World Academy of Science, Engineering and Technology
International Journal of Structural and Construction Engineering
Vol:8, No:4, 2014

Seismic Vulnerability Mitigation of Non-Engineered Buildings

Muhammad Tariq A. Chaudhary

***Abstract*—**The tremendous loss of life that resulted in the aftermath of recent earthquakes in developing countries is mostly due to the collapse of non-engineered and semi-engineered building structures. Such structures are used as houses, schools, primary healthcare centers and government offices. These building are classified structurally into two categories viz. non-engineered and semi-engineered. Non-engineered structures include: adobe, unreinforced masonry (URM) and wood buildings. Semi-engineered buildings are mostly low-rise (up to 3 story) light concrete frame structures or masonry bearing walls with reinforced concrete slab. This paper presents an overview of the typical damage observed in non-engineered structures and their most likely causes in the past earthquakes with specific emphasis on the performance of such structures in the 2005 Kashmir earthquake. It is demonstrated that seismic performance of these structures can be improved from life-safety viewpoint by adopting simple low-cost modifications to the existing construction practices. Incorporation of some of these practices in the reconstruction efforts after the 2005 Kashmir earthquake are examined in the last section for mitigating seismic risk hazard.

***Keywords*—**Kashmir earthquake, non-engineered buildings, seismic hazard, structural details, structural strengthening.

I. INTRODUCTION – IMPACT OF NATURAL DISASTERS

ECONOMIC toll and mortality rate due to natural hazards (earthquakes, floods, hurricanes, storms etc.) is on the rise due to increased world population, urbanization, population density and inhibition of areas prone to these natural events [1]. Mortality rates due to the natural hazards has decreased steadily in the developed countries since later half of the twentieth century with increase in awareness and implementation of stringent building design codes and practices [2]. However, the economic cost associated with these events has shown an upward trend due to increased urbanization, technological dependency and increased volume and value of infrastructure exposed to the risk in these countries. The situation is grimmer when a similar analysis is conducted for developing and under-developed countries. Here, both mortalities and economic loss are on the rise [2]. In fact, more than 92% of the approximately 2.7 million fatalities due to geophysical hazards occurred in the developing countries over the period 1900 to 2012 [3].

Collapse of buildings and houses during earthquakes are the leading reason for worldwide fatalities caused by natural disasters in the last 110 years followed by floods and hurricanes [3]. Fig. 1 presents a comparison of frequency of four types of natural disasters and related fatalities and direct economic cost from 1900 to 2012. Earthquakes top both fatalities and economic impact despite lesser occurrence. The numbers are staggering and a reason for concern for policy makers, economists, seismologists and more importantly civil engineers and urban planners who are professionally responsible for ensuring the safety of buildings and cohesion of the urban infrastructure fabric in the aftermath of natural disasters.

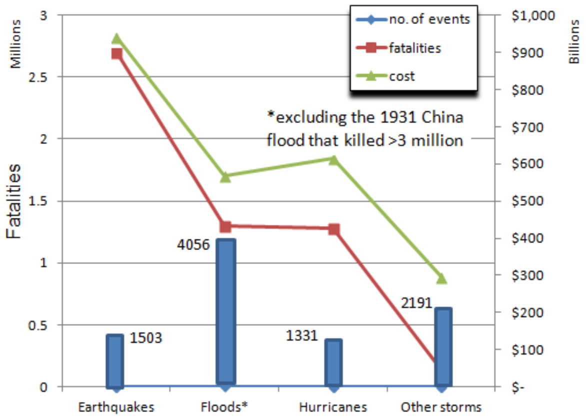

Fig. 1 Fatalities and economic impact of natural disasters (1900 – 2012)

II. OVERVIEW OF SEISMIC PERFORMANCE OF BUILDINGS

The saying 'earthquakes do not kill peoples but buildings do' is probably true for the vast majority of building structures in the world. Houses (single family as well as multi-family residences) comprise more than 80% of the building stock in the world. Single family houses are almost always built without the supervision of a professional engineer or an architect and are more likely to suffer damage during a seismic event.

