PERFORMANCE OF UNREINFORCED MASONRY BUILDINGS AGAINST NATURAL DISASTERS – REVIEW STUDY

W.S. Wasundara Mendis
Research Student
Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna
Email: wsumudumendis@gmail.com
G. Sudeera De Silva
Senior Lecturer
Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna
Email: sudhira@cee.ruh.ac.lk
G.H.M.J. Subashi De Silva
Senior Lecturer
Department of Civil and Environmental Engineering, Faculty of Engineering, University of Ruhuna
Email: subashi@cee.ruh.ac.lk

Abstract

Un-Reinforced Masonry (URM) buildings are popular due to their durability, low cost, construction easiness and architectural character, need of less skilled labour, eco-friendly and use of locally available materials such as ashlar or rubble, adobe and brick. URM buildings have a higher probability of failing under natural disasters such as earthquakes, tsunamis and storm surges, floods, cyclones and landslides. In Sri Lanka, landslides and floods have frequently occurred. Massive tsunami adversely affected the people in 2004 and its effect to islands on the Indian Ocean has been continued since December, 2004. Minor earthquakes have come off recently with experiences of only wall cracks. Besides, it is believed there is a defused plate boundary in the making some 500 km south of the southern tip of Sri Lanka as the cause of these tremors or minor quakes. Investigation on performance of URM buildings against these natural disasters is increasingly important.

In this review study an attempt was made to summarize types of damages on URM structures caused by natural disasters, different kind of retrofitting methods for URM structures to be seismic resistant. Common failure mechanisms for URM structures consist of separation of walls at corners, diagonal cracking in walls, separation of roofing from walls, vertical cracking in walls, out-of-plane wall failure, in-plane failure, shear cracks and de-lamination. These damages on a wall lead to diminish the service life of building. Simple technologies with low cost to strengthen the existing structures and damaged structures to resist dynamic loads are also discussed in this paper.

Keywords: Unreinforced Masonry Buildings (URM), retrofitting, natural disasters, failure mechanisms

1. Introduction

Throughout the centuries, natural disasters have taken a high toll of human lives and caused great property losses all over the world and unfortunately mostly in developing countries. The worst death toll from an earthquake, in the past century, occurred in 1976 in China, where it is estimated that 240,000 people were killed and most of the deaths were due to the collapse of brick masonry buildings (D'Ayala, 2011). Further, Sri Lanka had also experienced tsunami in 26th December, 2004 which caused large amount of deaths and damages. The most of the damaged structures in Sri Lanka were domestic buildings, which had been constructed using bricks and cement sand blocks.

In Sri Lanka, natural disasters such as minor earthquakes, tsunami and storm surges, floods, cyclones and landslides are encountered. An earthquake is the sudden motion of earth because of the breaking and shifting of rock under the earth's surface. Tsunami is a series of large waves generated by sudden vertical displacement of seawater due to under-sea movements (Maheshwari et al., 2005). These movements are caused by displacements of the earth such as earthquake, volcanic eruption or submarine landslide. A tsunami has an ability to propagate over large distances and causes a destructive surge on reaching land breaking on the shore. Flood is a general and temporary condition of partial or complete inundation of two or more acres of normally dry land area or of two or more properties (Rogers, 2012). This phenomenon may comprise the over flow of inland or tidal waters, rapid accumulation of runoff, mud flow, or the collapse of land along the shore (due to water exceeded anticipated cyclic level). This can be a coastal flood, river flood or urban flood.

Coastal flooding is typically associated with storm surges (Rogers, 2012). A storm surge is an off shore rise of water caused primarily by wind forces pushing water towards the land. Over flowing of rivers, streams, drains, and lakes due to excessive rainfall, rapid snow melt, or ice is stated as riverine flooding. Urban flooding is storm water that gets collected in city or urban areas after heavy rains due to blocking or under capacity of storm water drains. Landslides are said to which down slope movements of soil and/or rock materials other than surface erosion of a hillside. This event can be triggered by heavy rainfall, earthquakes or human activities such as road cuts, grading, construction, removal of vegetation, and changes in drainage.

