IMPROVEMENT OF SEISMIC PERFORMANCE OF STONE MASONRY STRUCTURE: A REVIEW

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Abstract*—Durable and locally available, stone has been used as a construction material since ancient times. Stone houses, palaces, temples, cultural buildings etc. can be found all over the world. Traditional stone masonry dwelling have proven to be extremely vulnerable to earthquake shaking. India faces threats from a large number of natural hazards such as earthquakes, floods, droughts, landslides, cyclones and tsunamis. During the period 1990 to 2010, India experienced 9 Damaging earthquakes that have resulted in over 30,000 deaths and caused enormous damage to property, assets and infrastructure. In many cases buildings and structures have proven inadequate to resist earthquake forces and the failure of these can be held responsible for most of the resulting human fatalities. Human and economic losses due to earthquakes are unacceptably high in areas where stone masonry has been used for house construction. Both old and new building of this construction type is at risk in earthquake prone area of the world. The masonry structures are complicated system that required a through and detailed knowledge and information regarding their behavior under seismic loading. This review paper explains the under lying causes for the poor seismic performance of stone masonry building and offers techniques for improving it for both new and existing building. The proposed techniques have been proven in field application, are relatively simple, and can be applied in area with limited artisan skill and tools. An effort has also been made to include some stone masonry construction techniques used in other part of the world, such as Europe, Chaina, etc. We believes that by implementing the recommendations suggested here, the risk to the occupants of non-engineered stone masonry building and their property can be significantly reduced in future earthquakes.

***Index Terms*— Earthquake-Resistant, Seismic Retrofitting, Stone Masonry Structure, Seismic Deficiencies.**

I. INTRODUCTION

Durable and locally available, stone has been used as a construction material since ancient times. Stone houses, palaces, temples, and important community and cultural buildings can be found all over the world. With the advent of new construction materials and techniques, the use of stone has substantially decreased in the last few decades. However, it is still used for housing construction in parts of the world where stone is locally available and affordable material. Traditional stone masonry dwellings have proven to be extremely vulnerable to earthquake shaking, thus leading to unacceptably high human and economic losses, even in moderate earthquakes. The seismic vulnerability of these buildings is due to their heavy weight and, in most cases, the manner in which the walls have been built. Human and economic losses due to earthquakes are unacceptably high in areas where stone masonry has been used for house construction. Both old and new buildings of this construction type are at risk in earthquake-prone areas of the world.

In order to predict the likely impact of an earthquake on the built environment in any part of the country, it is essential to know the seismic vulnerability of the built environment on the affected areas. This information depends on the structural systems of the buildings to resist vertical and lateral loads, performance of similar buildings in past earthquakes, and engineering standards adopted during construction. The assessment of likely impact also depends on the location and distribution of vulnerable building stock in the affected areas.

Very limited data currently exists in our country to quantify the building stock and their seismic vulnerability in different parts of the country. The Housing Census data collected every decade compiles information on the construction materials used for walls, floor and ceiling of dwellings. However, this information is technically very difficult to relate to the construction materials used for buildings as a whole due to the nature of data collection that separates out information regarding walls, floor and ceiling so that their combination for buildings is not reported. Even where such information is available based on detailed field surveys, the use of construction materials has not been related to the seismic vulnerability of the buildings. As a result, the technical information on building constructions cannot be fully used for earthquake risk management strategies and programs.

II. LITERATURE REVIEW

Lakshmi Keshav et.al (2012) Conducted shake table tests on two reduced models that represent normal single room building constructed by Compressed Stabilized Earth Block (CSEB) from locally available soil. One model was constructed with earthquake resisting features (EQRF) having sill band, lintel band and vertical bands to control the building vibration (model S2) and another one was without Earthquake Resisting Features (model S1). Acceleration, Velocity, and displacement at roof level for CSEB-solid block model without EQRF are 1.056 times more than that of CSEB-solid block model with EQRF. Many of the damages observed in Model S1 during testing were similar to the actual earthquake damage. Separation of Brick layer (failure) occurred at CSEB solid block model without EQRF.

Hakkar K Shashi et. al. (2000) Constructed full scale models of one storied stone masonry houses with two different combinations of strengthening measures and have been tested under progressively increasing intensity of shock on shock table facility. After the damage of models during shock table testing, these are retrofitted by existing techniques prescribed in the IS code and tested again. But the cracking in the piers of walls still occur. There is a good agreement in the region of cracking in the shock table tested model with that determined by finite element analysis. The injection of cementitous grout on localized damaged areas can restore the original strength and stiffness. The introduction of external horizontal tie bar to a wall can increase the strength and ductility of the model. Moreover, welded wire mesh in damaged region not only increases the lateral resistance of the wall but also prevents shear and flexure failures of the models.