The traditional materials for house construction are: adobe, natural stone, masonry (burnt clay bricks, concrete blocks) set in mud/lime/cement-sand mortar timber, and light reinforced concrete frame. The roof consists of wood joists infilled with thatch or tree branches and plastered with mud, corrugated metal sheets or reinforced concrete slab. Traditional knowledge, past experience and rules of thumb are the only available design guides for construction of these dwellings. The structural components are usually adequate for withstanding the gravity loads but grossly inadequate to withstand the lateral inertia loads imposed by earthquakes. In fact, the collapse of such non-engineered and semi-engineered

M.T.A. Chaudhary is with College of Engineering, Al Imam Mohammad Ibn Saud Islamic University, Riyadh, Saudi Arabia (phone: +966-565949865; e-mail: mtchaudary@imamu.edu.sa / mtariqch@hotmail.com).

structures has caused more than 90 percent of the earthquake fatalities throughout the world [4].

The focus of this paper is to: (i) examine the performance of 'non-engineered' buildings in recent earthquakes, (ii) suggest appropriate structural modifications to these structures in the seismically vulnerable areas in Pakistan so that a reasonable level of life-safety can be achieved at a minimal cost.

III. SEISMIC PERFORMANCE OF NON-ENGINEERED BUILDINGS

Non-engineered buildings are mostly houses built by the owner or a local craftsman with indigenous materials and traditional construction methods. The structures in this class comprise of the following: (a) adobe, (b) stone, (c) unreinforced burnt-clay or concrete masonry (URM) (d) timber or other biological material. Coburn & Spence [5] rightly argue that replacement of these traditional dwellings with modern ‘earthquake-resistant’ houses made of prefabricated or modular elements donated by aid agencies is neither feasible nor sustainable. It is more realistic to try to improve the performance of traditionally used structures by upgrading certain structural elements with the aim of extending the collapse time in the case of once-in-a-lifetime earthquake and limiting damage in the case of normal earthquakes. In this section a brief description of the salient characteristics of these building types will be provided along with their performance in earthquakes.

Non-engineered structures made of adobe (sun dried earthen brick), natural stone (dressed or undressed) and unreinforced masonry (burnt clay, concrete masonry) are discussed in this section. Despite different strength properties of each of the three materials, the construction process (i.e. building an enclosure using mortar and stacking smaller pieces of the building block to get the final vertical elements of the enclosure), gravity and lateral load resisting mechanism and failure patterns in earthquakes are similar for dwellings made of these materials. This also means that improvement techniques for these materials will also be similar with some changes to suit the strength characteristics of each material as discussed in Section VI.

A. Salient Features of Adobe Houses

Adobe (sun dried earthen brick) is the most widely used material for house construction in the world. Approximately 30% of the world’s population and 50% of the population in developing countries live in earthen dwellings [6]. This type of houses are common in the developing countries of Asia and Americas prone to earthquakes, such as Bangladesh, India, Pakistan, Afghanistan, Iran, Turkey, Mexico, Peru, Haiti and Guatemala. Fig. 2 provides an overview of the wide distribution of houses made of this material in the seismically active regions of the world.

B. Stone Houses

Houses made of natural stone are prevalent in the hilly areas where the basic building block (i.e. stone) is abundantly available and it is difficult to make adobe bricks due to lack of suitable soil and means of its extraction. Natural, rough cut and dressed stone have been traditionally used depending on the economic affordability of the owner. The stones are laid with clay mortar, lime mortar or cement sand mortar or stacked dry. The walls can be as thick as 500 mm. The roof is constructed of wood logs, timber joists, light steel beams that are covered with thatch and infilled with stone, timber tiles or burnt clay bricks. Timber roof trusses, wood planks, corrugated metal sheets and more recently RCC slabs have also been used. Usually, the roof bears on the stone walls with no positive connection.