Apart from the environmental implications, deforestation in Sri Lanka has caused ill effects such as flooding, landslides and soil erosion from exposure of the deforested areas (Keerthisinghe, 2012). Weather changes in Sri Lanka showed that, not only landslides and floods (originated with precipitation), but also extreme wind events are frequently occurred. Minor earthquakes have come off recently with experiences of only wall cracks and no human death. Besides, it is believed there is a defused plate boundary in the making some 500 km south of the southern tip of Sri Lanka (Dissanayake, 2005). Sri Lankans were adversely affected by the largest tsunami created in the world because of earthquake occurred in the coastal zone near Sumatra Island in December, 2004 with a huge catastrophe to human lives. Reasons for such a loss of human lives are that, people have no awareness on behaving in a disaster and the collapse of man-made buildings/structures resulted in the most of death.

In general, buildings can be divided into two main categories: engineered buildings and non-engineered buildings. Their percentages are being quite different in developed, developing, and under-developed countries. Past destructive disasters showed that most of the disasters occurred to non-engineered buildings. Skilled technicians (engineers and architects) are generally not involved in this type of construction (Blondet, 2003). In Sri Lanka, most dwellings (non-engineered buildings) constructed in small towns and villages are URM buildings. URM buildings are popular because of having inherent advantages such as its durability, low cost, construction easiness and architectural character, need of less skilled labour, use of locally available materials, eco-friendly, heat and sound insulation and fire resistance. Unfortunately, many of the URM buildings were damaged or collapsed during the recent earthquakes in many countries (Kaplan et al., 2008).

URM buildings can be categorized into three: earthen, stone and brick masonry buildings. The most common types of earthen construction are adobe and rammed earth. Adobe bricks are made in a mold and are usually 16 to 20 inches long and 8 inches or more wide. Adobe buildings are constructed in a running-bond pattern with a mortar of adobe mud between blocks (Blondet, 2003). In the rammed-earth construction method, earth is packed into forms in a manner similar to the placement of concrete to build unit of 4 feet high by about 6 feet long, depending on the thickness of the wall. Joints between units are packed with mud. Further, other two types of earthen building can be identified as mud wall buildings and mud walls with wood elements (Earthquake Engineering Research Institute, 2003). In Sri Lanka, the construction of earthen buildings called wattle and daub houses, which of mud walls with vertical and horizontal cleaved wood trunks have been available since of ancient times (Nandadeva, 1990). Stone has been the traditional construction material for walls, in mountainous areas. These stone walls are erected as typical masonry lay-up with bond blocks between withes or as single-wythe or as unbonded, multi-wythe construction.

The damages of structures due to natural disasters are encountered day to day and these damages cause structural failures, casualties and deaths. The most of damages were occurred because of the use of lack of engineering knowledge for constructing of structures, specially dwelling houses. The most of existing building, specially dwelling houses, are constructed by using unreinforced masonry techniques. When the natural disasters are encountered, these buildings can be collapsed very easily. Therefore, investigation of performance of URM buildings and introducing required retrofitting methods to improve the resistance against these natural disasters are increasingly important.

Objective of the current study is to review published literature and identify retrofitting methods to existing building, to enhance the strength of structural components, decrease the amount of damage and enhance the time duration for collapse which helps people to leave from building. However, a suitable retrofitting technique for Sri Lanka should be efficient not only in improvement of seismic resistant characteristics such as strength, ductility, but also in economy and availability of used material and required labour skill. Damages in URM buildings due to natural disasters (e.g., earthquakes, tsunami and floods) are identified and presented in this paper. In addition, retrofitting methods that can be applied to unreinforced masonry buildings so as to resist dynamic loads induced by earthquakes, tsunami and floods are presented.

2. Damages in URM buildings

From the observation of structural performance of buildings during an earthquake, it can be clearly identified the strong and weak aspects of the design as well as the desirable qualities of materials and techniques of construction and site selection (Boen, 2012). This can be applied to other natural disasters as well and the study of damage provides an important step in the evolution of strengthening measures for URM buildings. The performance of a building during an earthquake depends on its design, quality of construction, age, together with the materials used, how well it has been maintained and the level of shaking it has had to experience.

