If the net length of the wall increase without proper connection between crossing walls give rise to possibility of out-of-plane failure. Lack of interlocking units or proper bond between external and internal part of the wall section during construction leads to delamination of wall. Flexibility of the roof or floor diagrams and their connection are the main factors to take into account for capability to distribute the seismic loads in the masonry wall. During earthquake in Nepal, most of the houses which were constructed with placement of roof directly on the walls without roof band or bond beam are damaged in a huge number due to out-of-plane failure mechanism. Because, it does not provide a diaphragm and due to free end at the top of the walls most of the masonry houses failure by out-of-plane failure mechanisms.

2.2 Out-of-Plane wall collapse

Out-of-plane wall collapse is one of the main causes of destruction of masonry buildings, particularly in buildings with flexible floors and roofs. Following are the key factors influencing out-of-plane wall collapse;

a) Inadequate anchorage between wall to wall and wall into the roof diaphragm.
b) Long and slender walls
c) Limited tensile strength of masonry
d) Limited tensile strength of mortar

Some of the characteristics of out-of-plane failure shown after earthquake are listing below;

a) Vertical cracks at wall corners and junctions
b) Horizontal cracks at floor levels
c) Horizontal cracks at lintel and top of piers
d) Wythe separation
e) Partial or full collapse of exterior walls
f) Out of plane failure more critical than in plane failure.
g) Out of plane failure is critical in upper stories

Figure 1: Failure of exterior walls on Masonry building [6]

Figure 2: Delamination on masonry building [6]

2.3 In Plane failure

At the time of earthquake shaking, masonry walls get grouped into three sub units: spandrel, wall pier, sill masonry which is also presented in the figure below [6].

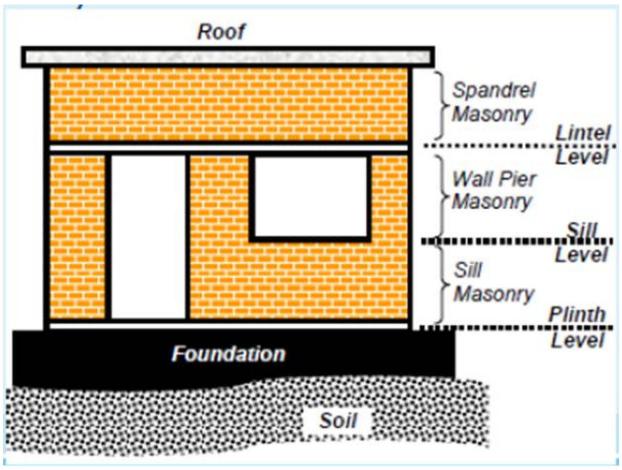


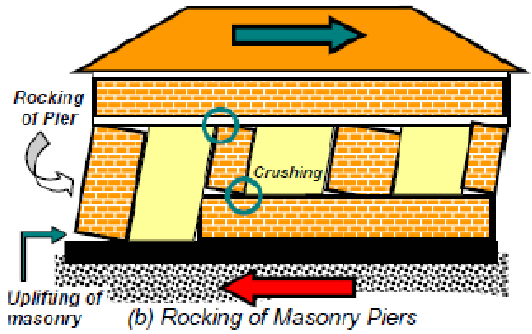
Figure 3: Masonry wall [6].

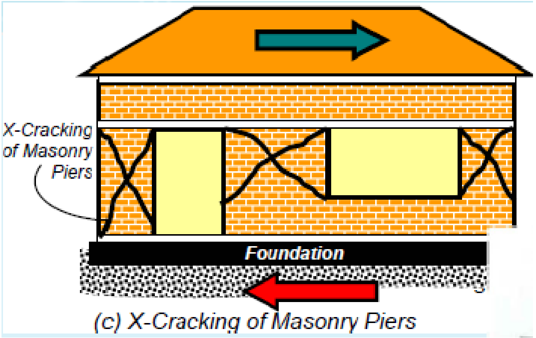
In-plane lateral loads induce shear deformation in masonry wall. These type of deformation elongates one diagonal with tension and shorten the others with compression perpendicular to the tension. Since, masonry structure have lower strength in tension, in-plane lateral forces typically induce diagonal cracking perpendicular to the tension axis. It is very common crack in the masonry structure.