Saeid Mojiri et. al. (2014) This paper presents detailed analyses of experimental shake table test results with the goal of providing a better understanding of the seismic performance of lightly reinforced fully grouted masonry shear walls. This includes quantifying the walls' displacement ductility levels, extent of plastic hinge zones, and equivalent plastic hinge lengths based on the experimental results. Separation of the various energy components of the system, including those of the shake table, the walls, and the external mass support system, based on the experimental results, is also carried out. The results from this study demonstrate that the displacement ductility capacity of the reinforced masonry (RM) walls and their capability to dissipate energy through plastic hinging are higher than what is currently recognized by the National Building Code of Canada.

M. Umair Saleem et. al. (2016) Evaluates the seismic performance of fiber-reinforced polymer (FRP) retrofitted buildings with openings at different FRP reinforcement levels. Required objectives are achieved by performing five shake table tests on 1=4-scale models of single-story boxlike masonry buildings. Out of five building models, one was an unreinforced masonry (URM) building model whereas the other four were retrofitted with different quantities and layouts of FRP reinforcement. FRP reinforcement is reduced by decreasing FRP strip widths and strip spacing and applying FRP strips on either the inside or outer faces of walls. Each building model was subjected to the same series of input ground motions with gradually increasing amplitudes. The results of diagonal compression tests and building model shake table tests show that FRP can significantly enhance the seismic resistance of new and existing URM buildings.

III. STONE MASONRY CONSTRUCTION IN INDIA

Stone masonry is the art of building the structure in stones. Owing to the expense in working the material, the face stones usually are squared and the interior or hearting is filled up with smaller stones roughly positioned with hammer. Stones are in the great majority of case of varying dimension, thereby making it a matter of great skill to obtain a proper bond in the work, and owing to the irregular shape of material the wall have to made considerably thicker with the exception where the wall are built of coursed stones properly squared

Stone masonry is a traditional form of construction that has been practiced for centuries in regions where stone is locally available. Stone masonry has been used for the construction of some of the most important monuments and structures around the world. 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. Houses of this construction type are found in urban and rural areas around the world. There are broad variations in construction materials and technology, shape, and the number of stories. Houses in rural areas are generally smaller in size and have smaller- sized openings since they are typically used by a single family. Multi-family residential buildings in urban areas are often of mixed use - with a commercial ground floor and a residential area above. Houses in rural areas and suburbs of urban centers are built as detached structures, while housing units in urban centers often share a common wall. 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 1 Stone masonry construction in 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 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, account for the heavy weight of these buildings, thus resulting in significant inertia forces being developed during an earthquake. As a building material, stone usually has a significant strength when subjected to compression, and it is stronger than most other conventional masonry units (bricks and concrete blocks). However, when round, unshaped stones and low-strength mortar are used and artisan skills are at a low level, the resulting structures are extremely vulnerable. These unsafe practices are the result of economic constraints and lack of proper training for local artisans in countries and regions that use stone masonry.

Stone masonry buildings have shown poor performance in earthquakes, leading to significant human and economic losses. This includes performance in earthquakes in Italy, Greece, Turkey, Montenegro, Slovenia, Algeria, Iran, Pakistan, India, Nepal, and many other countries. In the 2005 Kashmir earthquake (M 7.6), over 74,000 people died in Pakistan, most of them buried under the rubble of traditional stone masonry dwellings. In India, most of the 13,800 deaths during the 2001 Bhuj earthquake (M 7.7), and more than 8,000 deaths in the 1993 Maharashtra earthquake (M 6.4), were attributed to collapses of this type of construction. Examples of devastation caused by heavy damage or the collapse of stone masonry buildings in past earthquakes are shown in Figures 2 to 4.

Figure 2 Damage to Stone Masonry Building in Bhuj, Gujrat Earthquake 2001

Figure 3 Damage to Stone Masonry Building in Kashmir Earthquake 2005

Figure 4 Damage to Stone Masonry Building in Maharastra

The Deficiencies of stone masonry buildings are:

- Lack of structural integrity
- Roof collapse
- Delamination of wall wythes
- Out-of-plane wall collapse
- In-plane shear cracking
- Poor quality of construction
- Foundation problems

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 5. 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 5.

Figure 5 Roof collapse due to a loss of the gravity load-bearing capacity of stone walls in the 2005 Kashmir

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 6.