It has been reported that the most important weaknesses of the damaged masonry structures were the lack of interlocking units between external and internal wythes of the wall sections and the lack of connection between crossing walls (Velazquez-Dimas et al., 2000). Both of them give rise to possibility of out-of-plane behaviour, as their formation increases net length of the walls. Also, roof placed directly on the walls without bond beams does not provide a diaphragm and due to free end at the top of walls, probability of out-of-plane failure mechanisms increases. Formation of openings near the corners of the walls is another common problem where crack propagation is concentrated around these openings. In the mass of evidence from past earthquakes, tsunamis and floods, the typical damages to URM buildings are discussed**.**

2.1 Damages due to earthquake

During earthquakes, the ground shakes in all directions and generates inertia forces that the construction material should be able to withstand. According to Saatcioglu et al. (2005), under seismic loading, URM walls have two possible failure mechanisms: in-plane and out-of-plane. In-plane failures are characterized by a diagonal tensile crack pattern while out-of-plane failures are characterized by cracks that are primarily along the mortar bed joints. The principle in-plane failure mechanisms of URM walls subjected to earthquake actions are shear failure, sliding failure, rocking failure and toe crushing (Figure 1).

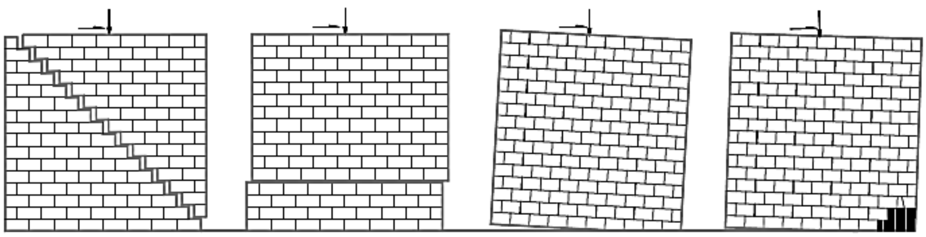


Figure 1: In-plane failure modes of a laterally loaded URM wall (ElGawady et al., 2006b)

The typical out-of-plane failure patterns of URM wall resulted from an earthquake are shown in Figure 2.

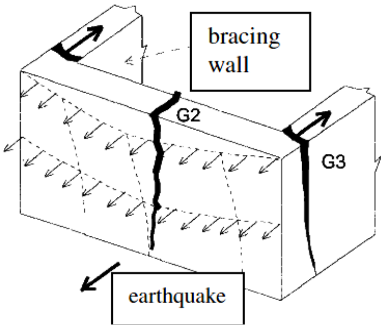


Figure 2: Typical crack patterns of URM buildings due to out-of-plane failure (Bartolome et al., 2004)

The performance of small adobe and low-quality mud-brick constructions varied from no damage to collapse and, within any specific area, the performance of these buildings depended on a number of parameters, including wall thickness, roof mass, size of rooms, and quality of materials (Webster, 2008). Earthen structures have less ductility and are very brittle resulting in sudden failures under seismic loading without any warning. The traditional earthen buildings are vulnerable due to a perverse combination of the mechanical properties of their walls where earthen walls are dense and heavy, have extremely low tensile strength resulted from weak material, lack of reinforcement, poor workmanship and null maintenance (Bartolome et al., 2008 and Blondet et al., 2008). Common failure modes of adobe structures were reported by Blondet (2003) (Figure 3). The same failure modes can be expected for other types of masonry buildings.

