Estimation of Losses for Adobe Buildings in Pakistan

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SUMMARY:
Adobe buildings are vulnerable to seismic forces. Large scale destructions and casualties have been caused due to the collapse of adobe buildings during the past earthquakes. A significant number of adobe structures exist in different parts of Pakistan, similar to other parts of the world. Since Pakistan lies in a seismic active region, it is necessary to assess the level of vulnerability of these buildings in order to estimate associated losses during a seismic event. This paper presents the results of a study which was conducted to quantify damages to adobe buildings based on their fragility curves. The adobe buildings were found to be highly vulnerable to low intensity earthquakes. The vulnerability of these buildings has been compared with the European adobe buildings. It was noted that Pakistani adobe buildings were slightly less resistant to earthquakes as compared to similar buildings in Europe. Retrofitting solutions were suggested in order to increase the seismic capacity of adobe buildings in Pakistan.

Keywords: adobe, fragility, losses, damage grade, earthquakes

1. INTRODUCTION

Adobe buildings exist in different parts of the world. These are classified as unreinforced masonry structures which are constructed with unfired clay bricks. The bricks are joined together with mud mortar. This is an ancient method of construction which dates back to 8000 B.C. (Houben and Guillard 1994). Adobe structures are mostly located in low income communities owing to their low construction cost. Other factors that contribute to the existence of adobe construction include social and cultural factors, and local availability of material (Gavrilovic et al. 1998). In addition, these structures have low energy requirement and they are environmental friendly (Islam and Watanabe 2004). 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). The construction of adobe structures is still observed 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 services.

Adobe buildings are vulnerable to lateral seismic forces as clay bricks are weak in tension and shear. The vulnerability of these buildings is found to be higher compared to other types of earthen structures (Levtchitch et al. 2005) and adobe structures have performed poorly during past earthquakes (Gavrilovic et al. 1998, Mahdi 2005, Hardwick and Little 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. There is an outstanding need to carry out more studies to increase 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).

The NED University of Engineering and Technology, Pakistan and the University of Aveiro, Portugal are collaborating on research related to the assessment of seismic safety of adobe structures in the two regions. This paper presents a study of determining seismic vulnerability of adobe structures in Pakistan. Possible methods of retrofitting for these structures have also been suggested.

2. SCOPE AND BACKGROUND

Like many other parts of the world, adobe structures exist in 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) (IS), Federally Administered Tribal Areas (FATA) and Azad Jammu and Kashmir (AJK) are included in Table 2.1. The provinces include Baluchistan (BL), Gilgit-Baltistan (GB), 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 building comes out to be 36% of all the building typologies in Pakistan. Figure 2.1 illustrates the proportion of adobe buildings in each administrative unit in Pakistan. It is noted in Figure 2.1 that, except the capital city, the adobe proportion in each of the administrative unit is more than 30%. Since the majority of population in Baluchistan and FATA lives in rural areas adobe buildings comprise of nearly 70% of all buildings in these parts of the Country. Although similar statistics are not available for many countries existence of significant number of earthen structures in these countries is indicated in the available technical literature (Korkmaz et al. 2010, Bakhshi et al. 2005). This popularity of earth structures is owing to the fact that construction of these structures can be carried out economically using locally available materials and skills that do not require use of modern machinery.

Seismic vulnerability refers to the damage potential of elements at risk due to lateral seismic forces. Seismic performance of an element can be judged by quantifying the vulnerability as a function of level of seismic hazard; this relation is termed as fragility relation or fragility curve. Fragility curves are required to estimate the probabilities of a population of structures reaching or exceeding various damage grades under a particular intensity of an earthquake. These curves define the probability that the expected damage of a structure, under various levels of seismic excitation, exceeds a given damage state. Rafi et al. (2012) presented the methods of construction of adobe buildings in Pakistan. This paper assesses the vulnerability of these existing adobe structures. Fragility curves for adobe buildings have been plotted and are compared with the adobe buildings in Europe. A review of different methods of developing fragility curves has been provided in the forthcoming sections. This is followed by the discussion both on the method adopted and the results obtained.