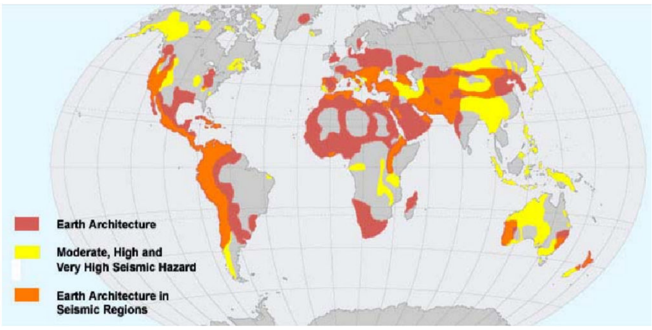

Fig. 2 World distribution of earth architecture in seismic regions [7]

This type of construction is found often in buildings of cultural and historical significance in the developed countries, and in developing countries where it represents affordable and cost-effective housing construction. This construction type is present in earthquake-prone regions of the world, such as Mediterranean Europe and North Africa, the Middle East, India, Nepal, Pakistan and other parts of Asia. Seismic performance of stone buildings has been similar to adobe buildings. However, the potential to cause injury or death is more than the adobe houses due to the weight of the stone walls and the heavier roof components.

C. Unreinforced Masonry (URM)

Unreinforced masonry is a relatively superior type of construction and is mostly found in the urban areas. The main load resisting element is the masonry walls which act to cater for the gravity loads as well as the lateral loads. Masonry units are either burnt clay bricks or cement masonry units with varying configurations and sizes. The masonry units are usually laid in cement sand mortar and use of reinforced concrete lintels above openings is also common. In older construction, lintels are of masonry arches as well. The roof or floor structure in this kind of construction is usually heavy in weight consisting of reinforced concrete slab, timber or steel joists with metal deck and concrete topping, precast concrete planks. This kind of construction can be found in historic structures in the developed as well as developing countries and modern era structures (less than 50 year of age) in developing countries.

Serious loss of life and damage to property has resulted due to the poor performance of these structures because use of this type of construction has been extended beyond single family residences to multi-story offices, schools, hospitals, government buildings, shopping centers etc. due to its perception of a modern and superior construction material. However, deficiencies of URM are similar to adobe and stone when it comes to resisting seismic loads and the relatively increased compressive strength of the material is of little value in withstanding the seismic shaking. These structures have suffered extensive damage during earthquakes in the developed countries (USA, Japan, New Zealand, Armenia, and Italy) as well as developing countries (Turkey, Pakistan, Algeria, Haiti, Mexico, India).

Upgrading the strength and capacity of a multi-story URM structure is a specific structural engineering task that requires careful evaluation of the load paths and examination of strength of various components. Therefore, in this paper the focus will only be on seismic upgrading of small URM structures which are mostly used for residences or small offices.

IV. ANALYSIS OF SEISMIC DEFICIENCIES OF ADOBE/STONE/URM DWELLINGS

Unfortunately, very limited research has been conducted on understanding the material properties and load transfer mechanics of these traditional structures. The major difficulty is that due to their low strength, these materials enter the non-linear range almost immediately upon load application. On the other hand, modern structural mechanics deals mostly with linear elastic behavior of materials and structural systems that is taught in the universities all around the globe. Non-linear material models and mechanics are the topic of graduate research only. This is one of the reasons that graduate civil/structural engineers worldwide are unable to satisfactorily analyze and design these simple traditional structures. Furthermore, it is only recently that government / UN funded experimental and analytical research on the seismic behavior of such structures has gained some significance in the wake of high death toll.