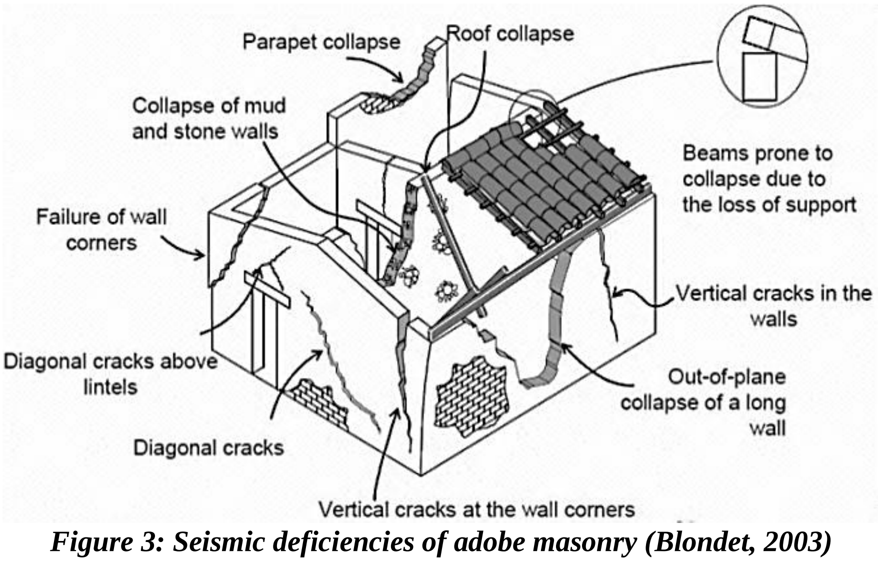
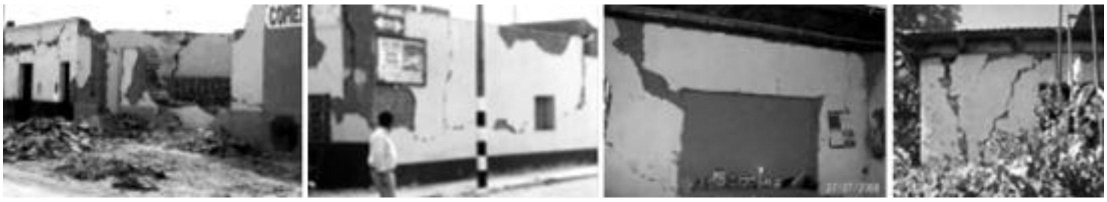


Figure 3: Seismic deficiencies of adobe masonry (Blondet, 2003)

Since the tensile strength is very low, significant cracking starts (with the initiation of an earthquake) in the regions subjected to tension. Vertical cracking starts at the lateral corners of the walls, where the tensile stresses are higher due to out-of-plane bending produced by seismic forces perpendicular to the walls (Figures 2 and 3). The continuity of ground movement produces large vertical corner cracks tend to separate the walls from one another (Figures 2 and 3). Shear forces generated by lateral seismic forces acting within the plane of the walls, produce diagonal cracks, which usually follow stepped patterns along the mortar joints (Figures 1and 3).

Due to the stress concentration at the corners of openings (i.e., doors and windows), diagonal cracks often start at these locations (Figure 3). Front walls are usually the first to collapse in an earthquake and overturning onto the adjacent street (Blondet et al., 2008). According to available literature (Bartolome et al., 2004, Bartolome et al., 2008, Blondet et al., 2008, D'Ayala, 2011 and Kaplan et al., 2008), seismic failures illustrated by Figure 3, are also common in other URM structures as well as adobe houses. Examples for these types of failures of URM buildings are illustrated by photos in Figure 4.



(a) (b) (c) (d)

Figure 4: Seismic cracks in URM houses: (a) Collapse due to out-of-plane failure (severe earthquakes in Peru) (Bartolome et al., 2004), (b) Typical cracks on adobe houses due to out-of-plane seismic forces (Bartolome et al., 2004), (c) Shear cracks initiated at the corners of openings in wall of house in La Tinguiña (in-plane failure) (Bartolome et al., 2008), (d) Wall-diagonal crack and vertical corner crack (both in-plane and out-of-plane failure) (Kaplan et al., 2008)

Blondet et al. (2008) claimed that, earthen houses built without any structural reinforcement, with several stories, thin walls, large window and door openings, and irregular plan and elevation configurations are extremely vulnerable and suffer significant damage or collapse during earthquakes.

2.2 Damages due to tsunami

Damages of URM buildings by tsunami effects could be occurred due to hydrostatic, hydrodynamic, impulsive, impact and buoyancy forces (Figure 5) (Renuka and Lewangamage, 2011). Authors have conducted an investigation using a single storied and two storied house modeled in a Finite Element Modeling (FEM) program based on common sizes of houses in Sri Lankan coastal line and inundation depth of 1.5 m and 2 m of Sumatra Tsunami, 2004. Results showed that, main failure types in URM structures had caused by bending, diagonal tension and compression, overturning and sliding (Figure 6).