Figure 4: Diagonal Cracks on Masonry wall (NSET, Nepal)[6]

During strong shaking, the building may slide below the lintel or sill band or at plinth level. Sliding is most common in moderate to low axial loads [6].

a) Rocking and sliding of piers are more stable than X-shear cracking.
b) In-plane cracks are more stable than out-of-plane cracks.
c) In plane cracks happen to be worse at the lower story.
d) Inadequate In-Plane capacity of masonry piers cause in plane failure.
e) Reduction in wall portion due to large opening or too many openings reduces the in-plane strength of walls.





2.4 Roof collapse

When the walls and roof are perfectly not connected with each other, collapse is often caused. Another cause of roof collapse is due to the collapse of wall subjected to shear forces and gravity loads. Heavy roofs also contribute to the seismic vulnerability of masonry buildings.

Figure 5: Diaphragm Failure [6]

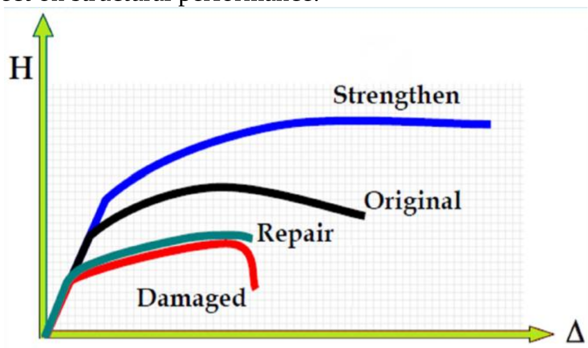
Figure 6: Weak Floor-Roof connection [6]

Figure 7: Weak Floor-Roof Connection [6]

Figure 8: Connection Failure[8]

3. Retrofitting methods for structure

In order to reduce damage on masonry building during earthquake, it is essential to improve and upgrade the earthquake resistance of an existing masonry building as well as should apply the recent seismic guidelines at the time of construction. Walls are the main structural element of masonry structure which primary resisting gravity and lateral load. Therefore, the primary focus of most of strengthening techniques is to enhance the structural integrity and capacity of the walls. Various techniques are used to retrofit damaged masonry buildings which can be categorized into the three categories on the basis of their effect on structural performance.



3.1 Repair

Repair is a cosmetic treatment of damage building to bring back original architectural shape of the building. It does not restore the original strength of the structure. It only consists of actions taken for patching up of superficial defects.

3.2 Restoration

The main objective of restoration is to regain the original performance of building by structural repairing of damage elements. The existing methods of restoring un-reinforced masonry buildings include;

a) Surface treatment using shotcrete
b) Stitching and grout/epoxy injection
c) Re-pointing with ordinary Portland cement.
d) Removal of portions of cracked walls and rebuilding them strongly with richer mortar.

3.3 Strengthening

Unlike repair and restoration, it should not be limited to increasing the strength of members that have been damaged, but should consider the entire behaviour of the structure.

Strengthening, increases the strength of the structure to withstand the future earthquake. Therefore, strengthening or retrofitting methods improve the ductility capacity and energy dissipation capacity of the masonry structure. Arya et al (2012) [7] reported strengthening procedures should aim at one or more of the following objectives;

a) Increasing the horizontal strength.
b) Unifying the structure by providing a proper connection between its resisting elements.
c) Avoiding the possibility of brittle modes of failure by proper reinforcement and connection of resisting members.

Many researchers assessed the feasibility of applying the various strengthening techniques for existing masonry building in developing countries but it is difficult to make direct comparison regarding the structural performance of the techniques also the availability of the materials. Some of them techniques used for strengthening masonry buildings are;

a) Mesh type retrofitting (Steel cage, G.I. wire mesh, Polymer, Polypropylene band, bamboo meshes and plastic carrier bar etc.)
b) Splint and Bandage
c) Confinement with steel sections
d) Adding steel bracings
e) confining the masonry

4. Mesh type Retrofitting Techniques for Masonry Structure

The main objective of mesh type retrofitting is to hold the masonry components into a single unit and prevent the collapse of masonry buildings. These type of retrofitting can be made of any ductile material which may be used steel cage, polymer, polypropylene band, bamboo meshes and plastic carrier bag as shown in figure (Meguro et al., 2012[8]; Sathiparan et al., 2012[9]; Tetley &Madabhushi, 2007[10]).