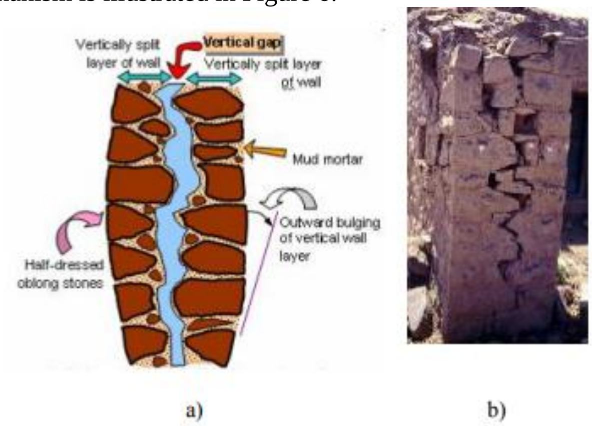

Figure 6 Delamination of stone masonry walls: a) delamination mechanism; b) delamination of wall wythes in the 1993 Maharashtra, India, earthquake

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 7. 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 show in figure 7.

Figure 7 Out-of-Plan Collapses of Two Parallel Walls

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).

V. Construction With Improved Seismic Performance

Unreinforced masonry structures are the most vulnerable during an earthquake. Normally they are designed for vertical loads and since masonry has adequate compressive strength, the structures behave well as long as the loads are vertical. When such a masonry structure is subjected to lateral inertial loads during an earthquake, the walls develop shear and flexural stresses. The strength of masonry under these conditions often depends on the bond between brick and mortar (or stone and mortar), which is quite poor. This bond is also often very poor when lime mortars or mud mortars are used. A masonry wall can also undergo in-plane shear stresses if the inertial forces are in the plane of the wall. Shear failure in the form of diagonal cracks is observed due to this. Damage is expected during major ground shaking even in buildings designed and constructed according to the latest building codes. However, even in severe earthquake shaking, buildings should not collapse, threatening the life safety of the occupants. It is usually not economically viable to construct a stone masonry building to resist a strong earthquake without significant damage. However, the provision of seismic measures during construction is critical for limiting the extent of damage and preventing collapse. This chapter provides important considerations to be taken into account before and during the construction of a new stone masonry house to ensure its enhanced seismic performance. Some key points that must be considered when constructing a building with improved seismic performance.

- Building Site
- Building Plan
- Building Elevation
- Building Height
- Structural Integrity (Box Action)
- Seismic Bands (Ring Beam)
- Reinforced Concrete Bands
- Stone Masonry Walls
- Size and Location of Opening
- Bonding of Wall Wythes with through Stones
- Construction Details at Wall Intersections
- Foundation
- Construction materials

VI. IMPROVING SEISMIC PERFORMANCE OF STONE MASONRY STRUCTURE BY RETROFITTING

Past earthquakes have shown that damage to and the collapse of stone masonry buildings cause major human and economic losses in areas where this construction type is widespread. The causes of poor seismic performance of these buildings are explained in Previous Chapter. Massive demolition and replacement of these vulnerable buildings is neither affordable nor feasible due to historical, cultural, social, and economic constraints. This chapter presents cost-effective strategies for retrofitting stone masonry buildings in order to enhance their seismic performance.

Many stone buildings have been constructed using weak mortar and local construction materials; this indicates that their initial construction cost was very low. Most of these buildings were built in an informal manner by the owners themselves, avoiding any major cash outlay. These buildings need a significant and costly intervention to bring them up to the safety levels required by current building codes.

The following strategies have the highest cost-to-benefit ratio in terms of improving the seismic safety of stone masonry buildings:

- Enhancing integrity of the entire building by ensuring a boxlike seismic response,
- Enhancing the wall strength for in-plane and out-of-plane effects of seismic loads, and
- Improving floor and roof diaphragm action.

An additional strategy is to strengthen the existing foundation, but this is not considered practical and economically feasible in most cases. This chapter provides an overview of established seismic retrofitting strategies for stone masonry buildings that have been used in post-earthquake rehabilitation efforts around the world; some examples include the 1993 Maharashtra and 2001 Bhuj (India) earthquakes, The 2005 Kashmir (Pakistan) earthquake.

Floor structure can be stiffened by providing new diagonal braces made of steel underneath the existing floor or roof. The braces must be anchored to the walls as shown in figure 8.