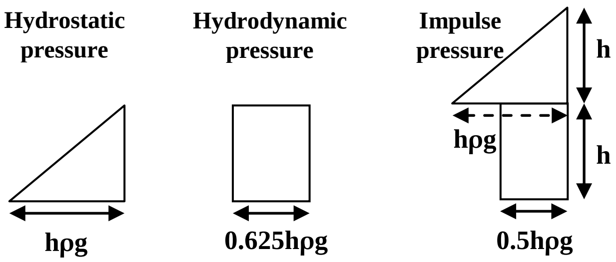


Figure 5: Components of tsunami induced forces (Renuka and Lewangamage, 2011)

The URMs performed very poorly in resisting the lateral forces of the tsunami. Bending capacity of unreinforced brick masonry was very low against the hydrostatic forces of the tsunami (Maheshwari et al., 2005 and Renuka and Lewangamage, 2011). Overturning moment increases with higher pressure while resisting moment reduces due to small lever arm. Higher building weight and gravel type soil around base will reduce the overturning effect.

(a) (b) (c)

Figure 6: Damage to URM buildings by December 26, 2004 Sumatra Earthquake; (a) Brick masonry walls in Talenguda-sliding failure (Maheshwari et al., 2005), (b) Brick masonry in Trincomalee- overturning due to foundation scouring (Khazai et al., 2006), (c) Buildings in Meelamanakudy- bending failure (Maheshwari et al., 2005)

2.3 Damages due to flooding

Damages of URM structures by a flooding resulted from storm surge, riverine flooding, or urban flooding are mainly occurred due to physical forces such as hydrostatic loads, hydrodynamic loads, impact loads and buoyancy (Figure 7) (Caraballo-Nadal et al., 2006 and Rogers, 2012).

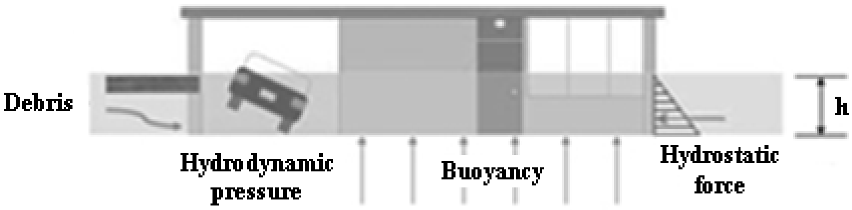


Figure 7: Typical forces generated by flooding (Caraballo-Nadal et al., 2006)

Hydrostatic forces occur when slow rising flood water comes into contact with a building or its components. Lateral hydrostatic forces are generally not sufficient to cause deflection or displacement of a building unless there is a significant difference in water elevation on opposite sides of the wall in contact with the flood water. However, if there is the significant difference, permanent deflections and damage to structural elements within the building may be occurred. Hydrodynamic forces are lateral loads induced by flowing flood water around the buildings. These forces are a function of flood water velocity and the building geometry and have capability to collapse structural walls or floor systems. The buoyant forces are the vertical uplift of the structure due to the displacement of water. When the buoyant forces associated with the flood exceed the weight of the building components and the connections to the foundation system, the structure may float from its foundation. Impact loads are the direct forces associated with waves, as typically encountered during coastal flooding, or the impact of floating debris within the flood waters. These loads especially destructive because the forces associated with them may be higher in magnitude than the hydrostatic and hydrodynamic forces.

3. Retrofitting techniques

The purpose of introducing a retrofitting method is to prevent the sudden collapse of buildings during natural disasters to allow people to evacuate (Bartolome et al., 2004). Further, according to Arya (2000), it can be said that, retrofitting is refer to upgrade the disaster resistance of an existing unsafe building, or a damaged building while repairing. Accordingly retrofitted building becomes safer for future disaster occurrences. Though it may not be designed to be totally disaster-resistant but to avoid its collapse, adequate reinforcements should be provided. Retrofitting of masonry buildings against earthquakes, tsunami and flooding are discussed in this section. Several seismic retrofitting techniques for URM buildings are shown in Figure 8.