Table 2.1. Housing Typology in Pakistan

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

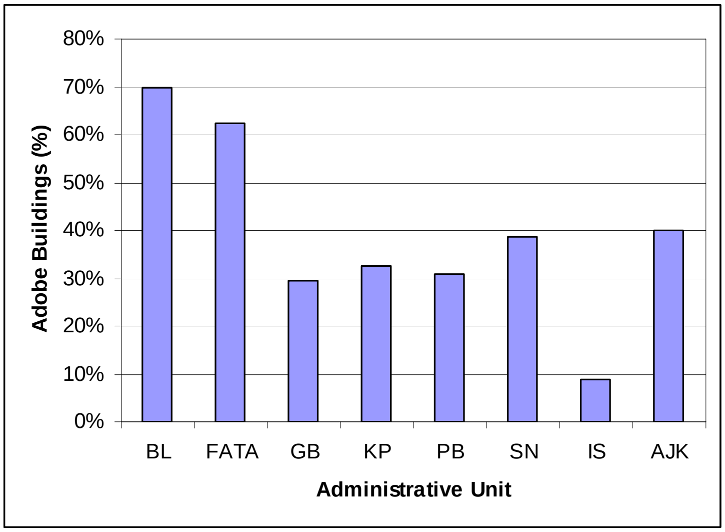

Figure 2.1. Proportion of adobe buildings in each administrative unit of Pakistan

3. METHODS OF FRAGILITY CURVE DEVELOPMENT

There are different methods available for developing fragility curves or damage probability matrices. These are discussed in the following.

3.1 Empirical Methods

Empirical methods are based on the information collected from the post-earthquake surveys. The data from these surveys is elaborated using statistical procedures. The damage data regarding each housing typology is obtained and employed to develop fragility curves or damage probability matrices. As a result, the most realistic data are used which account for the characteristics of entire building stock.

3.2 Judgment Based Methods

The judgment based fragility curves are derived on the basis of statistical treatment of the information provided by experts. Teams of experts provide their opinions on the previously defined average damage levels. The data are analysed and are sent back to the experts for their review of previously provided responses regarding damage level estimates. Experience and level of confidence in the responses of experts is also obtained using appropriately designed forms. The damage estimates are then fitted with some known probability distribution and are plotted against an intensity parameter. This method was employed to obtain damage probability matrices for many regions in the World. For example, the method was used for California and the results are summarized in ATC-13 (1985).

3.3 Analytical Methods

To develop the fragility curves using the analytical methods, numerical analysis of the structures is carried out. The results of the analysis are processed through statistical elaboration to develop the fragility curves. These methods are used when detailed information of structures is known. Analytical methods are employed for the vulnerability assessment of individual structures. As a result, the data are less biased as compared to those obtained from the earlier two methods.

3.4 Hybrid Methods

There are certain limitations in all the above mentioned methods as these methods are based on the single set of information. For example, the data at a particular ground shaking is elaborated using statistics associated to the empirical methods which may cause inaccuracies. For the judgment based methods, the results are based on the responses of individuals. The accuracy of individual's judgement (especially at higher intensity levels) may be difficult to be relied upon. In addition, the chances of human error in the opinion may over-rate their experience and could create misleading results. The mathematical models employed in the analytical methods have inherent modelling deficiencies in the procedures adopted. One of the deficiencies is a disagreement among researchers over the use of static pushover analysis versus incremental dynamic analysis for the prediction of building behaviour.

Hybrid methods provide an alternative in order to overcome these limitations. These methods use the information from different sources which is combined together to overcome the aforementioned limitations. Other use of hybrid methods is the integration of results of the analytical or the judgment based methods with the observed data from the earthquakes.

4. METHODOLOGY OF FRAGILITY CURVE DEVELOPMENT

A macroseicmic method proposed by Giovinazzi (2005) has been employed to develop fragility curves for adobe buildings in Pakistan. This method is based on empirical approach and relates the data of building damage from the previous earthquakes with the earthquake intensity in order to obtain damage probability matrices (DPM). DPM provides probabilistic prediction of damage from future earthquakes and can be represented as fragility curves.

The macroseismic method is developed on selecting earthquake intensity parameter and corresponding damage grades. The Modified Mercalli Intensity scale (MMI) is employed as a measure of earthquake intensity (Table 4.1) whereas damage grades (Table 4.2) were selected as defined by the European Macroseicmic Scale 98 (EMS-98) (Grünthal 1998). Giovinazzi (2005) suggested beta distribution to develop DPM as it was able to adequately control the data scatter in the reported building damage. This distribution is employed in the presented study.

For a continuous variable *x* which ranges between *a* and *b*, the beta probability density function (PDF) and the beta cumulative density function (CDF) are given as Eqns. (4.1) and (4.2), respectively

$$PDF: P_\beta(x) = \frac{r_{(t)}}{\Gamma_{(r)}\Gamma_{(t-r)}} \frac{(x-a)^{r-1}(b-x)^{t-r-1}}{(b-a)^{t-1}} \quad a \le x \le b \tag{4.1}$$

$$CDF: P_\beta(x) = \int_a^x p_\beta(y)dy \tag{4.2}$$

where *t* is equivalent mean; *r* is equivalent variance and Γ is the gamma function. The parameter *t* governs the distribution of scatter in such a way that increasing value of *t* decreases the scatter and vice versa. As a result, it helps controlling the scatter and brings it to the desired level.