Seismic deficiencies of such structures are mainly due to brittleness and low tensile and bending strength of the adobe/stone/brick/blocks; low strength as well as poor bonding of mortar and lack of cohesiveness of structural elements (i.e. walls and roof). Typical modes of failure observed during earthquakes are depicted in Fig. 3 and include: (i) severe cracking and disintegration of walls; especially around openings, (ii) separation of walls at the corners due to lack of 'teething', (iii) separation of wythes in multi-wythe construction (especially true for stone construction), (iv) separation of roof from the walls due to loss of bearing, which, in most cases, leads to collapse of roof and subsequently of the unbraced wall(s) causing severe injuries/deaths.

A 3-D finite element model (FEM) of a typical house was constructed in a commercial FEM package to investigate its behavior under seismic shaking as depicted in Fig. 4. The walls of the structure consisted of 4-node shell elements with six degrees of freedom at each node. The roof diaphragm was not modeled due to lack of connectivity with walls. However, weight of the roof was applied to the walls as line load for inclusion in the seismic force calculations. The model is a linear elastic one and therefore non-linearity related to material properties are considered by using the equivalent linear properties, while geometric non-linearity due to cracking and wall separation is not modeled. The purpose of the model is to qualitatively compare the results with observed performance of these structures in the past earthquakes and draw some conclusions and suggest some engineering solutions for life-safety improvement of these structures. Further experimental and analytical research is needed to capture structural behavior of these structures quantitatively.

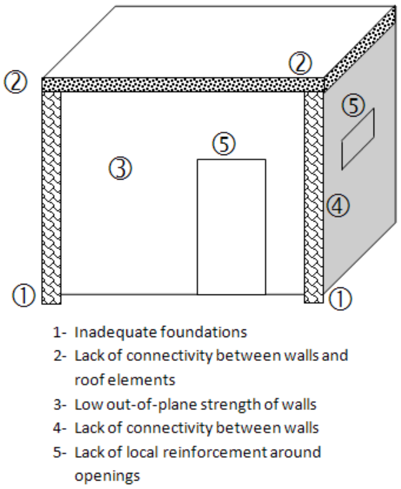

Fig. 3 Salient structural deficiencies in non-engineered buildings

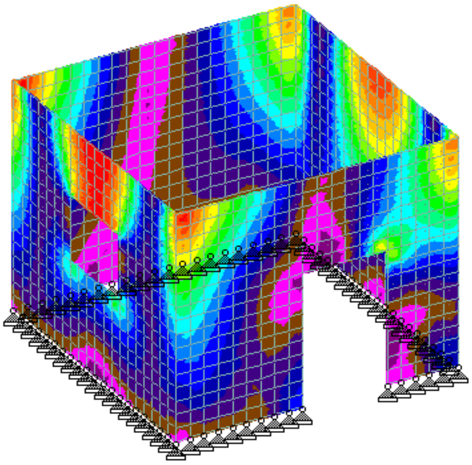

Fig. 4 Stress distribution in a non-engineered house under seismic loads

Fig. 4 shows the analysis results and high stress concentration can be observed around the openings and corners and in the out-of-plane wall. Fig. 5 depicts some of the deformation modes which shows marked similarity with the observed damage patterns of such structures.