(a) (b) (c) (d) (e)

Figure 8: Retrofitting techniques; (a) Ferrocement (Shah, 2011), (b) PP-band mesh reinforcement in testing stage (Sathiparan et al., 2008), (c) External horizontal bamboo (outside), external vertical bamboo (inside), internal horizontal chicken wire mesh and ring beam (Dowling et al., 2005), (d) Old tire strips (Kaplan et al., 2008), (e) Application of FRP reinforcement (Velazquez-Dimas, 2000)

3.1 Retrofitting of URM buildings against earthquake

3.1.1 Ferrocement

Shah (2011), has conducted an experiment on evaluating the effect of ferrocement (Figure 8-(a)) using twenty one masonry columns of 221 mm x 221 mm x 784 mm and they were tested under axial compression. Author proved that, ferrocement cover of 6.125 mm and 1:2 cement sand mortar with water cement ratio of 0.5 (w/c=0.5) and mesh spacing of 12.25 mm on masonry columns substantially improved the load carrying capacity, ductility and serviceability of unreinforced masonry columns. Author found that, encasement of unreinforced masonry brick columns by ferrocement double the failure load, increased ultimate load by 121%. When lower the wire spacing in mesh, lower the average crack spacing. However, mortar strength has comparatively smaller influence on failure load. Clear cover to reinforcement shall not be greater than 2 mm and one layer of reinforcement may be satisfactory for each 6 mm thickness of ferrocement casing. Premature failure may occur if mesh is not properly wrapped and plaster does not fully penetrate into it. Ferrocement can be used to repair column, which have been loaded close to failure. It seems that this method is simple, cost effective, required low technology and adding limited mass to the existing structure.

3.1.2 Polypropylene packaging (PP-band) strip mesh reinforcement

Sathiparan et al. (2008), tested four 1/4 scale wallets (with dimensions of 50 mm thickness, 275 mm width and 275 mm height): two wallets for diagonal shear test (Figure 8-(b)) and two wallets for out-of-plane test. Authors found that, using PP-band mesh reinforcement for strengthen the URM wall can be increased both in-plane shear and out-of-plane resistance of the wall. Further authors found that, residual strength after crack initiation and residual stiffness of masonry wall with PP-band mesh retrofitting are directly proportional to PP-band density up to some value and after the optimum value, they do not increase with the PP-band density; and looseness of the PP-band attachment with specimen reduces the residual strength after crack initiation of the specimen. However, an application of surface finishing makes beneficial effect in residual strength as it fills the gap between mesh and wall.

Macabuag et al. (2008), has also carried out diagonal shear test and claimed that, the main effect of the PP-band mesh is to restrain separated sections of masonry allowing for redistribution of the load within the masonry itself while vertical bands apply normal compression once sliding of rows occurs, resulted in increasing the masonry's frictional resistance to shear sliding and horizontal bands directly bear load by resisting the separation of bricks within the same row. The method is simple, cost effective, no requirement of special technology and knowledge. Polypropylene is durable, inexpensive, harder, possesses excellent resistance to organic solvents and degreasing agent as well as electrolytic attack and worldwide available. Material has also no corrosion or insect failure effect.

3.1.3 Bamboo reinforcement

Dowling et al. (2005), suggested that a significant improvement in the earthquake resistance of adobe mud-brick structures can be obtained by using external vertical and horizontal bamboo reinforcement, internal horizontal chicken wire mesh reinforcement and a ring beam (Figure 8-(c)). They tested five 1:2 scale u-shaped adobe mud-brick walls; each had 150 mm thick, 1800 mm wide and 1200 mm high wall. One of them was a control specimen with no retrofitting and others were retrofitted as one with only corner pilasters; one specimen with internal horizontal chicken wire mesh, external vertical bamboo (inside and outside) and timber ring beam; one specimen with internal vertical bamboo reinforcement, internal horizontal chicken wire mesh and a timber ring beam; and another specimen with external vertical (inside) and horizontal (outside) bamboo reinforcement, internal horizontal chicken wire mesh and a timber ring beam. Authors have named each specimen for better identification. Above mentioned specification of five wallets are summarized in Table 1. A downward restraining force of 125 kPa was applied to the tops of the 'wing' walls (acting as in-plane shear walls) of all specimens by tension bars between timber plates and beam resting on the walls, and the concrete base.

