Assessment of Seismic Performance of Adobe Structures in Pakistan and Portugal

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SUMMARY:
Adobe buildings exist in different parts of the world. The construction of these buildings can be carried out economically, using locally available materials and skills that do not require use of modern machinery. Therefore, adobe buildings provide an economic housing option. The construction of adobe structures is carried out based on traditional construction practices which vary from region to region. This paper presents the results of a study which was conducted to study the construction practices of adobe buildings in Pakistan and Portugal in the context of their seismic vulnerability. The adobe buildings in both these countries were found to be subjected to seismic hazard levels which, although is low in some regions, may cause significant damages. Lack of essential elements or details for the adequate seismic performance was found in the adobe buildings in both regions.

Keywords: adobe, typologies, construction, earthquake, seismicity

1. INTRODUCTION

Soil has been an important construction material from ancient times. The history of human civilizations provides evidence that they have carried out various types of construction with soil (Blondet and Garcia 2004). The popularity of earthen structures is owing to the fact that their construction can be carried out economically using locally available materials and skills that do not require use of modern machinery. The existence of earthen structures in different countries around the world is indicated in the available technical literature (Korkmaz et al. 2010, Bakhshi et al. 2005, Fernandes and Correia 2005). This is no surprise that according to some estimates more than half of the world's population (including at least 20% of the urban and suburban population) presently live in earthen structures (Morris et al. 2011, Guillaud 2008, Houben and Guillard 1994, Baker 2011).

Adobe buildings exist in different parts of the world. The walls of these buildings are constructed with unfired bricks which, in most of the cases, are made up of a mortar of mud and straw. The former is prepared using a mix of clayey soil and water. The mortar is filled into moulds to prepare blocks which are left to dry in the air and sun. This is an ancient method of construction which dates back to 8000 B.C. (Houben and Guillard 1994). After the bricks are cured and dried they are laid in the walls and are joined together with a mortar with similar composition. Owing to their low construction cost these structures exist in many areas of low income population. In addition to economic factors, social and cultural factors, and availability of material locally also contribute to the existence of adobe structures (Gavrilovic et al. 1998). The construction of adobe structures is increasing in different countries such as Spain, France, Germany, Peru and North America (Vera and Miranda 2004). These structures are also termed as non-engineered structures since in many cases they are not built using engineering principles and/or practices.

Adobe is a weak material in tension and cracks easily when subjected to tensile stresses. Another weakness is also the low shear capacity of adobe material. Therefore, adobe buildings are vulnerable to lateral seismic forces as induced by earthquakes. The vulnerability of these buildings is found to be higher when compared to other types of earthen structures (Levtchitch et al. 2005) and adobe structures have performed poorly during many past earthquakes (Gavrilovic et al. 1998, Mahdi 2005, Hardwick and Jonathan 2010). Since a significant number of these structures are located in earthquake prone regions they pose a constant threat to the lives of their inhabitants. Detailed studies were carried out at the Catholic University of Peru (Blondet et al. 2004, Blondet et al. 2005, Blondet et al. 2006a and b, Blondet et al. 2008) to study the seismic behaviour of adobe structures. Nonetheless, technical literature on this subject is limited and more studies are needed in order to increase the level of understanding of the behaviour of adobe structures. Only a few design codes are, presently, available which are based on limited published work (Hardwick and Little 2010).

Like in many other parts of the world, adobe structures exist both in Pakistan and Portugal. The NED University of Engineering and Technology, Pakistan, and University of Aveiro, Portugal, are collaborating with each other to study seismic performance of adobe structures in the two regions. This paper presents a comparative study on the material used and methods employed in the construction of adobe buildings in Pakistan and Portugal. Northern region of Pakistan and city of Aveiro in Portugal were selected as case-study regions for the presented work.

2. HOUSING TYPOLOGY

2.1 Pakistan

Table 2.1 presents a distribution of housing typology in Pakistan which is based on the census data conducted in 1998 (PCO 2001). The data for five provinces, capital city (Islamabad), Federally Administered Tribal Areas (FATA) and Azad Jammu and Kashmir (AJK) are included in Table 2.1. The provinces include Baluchistan (BL), Gilgit-Baltistan (BG), Khyber-Pakhtoonkhwa (KP), Punjab (PB) and Sindh (SN). It is noted in Table 2.1 that a huge proportion of houses consists of rural housing types such as brick masonry, stone masonry, adobe and wood reinforced masonry. The total proportion of these housing types comes out to be 87%. Further, it is noted in Table 2.1 that adobe is the second largest housing type in Pakistan, after block masonry construction. The proportion of adobe buildings comes out to be 36% of all the building types in Pakistan.