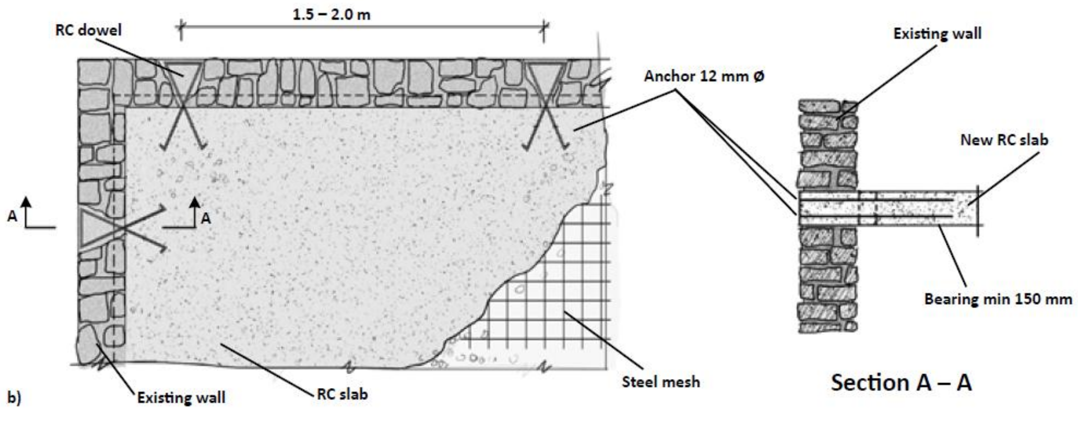

Figure 8 Retrofitting the floor and roof structures a new RC slab

Enhancing the Lateral Load Resistance of Stone Masonry Walls

Commonly used wall retrofit techniques include the installation of through-stones and jacketing, which can be used to increase the wall strength both for in-plane (parallel to the wall length) and out-of-plane (perpendicular to the wall surface) seismic effects. Other techniques include grouting and the installation of buttresses. Some of these techniques are discussed next.

Through-stones

Reports from past earthquakes show that the withes in stone masonry walls delaminate (separate) vertically down the middle due to the absence of through-stones, thereby causing disintegration of the interior and exterior wall wythes. In an extreme case, collapse of the entire building may occur. Chances of wall delamination are considerably seduced when wall wythes are “stitched” together by means of through-stones. The purpose of this retrofit provision is to mimic good construction practice for stone masonry where long stones (bonding stones) are provided.

The installation of through-stones is labor-intensive, but it may be a feasible retrofit option for stone masonry walls provided that the wall thickness is not excessively large. The procedure is illustrated in Figure 9. First, a hole needs to be created in the wall by removing stones. To create a hole, stones need to be loosened by means of gentle pushes sideways, upward and downward using a small crowbar, so that the other stones in the wall are not disturbed. The hole should be dumbbell-shaped, that is, it will be larger on the wall surfaces than in the interior. A hooked steel bar needs to be installed and the hole should be filled with concrete. Finally, the exposed surface should be covered with a rich cement and sand plaster coating and cured for at least 14 days. Through-stones should be installed very carefully; otherwise surrounding portions of the wall may be damaged. Examples of throughstone applications are shown in Figures 10.

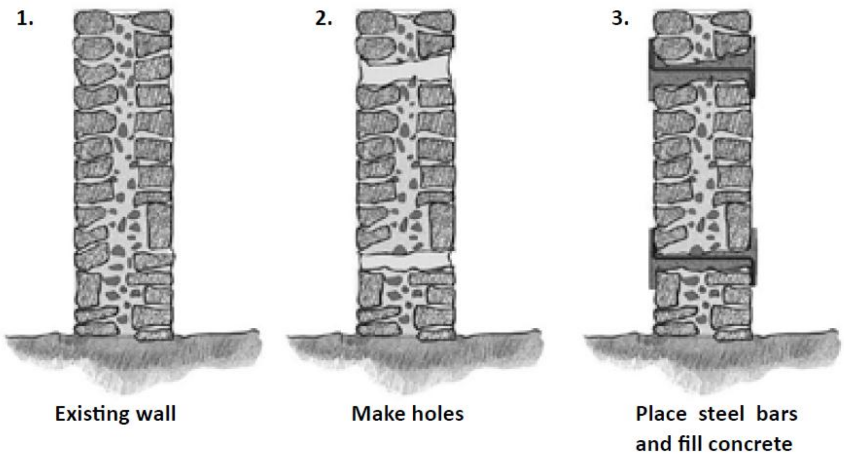

Figure 9 Procedure for the installation of through-stones

Figure 10 Examples of completed through-stone retrofit projects in Maharashtra, India