Table 1: Specification of u-shaped wall units (Dowling et al., 2005)

Specimen	*System*
3A	*Unreinforced, traditional*
3B	*Corner pilasters / buttresses only*
3E	*Internal horizontal chicken wire mesh (every three courses), External vertical bamboo (inside and outside), Timber ring beam*
3G	*Internal horizontal chicken wire mesh (every three courses), Internal vertical bamboo, Timber ring beam*
3I	*Internal horizontal chicken wire mesh (every three courses), External vertical bamboo (inside), External horizontal bamboo (outside), Timber ring beam*

The specimens were subjected to transient dynamic loading using the uni-axial shaking table to evaluate the response to out-of-plane seismic forces. Test results indicated that significant improvement in the earthquake resistance of adobe mud brick structures can be obtained by using technique specification used in 3I specimen. Although the specimen has showed severe damage at (100%) x 4 intensity time-scaled simulation of the January 13, 2001 El Salvador earthquake (Mw 7.7), the collapse of wall was not imminent. This method seems to be relatively simple and easy to undertake, and utilize low-cost and readily-available materials, making them appropriate for application in developing countries. It is important to consider precautions against insect failures of bamboo. The behaviour of URM walls reinforced by internal vertical bamboo reinforcement should be the focus of further investigation.

3.1.4 Old tires

Kaplan et al. (2008), has performed an experiment with axial load, lateral load and incremental reversed cyclic imposed sway to the models to obtain hysteretic behaviour, to identify the effect of old tire strips as reinforcement on strengthen of URM buildings against earthquakes. They used six full scale masonry wall constructed by standard masonry bricks with vertical holes; three walls are having window opening and other three are with no openings. One from each two types was used as control specimens. Groves were formed by removing plaster on other four walls according to the pattern of tire strips to be placed. One of two walls with no openings was retrofitted diagonally by tire strips and other one was retrofitted by both vertically and horizontally placed tire strips. Two walls with openings were retrofitted by diagonally placed tire strips; and additional vertical and horizontal tire strips for one of them and only horizontal tire strips for other, were placed around the wall openings to prevent local crushing around the wall openings. After placing tire strips, groves were covered by plastering or high quality mortar, (Figure 8-(d)). In addition to the experiment, models were also analyzed by using commercially available software, ANSYS. Authors found same results from numerical and experimental investigations. Tire strips have no significant effect on lateral load capacity of walls, whereas use of the strips improves ductility and energy consumption capacity of the walls significantly with improvement in displacement capacity about 250~300% in the case of no openings and about 30~40% in the case of the walls with openings. Introduction of strips do also have some minor effect on the damage pattern. Kaplan et al. (2008), identified that, the method is an economic and easily applicable method and has an environmental aspect with important contribution to the waste problem caused by old tires. When looking at the method, it can be said that it is less technical requirement and less labour intensive method. Therefore, seismic strengthening of unreinforced masonry walls by strips from old car tires is possible even in Sri Lanka.

3.1.5 Fibre-Reinforced Polymer (FRP) reinforcement

Velazquez-Dimas (2000), tested four half-scale slender masonry walls, each had height-thickness ratio of 28 and 1220 mm length, using running bond pattern with a mortar joint of a 6.35 mm. Three of the tested walls were constructed in single wythe, with 1420 mm height and fourth wall was constructed in double wythe, with 2470 mm height and a header course placed every six courses. The specimens were strengthened by attaching strips of a fabric constructed with E-glass, in which glass fibres were aligned vertically to each face of walls using two-component epoxy resin and the wet layup procedure. The specimens were subjected to cyclic out-of-plane loading. Lateral pressure was applied through an air bag system. From experimental, authors found that the out-of-plane capacity (ultimate pressure supported by the walls or supporting pressure) of walls was increased up to 25 times their weight and ultimate deflection was increased as much as 5% of the wall height by using FRP technique (Figure 8-(e)). It was also observed that the ultimate strain on composite strips was not dependent on the reinforcement ratio. Limitation of the reinforcement ratio up to two times that of the balanced condition to avoid very stiff behaviour and for improved hysteretic response was also found. They suggested, however, that further studies are needed to investigate the influence of an uneven brick surface in the development and propagation of delaminated areas. When considering the method, use of epoxy resin is costly and technical requirement is higher. Therefore this is suitable for buildings which have more social economic value such as power generating center, water purification and delivering center, industrial buildings, etc. rather than domestic household one or two story buildings. A number of other studies have also been carried out on masonry buildings that were strengthened by using FRP reinforcement (Ehshani et al., 1999, Ehshani and Saadatmanesh, 1996, ElGawady et al., 2006a and Grillo, 2003).