Gilgit-Baltistan and Chitral lie in the northern part of Pakistan (Fig. 2.1). Adobe construction is prevalent in this part of the Country. Although with the passage of time construction of adobe structures has reduced, they are still popular owing to their low cost and excellent insulating properties. Local tradesmen have good expertise in the construction of adobe structures in these areas.

2.2 Portugal

The distribution of building types in Portugal is given in Table 2.2. These data have been obtained from (INE 2001)

Presently, according to global information from Aveiro municipality, about 25% of the existing buildings in Aveiro city are made of adobe. It is estimated that this percentage rises to 40% when referred to the entire district.

Recent studies (Silveira et al. 2010, Varum et al. 2011, Silveira et al. 2012) point to a higher percentage of adobe buildings in the Aveiro city. This percentage, of approximately 40%, is close to

Table 2.1. Housing Typology in Pakistan (PCO 2001)

Administrative Unit	RCC	Brick Masonry	Block Masonry	Stone Masonry	Adobe	Wood Reinforced Masonry	Misc
BL	4,887	65,433	12,924	20,467	588,802	106,638	42,213
FATA	286	44,988	5,229	42,967	185,580	5,809	13,035
GB	104	3,338	11,373	41,340	27,070	2,469	5,636
KP	31,356	577,394	61,456	375,900	539,586	40,072	39,696
PB	444,919	5,039,979	163,441	174,619	2,664,993	54,946	75,934
SN	419,811	604,108	619,837	39,310	1,510,318	633,629	72,333
IS	28,980	25,131	530	794	5,473	350	228
AJK	4,052	125,227	13,956	47,691	137,135	6,971	7,536
Total	934,395	6,485,598	888,746	743,088	5,658,957	850,884	256,611

Figure 2.1. Faults and recorded earthquakes around Gilgit-Baltistan

Table 2.2. Building Typology in Portugal (INE 2001)

Geographical area/region	RCC	Stone masonry with mortar	Adobe, rammed earth or loose stone masonry	Other
North	314,446	688,165	92,439	5,279
Centre	254,018	611,344	122,562	4,397
Lisbon	211,033	167,626	14,047	1,814
Alentejo	60,017	207,809	81,259	861
Algarve	69,838	65,915	23,809	981
Azores	26,509	47,431	12,155	1,490
Madeira	32,116	36,092	6,195	396
Total	967,977	1,824,382	352,466	15,218
District of Aveiro	69,788	129,791	25,760	967

the percentage of buildings registered in the census conducted in 2001 (INE 2001) as belonging to the categories “stone masonry with mortar" and "adobe, rammed earth or loose stone masonry", suggesting that both of these categories, in Aveiro, correspond, in fact, to adobe buildings.

It, therefore, is clear from the previous discussion that a significant number of adobe buildings exist both in Pakistan and Portugal.

3. SEISMICITY OF REGION

3.1 Northern Pakistan

Pakistan is situated at the triple junction of Arabian, Eurasian and Indian plate. The active fault system in the northern part of Pakistan is the result of a northward movement of the Indian plate towards the Eurasian plate. This collision of plates is taking place for the last 30-40 million years (Aitchinson et al. 2007). The Indian plate is being subducted beneath the Eurasian plate at a rate of about 45-50 mm/year (Besse et al. 1988, Rowley and Currier 2006, Aitchison et al. 2007). As a result, some of the world highest mountains, such as Pamir, Himalaya, Karakoram and Hindu Kush, have been created in this region.

The fault system around Gilgit-Baltistan is shown in Figure 2.1. It is noted in Figure 2.1 that the region is surrounded by several active faults. Hindu Kush and Pamir are considered to be seismically active regions (Nowroozi, 1971). The earthquakes of magnitude 5 and above in this region are also illustrated in Figure 2.1. These data have been taken from different sources such as International Seismological Centre (ISC), National Earthquake Information Center (USGS), Pakistan Meteorology Department (PMD), British Geological Survey (BGS), etc. No damage to adobe buildings due to earthquake has so far been recorded in the area. This may partly be attributed to the ground characteristics of this mountainous region.