The mean value of x (μ_x) and its variance (σ_x^2) are given by Eqns. (4.3) and (4.4), respectively

$$\mu_x = a + \frac{r}{t}(b-a) \tag{4.3}$$

$$\sigma_x^2 = (b-a)^2 \frac{r(t-r)}{t^2(t-1)} \tag{4.4}$$

Giovinazzi (2005) suggested that the values of *a* and *b* are taken as 0 and 6, respectively. μ_x is related to the mean damage grade (μ_D) as a third degree polynomial (Eqn. (4.5))

Table 4.1. Modified Mercalli Intensity scale

Intensity	Description
I	Not felt except by a very few under especially favourable conditions
II	Felt only by a few persons at rest, especially on upper floors of buildings
III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated
IV	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably
V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop
VI	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight
VII	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken
VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations
X	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly
XII	Damage total. Lines of sight and level are distorted. Objects thrown into the air

Table 4.2. Damage Grades for EMS-98

Damage Grades	Description
Grade 0 (D0): No damage	No structural and Non-structural Damage
Grade 1 (D1): Negligible to slight damage (no structural damage, slight non-structural damage)	Hair-line cracks in very few walls. Fall of small pieces of plaster only. Fall of loose stones from parts of buildings in very few cases.
Grade 2 (D2): Moderate damage (slight structural damage, moderate non-structural damage)	Cracks in many walls. Fall of fairly large pieces of plaster. Partial collapse of chimneys.
Grade 3 (D3): Substantial to heavy damage (moderate structural damage, heavy non-structural damage)	Large and extensive cracks in most walls. Roof tiles detach. Chimneys fracture at the roof line; failure of individual non-structural elements (partitions, gable walls)
Grade 4 (D4): Very heavy damage (heavy structural damage, very heavy non-structural damage)	Serious failure of walls; partial structural failure of roofs and floors.
Grade 5 (D5): Destruction (very heavy structural damage)	Total or near total collapse

$$\mu_x = 0.042\mu_D^3 - 0.315\mu_D^2 + 1.725\mu_D \tag{4.5}$$

The mean damage grade is also related to the parameters *t* and *r* as given in Eqn. (4.6)

$$r = t\left(0.007\mu_D^3 - 0.0525\mu_D^2 + 0.287\mu_D\right) \quad (4.6)$$

Giovinazzi (2005) proposed the relation between μ_D, vulnerability index (V), and ductility index (Q) (Eqn. (4.7)). Note that V is a measure of the ability of a building/building stock to resist lateral earthquake loading. The higher the value of V the lesser is the building resistance and vice versa. Giovinazzi (2005) suggested that the value of V is chosen between -0.02 to 1.02 for the European buildings. The ductility index describes the ductility of a building/building stock.

$$\mu_D = \left[1 + \tanh\left(\frac{I + 6.25V - 13.1}{Q}\right)\right] \quad (4.7)$$

Q in Eqn. (4.7) is taken as 2.3, as suggested by Giovinazzi (2005). The value of V is determined with the help of Eqn. (4.7) by back calculation using μ_D obtained from the 2005 Kashmir earthquake damage data. Similarly, r was calculated from Eqn. (4.6) using the same μ_D. The data for r, t, a, b and damage grade were combined in the beta function to develop DPM for the adobe buildings.

5. RESULTS AND DISCUSSION

The value of μ_D which was obtained from 2005 Kashmir earthquake damage data comes out to be 4.233. This was employed in Eqn. (4.7) which provided the value of V as 0.933 for the adobe buildings in Pakistan. Further, a value of t = 6, using some trial and error calculations, enabled to minimise the data scatter to the required level, as compared to the data obtained from the 2005 Kashmir earthquake. As a result, this value was employed in (Eqn. (4.6)) in the presented study.