3.2 Retrofitting of URM buildings against tsunami and flooding

Because there are similar causes of effect by tsunami and flooding as by hydrostatic, hydro dynamic, impulsive, impact and buoyancy forces, same techniques can be used in strengthen the URM buildings against them. Retrofitting techniques should be included anchoring the building or ensuring that the building itself is heavy enough against buoyancy forces and pressure. Also mechanical connections between the floor system and foundation must be involved against forces induced by flood and tsunami. Introducing the bracing members to the walls facing sea and minimizing the wall lengths can effectively reduce the flexural stresses developed by lateral pressure.

As suggested by Maheshwari et al. (2005), bending failure caused by hydrostatic forces of tsunami could only be avoided by using reinforce walls design for lateral forces of tsunami. To fulfill this purpose, retrofitting techniques of reinforcement such as bamboo, PP-band mesh, FRP which proved as seismic resistant may be effectively used. Increased wall thicknesses will enhance the overall resistance of the structure and 225 mm thick walls are suitable instead of 113 mm thick walls which are not suitable for structures in coastal zone having a threat of tsunami loading.

Kreibich et al. (2005), stated that, building a flood adapted house structure, e.g. using an especially stable building foundation or water proof seal the cellar, is generally quite expensive. These structures can fail especially during extreme floods. However, steel frame and brick buildings tend to be less susceptible to collapse than other material. Water proof dry wall will hold up for long periods of inundation. To prevent penetration of surface water and ground water, any openings in the building must be raised or sealing measures must be implemented. Buildings can be sealed by using bitumen or strips of plastic or by constructing the base and walls of buildings using concrete that is almost non-permeable. The maximum height of water proofing should be approximately one meter above the ground.

4. Conclusions

In Sri Lanka, natural disasters such as minor earthquakes, tsunami and storm surges, floods, cyclones and landslides are generally encountered. Weather changes showed that not only landslides and floods but also extreme wind events are frequently occurred. Forces induced by these disasters were identified as lateral loads including in-plane and out-of-plane induced by earthquakes and hydrostatic, hydrodynamic, impulsive, impact and buoyancy forces induced commonly by tsunamis and floods. In Sri Lanka, most of domestic buildings are constructed by using unreinforced masonry (URM) units. These URM buildings were frequently collapsed due to natural disasters. The most important weaknesses of the damaged masonry structures were the lack of interlocking units between external and internal wythes of the wall sections and the lack of connection between crossing walls. Possible failures of structures were identified as in-plane failure, out-of-plane failure and connection failure. The main in-plane failure mechanisms of URM walls due to earthquake actions are identified as shear failure, sliding failure, rocking failure and toe crushing while out-of plane failures consist of vertical center breaking on main wall perpendicular to the earthquake and vertical corner cracking on intersection of main wall and bracing walls. Bending, sliding, overturning, cracking by diagonal tension and crushing by diagonal compression are the failures induced by tsunami loading. It can be concluded that, failures due to flooding are also similar to those by tsunami where almost both of them induce similar forces acting on URM buildings. Formation of openings near the corners of the walls was identified as another common problem where crack propagation is concentrated around these openings.

Retrofitting of existing and damaged buildings to resist the forces induced by natural disasters is simple, cost effective and time saving than reconstruction of the building. There are numbers of retrofitting methods for URM buildings, including ferrocement, bamboo reinforcement, PP-band mesh reinforcement, FRP and old tire strips.

Use of low quality materials and construction techniques cause extensive damages to unreinforced masonry buildings even the magnitude of the natural disaster is quite low where no damages or very limited cracks are expected. Because of the less awareness of peoples living in rural areas, generally, the domestic/rural areas buildings are subjected to above situations. The most death cases occurred because low quality URM buildings have suddenly collapsed without giving sufficient time to clear off to peoples for safe areas. Increasing of public awareness about the important of strength properties of URM buildings are also recommended.

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