3.2 Aveiro

In the last centuries, earthquakes with moderate and strong impact occurred in Portuguese territory. The 1755 earthquake, which is widely studied and reported internationally, was the latest big earthquake occurring in Portugal. This earthquake destroyed a great part of Lisbon and affects other cities of southern Portugal. Its effect in Aveiro region, however, was not important, and since adobe construction had, at that time, little expression in the region, there is no detailed information regarding damage suffered by this type of construction.

Portuguese standards (RSA 1983) came into force until the recent introduction of the Eurocodes divided the country into four seismic zones, designated by A, B, C and D, in descending order of seismicity. Aveiro district was located in zone C. The influence of seismicity was translated by a coefficient which equals 1 in zone A and 0.5 in zone C. Thus, Aveiro district is not located in the most critical zone in respect to seismicity; however, the associated risk is still considerable, especially because seismic effect on structures may be highly amplified for soft foundation soils, which are very common in this region. The recently published Eurocode 8 confirms the relative level of seismic hazard for the region of Aveiro.

It is evident from the previous discussion that present seismicity of the regions studied in both countries is not high. Nevertheless, the presence of active faults indicates that the regions are seismically prone and larger return period earthquakes may represent a high threat for the built environment and societies.

4. ADOBE CONSTRUCTION

4.1 Northern Pakistan

The adobe structures consist mainly of single story dwellings. Figure 4.1 shows a plan of a typical house in Chitral. The size of the house is dependent on the number of family members. The house comprises of a spacious living room in the middle. The standard size of the living room is 6.4x6.0 m.

The floor of the living room is divided into two elevated and one depressed sections. The depressed section is used as kitchen during winter while the elevated portions are used for dinning and sleeping purposes. The cooking in the living room provides heat to keep the room warm and reduces the need for heating. The living room serves as a multipurpose room, as well. In some cases, wooden floor is provided on the elevated sections in order to reduce heat loss through floor.

Access to the living room is provided through a lobby. A door is provided at the entrance of the lobby to avoid loss of heat from the house. The kitchen attached with the living room is utilised during summer only. A roof opening of 600x600 mm is usually provided in the middle of the roof of living room for sunlight. The other rooms are provided with windows and ventilators. Guest room may also be used as animal stable in order to keep the house warm during winter. A view of adobe house is shown in Figure 4.2. The details of adobe house construction are discussed in the forthcoming sections.

4.1.1 Adobe blocks

Adobe blocks are made of locally available clay, and straw is added both for stabilization and to control shrinkage cracks. In some places, apricot slurry is added in the mix as a binder material in order to increase the block strength. The ratio of different materials for the mix varies and is dependent on the experience of workers. Recent practice is to include cement and sand with the clay both for stabilizing the clay and to obtain better strength. The ratio of cement:sand:clay is either 1:1:8 or 1:1:10.

The blocks are made using wooden moulds. Two sizes of blocks are usually manufactured. These include 300x225x150 mm or 450x225x150 mm. The duration of sun drying of blocks is dependent on the season and weather conditions. During the bright sunny days of summer three weeks are enough for sun drying. It may take longer time in winter.

4.1.2 Foundation

The foundation of the house consists of a strip footing which is constructed of locally available rubble stone. The bearing capacity of the soil is generally high in this area which is a mountainous region. Therefore, the foundation is typically laid 1 m below the ground level. Since the area provides natural slope for rain water plinth level is kept not more than 600 mm above the ground level. The stone layer