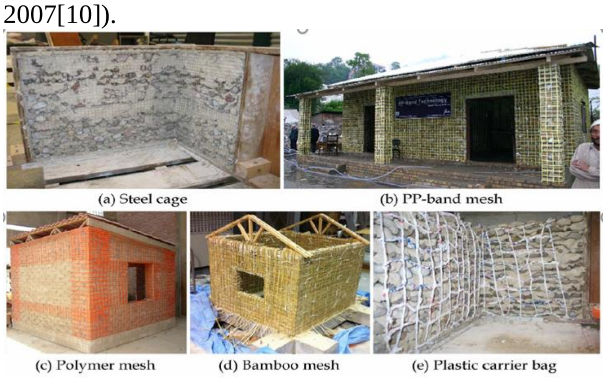


Figure 6: Various mesh type retrofitting techniques used for masonry structures.

4.1 Steel Cage & G.I. wire mesh

Steel reinforcement cage and G.I wire mesh is commonly used retrofitting technique to strengthening existing masonry structure. After massive earthquake 2015 in Nepal, the trend of strengthening existing building raised gradually. Government of Nepal also facilitate such house owner by providing government grant for retrofitting of houses. Depending upon the construction materials availability on site peoples are willing to implantation retrofitting techniques on their houses.

Steel cage of reinforcement or G. I wire mesh are placed in horizontal and vertical strips nailed with metal bottle caps to the walls and it is covered with a thick cement and sand mortar, see in figure 10. After placing mesh from both side and connected with each other, then it holds the masonry component in to single unit and prevent from the collapse of building which is also shown in different shaking table test where model suffered damage but did not collapse.

Figure 7: Steel Cage and G.I. wire mesh on masonry wall

4.2 Polymer mesh

This type of techniques mainly used for adobe walls. Which uses polymer mesh and the main advantage of this material lies in the compatibility with the earthen wall deformation and its ability to provide an adequate transmission of tensile strength to the walls up to the final state. The mesh is attached to adobe walls by plastic or nylon forming a confinement and consequently preventing the total collapse. The researchers found that it is possible for the walls to disintegrate into large blocks during severe ground shaking, however the mesh prevents the walls from falling apart, and collapse can be avoided (Blondet et al., 2006) [11]. Research performed in recent years also indicated that varies polymer mesh retrofitting system such as fibre-reinforced polymer (Ehshani et al., 1999[12]; ElGawady et al., 2006[13]), polymer textile (Triantafillou, 2010[14]) and polymer carbon mesh (Bischof& Suter, 2014[15]) are effective strengthening solutions for masonry structures.

4.3 PP-band mesh

PP-band retrofitting technique is one of the more appropriate method of strengthening wall of masonry building in a developing country. According to [16], These bands, which are worldwide used for packing, are inexpensive, resistant, and easy to handle. It is a simple and low-cost method that consists of confining all masonry walls with a mesh of PP-bands. PP-bands are an inexpensive, durable, strong, and widely available material, commonly used for packing. PP-band retrofitting technique is simple enough to be understood and applied by craftsmen and homeowners without any prior knowledge and special expertise, thus, it is expected to meet the very critical requirement of developing countries, the "easy-to-use" method by this retrofitting technique. Various testing result showed how the retrofit improved the house model seismic performance significantly, displaying increased deformation and energy dissipation capacity before failure. PP-band mesh retrofitting has had application in China, Nepal and Pakistan (JBIC, 2007[17]; NSET, 2009[18]).

5. Conclusion

Masonry is classified as a brittle material which shows fragile behaviour, when subjected to lateral forces during earthquakes. Masonry buildings have heavy mass, brittle in nature and it may attract large inertia forces at the time of earthquake which lead to progressive collapse of the structure. Many researches are emerging in the field of masonry structure in order to evaluate best alternate to seismic retrofitting techniques. In recent years, many researches work on mesh type retrofitting for masonry buildings to improve the seismic behaviour of masonry structures [19]. The main advantage of mesh retrofitting is to hold the masonry components into a single unit and to prevent the direct collapse of masonry structure. The mesh type retrofitting technique can be made of any ductile material, including: steel cage, polymer, polypropylene band, bamboo meshes and plastic carrier bag [19]. The existing strengthening/retrofitting techniques for masonry structure has been reviewed and discussed, and each of method possesses its own merits and shortcomings. It is impossible to predict the best strengthening approach. The significance of the improvement of each reinforcing method is dependent on the material that made the original building, as well as the material used to strengthen [5]. All in all, a good reinforcing technique must consider the factors of aesthetics, function, strength, ductility and stiffness and the cost requirements [20].

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