VII. CONCLUSIONS

Stone masonry is one of the oldest and most common vernacular construction practices. Stone masonry construction varies widely around the world depending on the type of locally available materials, the level of artisan skills and tools, and economic constraints. In the past, stone masonry construction was used to build simple dwellings and also palaces, temples, and heritage landmark structures. It continues to be used for housing construction in developing countries and in areas where stone is a locally available and affordable building material. Stone is one of the most durable construction materials, and many stone masonry buildings have remained in use for centuries. In many cases, earthquakes pose a major threat to these structures. The seismic vulnerability of stone masonry buildings is due to their heavy weight and, in most cases, the manner in which the walls have been built. Human and economic losses due to earthquakes are unacceptably high in areas where stone masonry has been used for house construction. Both old and new buildings of this construction type are at risk in earthquake-prone areas of the world.

This review study explains the underlying causes for the 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. We believe that there are two main challenges related to improving the seismic performance of stone masonry buildings: technical challenges and challenges related to the technology transfer.

REFERENCES

[1] Bothara, J., Beetham, R., Brunsdon, D., Stannard, M., Brown, R., Hyland, C., Lewis, W., Miller, S., Sanders, R., and Sulistio, Y., (2010). General Observations of Effects of the 30 September 2009 Padang Earthquake, Indonesia. Bulletin of the New Zealand Society for Earthquake Engineering, 43.3, 143–173.

[2] Bothara, J. K. and Hiçyılmaz, K., (2008). General Observations of Building Behaviour during the 8th October 2005 Pakistan Earthquake. Bulletin of the New Zealand Society for Earthquake Engineering, 41.4, 209–233.

[3] GOM. (1998). Manual for Earthquake-Resistant Construction and Seismic Strengthening of Buildings in Rural Areas of Maharashtra, Revenue and Forests Department, Government of Maharashtra, Mumbai, India.

[4] Jain, S. K., Lettis, W. R., Murty, C. V. R., Bardet,J. (2002). Bhuj, India Earthquake of January 26, 2001: Reconnaissance Report, Earthquake Spectra, Vol. 18, Supplement A.

[5] Maffei, J., Bazzurro, P., Marrow, J., and Goretti, A. (2006). Recent Italian Earthquakes: Examination of Structural Vulnerability, Damage, and Post-Earthquake Practices – Case Studies and Comparisons to U.S. Practice, Earthquake Engineering Research Institute, Oakland, CA.

[6] Murty, C. V. R., 2005. IITK-BMTPC Earthquake Tips: Learning Earthquake Design and Construction, National Information Centre of Earthquake Engineering, IIT Kanpur, India, www.nicee.org.

[7] Lakshmi Keshav, Srisanthi .V.G, Rajkumar.N, "Behavior Of 3-D Masonry CSEB Block Models Under Dynamic Loading", IJCESCAE, Vol 6, NO. 12, 2012.

[8] Thakkar K Shashi And Agarwal Pankaj, "Seismic Evaluation Of Earthquake Resistant And Retrofitting Measures Of Stone Masonry Houses", 12 WCEE, 2000

[9] Y. Belmouden and P. Lestuzzi "An equivalent frame model for seismic analysis of masonry and reinforced concrete buildings" Elsevier ,Science direct, Construction and Building Materials, 23 (2009), Pg 40–53

[10] Huanjun Jiang, Xiaojuan Liu and Junjie Mao, "Full-scale experimental study on masonry infilled RC moment-resisting frames under cyclic loads" Elsevier ,Science direct, Engineering structures, 91 (2015), Pg 70-84

[11] Ahmad N, Ali Q, Ashraf M.,Naeem Khan , Alam B, "Performance assessment of low–rise confined masonry structures for Earthquake induced ground motions" IJCSE, Volume 2,issue 3, 2012

[12] Sang-Cheol Kim, Donald W. White, "Nonlinear analysis of a one-story low-rise masonry building with a flexible diaphragm subjected to seismic excitation" Elsevier ,Science direct, Engineering structures, 26 (2004) 2053– 2067

[13] Saeid Mojiri, Michael J. Tait, and Wael W. ElDakhakhni, "Seismic Response Analysis of Lightly Reinforced Concrete Block Masonry Shear Walls Based on Shake Table Tests" ASCE, 2014.

[14] M. Umair Saleem, Muneyoshi Numada, Muhammad Nasir Amin, and Kimiro Meguro "Shake Table Tests on FRP Retrofitted Masonry Building Models", Journal of composites for construction, ASCE, 2016

[15] Khaled Galal and Navid Sasanian-"Out-of-plane flexural performance of GFRP-reinforced masonry walls", Journal of composites for construction, ASCE, 2010.