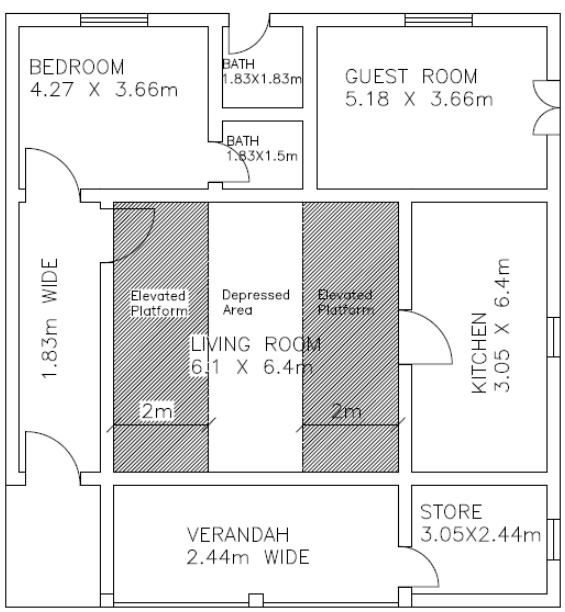

Figure 4.1. Plan of a typical house in Chitral

Figure 4.2. View of adobe house in Chitral

in the foundation could be up to 1.6 m deep. A damp proof course is provided at the plinth level in order to avoid seepage in the wall from the foundation through capillary action. For this purpose, a layer of mud mortar is spread on a plastic sheet laid over the stone layer. Recent practice is to provide a 50 mm thick layer of cement concrete instead of mud mortar.

4.1.3 Walls
The winter season in northern areas can vary from 6 to 8 months. As a result, the wall height is kept around 2.1-2.4 m, so as to reduce the heating requirement inside the house. The wall thickness is dependent on the placement of blocks. For the stretcher bond the wall is 275 mm thick whereas for the header bond the wall could be either 350 mm or 500 mm thick. Wooden beams are used at lintel levels.

The wall is plastered with mud mortar both internally and externally. Mud mortar is prepared by mixing apricot slurry with mud. The quality of plaster finish, however, normally is not good. Cement mortar plaster in some cases is employed in order to increase the quality of plaster finishing.

4.1.4 Roof
Generally the roof is made of wood and mud. Wooden rafters 100x150 mm or 100x125 mm in cross section are rested directly on the walls. Wooden planks are placed between rafters to fill the space. A layer of plastic sheet is provided on the wooden planks in order to avoid rain water seepage. Finally, a layer of fine soil is placed. Wood and soil being perfect insulators, protect inhabitants from severe temperature demands. In some cases, roofs are constructed using galvanized iron (GI) sheets supported on light wooden trusses.

4.1.5 Flooring
A mud layer is usually used as floor finishing which reduces loss of heat through the floor during winter. Local rugs made from sheep wool and goat hair are laid on the floor. These not only improve aesthetic aspects of the floor but also increase the floor capacity to trap the heat. Well-off families may opt for flooring made of wooden planks. This is provided on the mud floor layer.

4.2 Aveiro

In urban areas most of the buildings consist of one or two floors and, in rural areas, buildings with only one floor predominate (Silveira, 2010; Silva, 2010) (Fig. 4.3). Most buildings present simple geometry, with a rectangular geometry in plan, and regular configuration in height. The details of construction are discussed as under.

4.2.1 Adobe blocks
In Aveiro district, 'lime adobes' were produced since the nineteenth century until mid-twentieth century. These adobes consisted of coarse sand, generally with a moderated or reduced silt-clay fraction (Santiago, 2007), and lime, usually in a proportion of 25% to 40% (by volume). Adobes used in houses presented mean dimensions of 450×300×120 mm, and adobes applied in walls have mean dimensions of 450×200×120 mm.

At an earlier stage, before the production of 'lime adobes', 'clay adobes' were also produced, composed mainly of clay soils that were associated with sand, gravel and vegetable fibers (Santiago 2007).

4.2.2 Foundation
The foundations of adobe buildings are continuous, usually made of adobe masonry and less frequently of stone masonry.

Figure 4.3. Single and double storey adobe houses in Aveiro

Table 4.1. Details of Adobe Construction in Pakistan and Portugal

Element	Pakistan	Portugal
Blocks (mm)	300x225x150 150x225x150	450x300x120 450x200x120
Wall thickness (mm)	275-500	350-500
Foundation	Stone	Adobe
Roof	i) Wooden beams and mud ii) GI sheets and wooden trusses	Ceramic tiles, wooden structural systems
Flooring	Mud, wood	wood
Lateral Force Resisting System	No specifically defined	No specifically defined

4.2.3 Walls

Thickness of walls in adobe buildings depends on how the adobe units were placed. Walls built using stretcher bond are approximately 350 mm thick, and walls built using header bond are approximately 500 mm thick. Lintels usually consist of wooden beams or, sometimes, of arches made with stone, wood, ceramic bricks or adobes. The walls of buildings are generally plastered in the interior and exterior surfaces with mortar with composition very similar to the composition of the adobes. Often, the exterior surface of walls was covered with ceramic tiles, partially or totally.

4.2.4 Roof

The roofs of adobe buildings are generally sloped, with a support structure composed by wooden trusses, or other simpler structural systems, and covered with ceramic tiles.