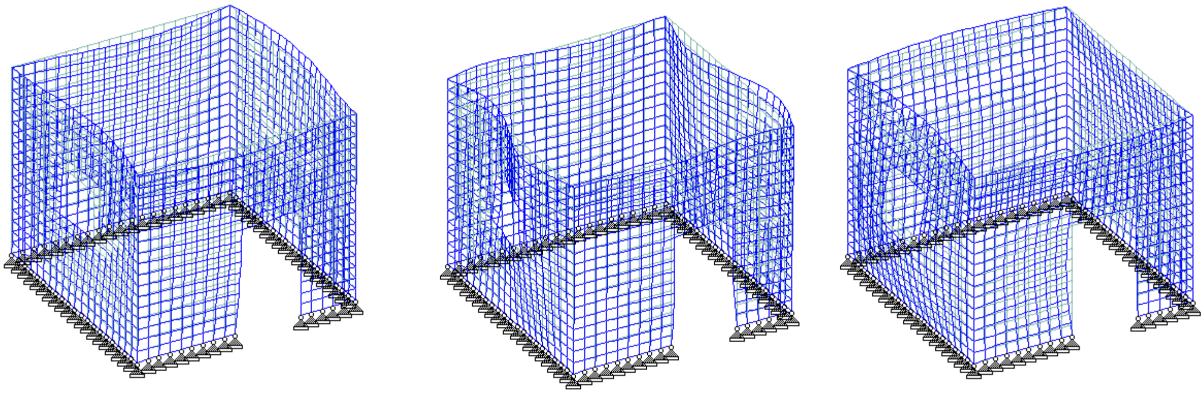

Fig. 5 Deformation modes of the non-engineered house

Effect of a properly constructed roof diaphragm was investigated in another model and it was observed that the wall deformations were reduced by more than ten times as compared to the model without a roof diaphragm. Significant reduction in stresses at the wall interfaces was also noted. Results of this simplified analysis were utilized in devising appropriate structural details for structural strengthening as discussed in Section VI.

V.KASHMIR EARTHQUAKE (2005)

Pakistan is located at the confluence of Indian, Eurasian and Arabian tectonic plates as illustrated in Fig. 8. The Indian plate is subducting under the Eurasian plate at an annual rate of 40mm and is the main reason for formation of the Himalayas and earthquakes in the northern parts of Pakistan. On 8th October 2005 at 08:57 local time Kashmir earthquake, with magnitude 7.6 on the Richter scale struck the Kashmir and NWFP region of Pakistan. The earthquake resulted due to rupture of about 100 km of Kashmir Boundary Thrust (KBT) fault (refer to Fig. 9). The earthquake affected nearly 30,000 km2 area, killed more than 75,000 persons, injured more than 110,000 and rendered about 3.5 million people homeless. The direct economic impact of the earthquake was estimated to be about US$ 3 billion.

Fig. 6 2005 Kashmir Earthquake

Buildings in the affected area consisted of non-engineered dwellings, as described in Section III and semi-engineered multi-storey (2 to 4) reinforced concrete frame buildings with non-seismic design and poor workmanship. Traditional timber frame structures are also present in the affected area and performed relatively better than the masonry construction. Analysis of performance and retrofit measures for timber structures is not the focus of this paper. The next section is, therefore, devoted to the suggested improvements to the structural details of non-engineered adobe/stone/URM buildings (mostly houses) for improving their life-safety.

VI. STRENGTHENING TECHNIQUES FOR ADOBE/STONE/URM

The idea of seismic retrofit of non-engineered buildings is that it should avoid incorporation of materials and construction techniques that are alien to the region. Improvements on the existing construction techniques are the best way for implementing a long-lasting and sustainable seismic safety and hazard mitigation initiative. The guidelines provided in this section are based on the results of analytical FEM study reported in Section IV, earlier work on this subject [8] and knowledge of construction practices in this area of Pakistan.

Walls are the primary gravity load as well as lateral load resisting elements in these structures. Therefore, the primary focus of most of the strengthening techniques is to enhance the integrity and capacity of the walls, to improve the integrity of the roof with the walls and to ensure that the collapse of walls and roof is prevented. Various methods to achieve this purpose are discussed in this section.

1- Connection of mutually perpendicular walls to enhance building integrity by tying the walls together. The tying is to be done by a material that has good tensile strength and ductility. It includes: (i) wire mesh reinforcing, (ii) use of polypropylene bands, (iii) use of corner stitches (L-stitch) made of reinforced concrete. Refer to Fig. 7 for salient details.
2- Install bond beam at roof level to tie together the walls and help to secure the roof with this beam. One example is shown in Fig. 8 for the case of brick masonry walls and reinforced concrete slab.