4.2.5 Flooring

Slabs in adobe buildings are generally constituted by a wooden structure, covered by wooden flooring.

A summary of the presented details in the foregoing sections is given in Table 4.1. It was noted in the previous discussion that no special connection between wall and roof is provided in the adobe buildings, which is an essential point for providing box behaviour to help in resisting the lateral forces. It can be inferred that the adobe buildings both in Pakistan and Portugal lack a lateral resisting system for earthquake demands and may, therefore, be vulnerable to earthquakes, as discussed in the forthcoming sections.

5. DEFECTS IN ADOBE CONSTRUCTIONS

5.1 Northern Pakistan

Very few defects were noted in the adobe houses analysed. The detail of these is given as under.

1) Mud mortar used for plaster lacks good quality binding material and the plaster is abraded off with time.
2) Cracks develop in the walls after the load is transferred from the roof. This is an indication of low strength of adobe blocks.
3) Since the walls are not protected from the rain dampness is noted in the walls after heavy rainfall.

5.2 Aveiro

Frequently observed anomalies in adobe buildings are listed as under.

1) Cracking and degradation of adobe masonry and plasters;
2) Cracking in the area of connection of walls, particularly at corners;
3) Located crush, in areas of stress concentration;
4) Cracking near openings;
5) Settlement of foundations and excessive deformation of walls;
6) Blistering and detachment of plaster;
7) Stains and moisture;
8) Efflorescence and crypto-efflorescence.

Common causes for the verified anomalies are listed as under.

1) Presence of water associated with the phenomenon of rising dampness (capillarity) from the foundations;
2) Poor functioning of the roof;
3) Poor ventilation;
4) Aging and degradation of materials;
5) Use of very thick and inadequate plasters;
6) Excessive deformation of roof structural elements;
7) Settlement and movements of the foundations;
8) Deficient connection between walls;
9) High concentrated loads transmitted by structural or non-structural elements attached to the walls.

6. SEISMIC BEHAVIOUR OF ADOBE STRUCTURES

The seismic performance of a structure is dependent on the behaviour of diaphragm and walls constructed in the two orthogonal directions. In addition, connections of walls with each other and with diaphragm play a vital role in improving seismic resistance of a structure. The walls which are perpendicular to the direction of ground motion are subjected to out-of-plane forces. They may behave as vertical cantilever to which they may not have enough resistance. A good connection of the wall with the diaphragm may provide support and thus the wall spans between the foundation and the diaphragm. As a result, capacity of the wall against out-of-plane forces increases. It can be seen that failure of this connection, or its inefficiency, may result in out-of-plane collapse of the wall.

It is noted in the above discussion that the walls are not adequately connected with the diaphragm for many adobe structures both in Pakistan and Portugal. Since the roof directly rests on the walls it provides a loose connection between the roof/floor and the wall. As a result, the roof is unable to act as a diaphragm and, at the same time, lack of connection with the walls leaves them to act as vertical cantilevers.

At low intensity of ground shaking, the structure is subjected to low levels of stresses and box action can be provided by weaker adobe material. High shaking intensity increases the applied stress levels on the structure and may create cracks at different locations. These cracks may cause a separation in the building elements and can change behaviour of the structure. The loss of box behaviour, due to crack formation, allows the structural members to behave independently which may fail owing to low strength adobe material. The roof may translate as a rigid body and an out-of-plane failure of the wall causes the roof to collapse. This behaviour of roofs in adobe structures has been mentioned by several authors in the technical literature such as Afshar (1961), Ambraseys (1963), Omote (1965), Razani (1974), Maheri (1990), Korkmaz et al. (2010). Therefore, it may be inferred that many of these adobe houses lack adequate seismic capacity and are vulnerable to ground shaking during an earthquake. A quantitative assessment of vulnerability of these structures is vital in order to determine their strengthening needs. The authors are continuing work on this aspect for adobe buildings.

8. CONCLUSIONS

This paper presented the details of typical adobe construction in Pakistan and Portugal. The seismicity of the regions in the two countries where adobe buildings exist was found to be not high, at present. The construction details of adobe buildings revealed similarity in these methods. Since the construction methods and details in the adobe buildings are based on traditional practices, they may lack of a specific seismic force resisting system, in both countries. A quantitative vulnerability assessment may help in determining the need of seismic strengthening of these buildings.

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