Fig. 7 (a) Roof band beam and wall L-stitches

Fig. 7 (b) Polypropylene band reinforcing

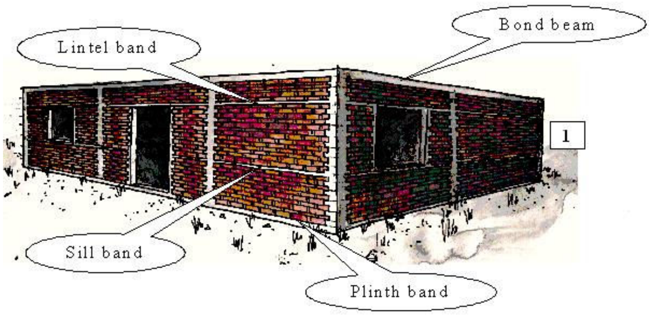

Fig. 8 Masonry confining structural elements

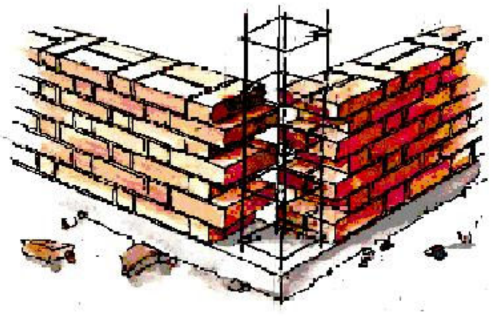

Fig. 9 Detail for improving wall connectivity

3- Secure the roof with the walls to prevent roof collapse and to improve the diaphragm action of the roof. This is achieved by providing a bond beam (or ring beam) at the roof level as discussed in item 2 and securing the roof elements to this beam.
4- Increasing the strength of the walls by using cement mortar, through stones, steel straps, wire mesh reinforcing, or a combination of vertical and horizontal steel reinforcement.
5- Construction of reinforced concrete columns with ‘teethed’ connections at corners and at intersection with perpendicular walls. The details are illustrated in Fig. 9. It is to be emphasized that this type of construction requires skills in concrete technology with proper attention to details for the reinforcing bars for enhanced seismic performance.

VII. CONCLUSIONS

Natural disasters are causing tremendous loss of life and property with earthquakes being the most serious risk. Loss of life in earthquakes mostly occurs due to collapse of buildings and non-engineered dwellings. Based on the results of an analytical study and evidence of damage to non-engineered construction in the past earthquakes, some important structural details are reviewed in this study which, based on engineering judgment and analytical results, can improve the life-safety of such structures in earthquakes. It is also to be emphasized that the curricula of most civil engineering schools hardly consider any teaching in the subject of non-engineered, traditional constructions which is also one of the reason for lack of improvements in the traditional construction technology to withstand extreme man-made or natural disasters.

REFERENCES

[1] UNDP. (2004). Reducing Disater Risk: A Challenge for Development. New York: United Nations Development Programme.
[2] Degg, M. (1992). Natural disasters - recent trends and future prospects. Geography, 77 (336), 198-209.
[3] OFDA/CRED. (2013). EM-DAT: The International Disaster Database. Louvain, http://www.em-dat.net/: Center for Research on the Epidemiology of Disasters.
[4] Spence, R., & So, E. (2009). Estimating shaking-induced casualties and building damage for global earthquake events. Cambridge, UK.: Cambridge Architectural Research Ltd.
[5] Coburn, A., & Spence, R. (2002). Earthquake Protection (2nd ed.). Chichester, England: John Wiley & Sons Inc.
[6] Blondet, M. G., Garcia, V., & Brzev, S. (2003). Earthquake-resistant construction of adobe buildings: A tutorial. EERI/IAEE World Housing Encyclopedia. Oakland, CA: EERI.
[7] Pollak, S. (2009). Earth building: participation and performance a locally tailored experiment. 11th International Conference on Non-conventional Materials and Technologies (NOCMAT 2009). Bath, UK.
[8] IAEE. (2001). Guidelines for Earthquake Resistant Non-Engineered Construction. Tokyo, Japan: International Association for Earthquake Engineering.