Figure 5.1 illustrates the fragility curves for adobe buildings in Pakistan. These were obtained using the method as described earlier. In Figure 5.1, earthquakes of intensity less than V were not included as these do not correspond to any damage (Table 4.1). Similarly, damage state D0 was not considered as it is a "no damage" state (Table 4.2). It is noted in Figure 5.1 that the probability of damage increases with the intensity of earthquake, as can be expected. For example, at earthquake intensity VI, 79% buildings suffer damage grades between 2 and 4 whereas this percentage increases to 97% at earthquake intensity VII. Further, it is noted in Figure 5.1 that significant number of buildings can be damaged by low intensity earthquakes. For example, 3% buildings are expected to suffer damage state 5 (collapse) at an earthquake of intensity VII on MMI scale which is considered as a moderate earthquake. Similarly, at earthquake of intensity XII nearly 97% of adobe buildings may collapse and may cause significant human and property losses.

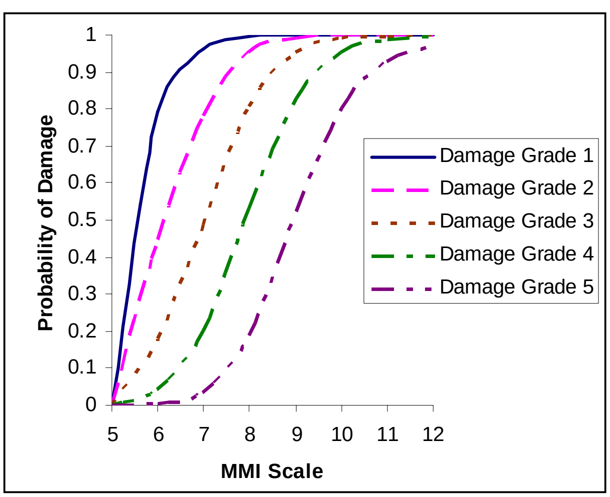

Figure 5.1. Fragility curves for adobe buildings

Table 5.1. Probability of Exceeding each Damage Grade

MMI	Damage Grades				
	D1	D2	D3	D4	D5
VI	84.7	52.5	23.2	6.2	0.5
VII	97.6	83.4	56.4	26	5.1
VIII	99.7	96.7	85.2	60.4	24.9
IX	100	99.5	96.8	86.7	59.6
X	100	100	99.4	96.4	84.1
XI	100	100	100	98.9	94.1
XII	100	100	100	99.6	97.7

Table 5.1 presents the probability of adobe buildings exceeding different damage grades at various intensity levels. It is noted in Table 5.1 that at an intensity of VI on MMI scale only 21% of buildings will escape damage and 79% buildings will be damaged to damage grade D1 which is considered as low damage grade. Further, damage in 45% of buildings exceeds moderate level damage (D2). Similarly, 18% of buildings will suffer substantial damage at damage grade D3. At an earthquake intensity of IX on the MMI scale, 100% of buildings will suffer damages of different grades.

6. COMPARISON WITH EUROPEAN ADOBE BUILDINGS

Giovinazzi (2005) suggested V, Q and t as 0.84, 2.3 and 8, respectively, for the European adobe buildings. These were employed to obtain DPM for the European buildings. Table 6.1 compares the results of damage probability for the European and Pakistani adobe buildings. It is noted in Table 6.1 that the damage probability of the Pakistani adobe buildings is high compared to European buildings. For example, at an earthquake intensity of VI 37% of European adobe buildings will remain intact as compared to 21% Pakistani adobe buildings. Note that Giovinazzi (2005) determined the vulnerability parameter for the European buildings as 0.84 which is 10% less than that for the Pakistani buildings (0.933). This indicates that the European adobe buildings could be 10% more resistant compared to the Pakistani buildings.

7. POSSIBLE RETROFITTING METHODS

The main objectives of seismic strengthening solutions for adobe buildings are: (a) to assure a proper connection between structural elements, which should provide a complete and continuous load path transferring the inertia forces to the foundation. In addition, the building works as a whole and instability and collapse of walls are avoided; (b) to strengthen and increase the capacity of walls.

Table 6.1. Damage Probability Matrices for Pakistani and European Adobe Buildings

MMI	Damage Grades											
	D0		D1		D2		D3		D4		D5	
	Pak	EU	Pak	EU	Pak	EU	Pak	EU	Pak	EU	Pak	EU
VI	15.3	37	32.3	39.8	29.3	18	17	4.6	5.7	0.5	0.5	0
VII	2.4	7.8	14.2	31	27	35.3	30.4	20.3	20.9	5.3	5.1	0.3
VIII	0.2	0.6	3	8.9	11.5	26.2	24.8	35.9	35.5	24.1	24.9	4.3
IX	0	0	0.4	1.1	2.7	7.5	10.1	23.8	27.1	41.1	59.6	26.4
X	0	0	0.1	0.1	0.6	1.2	3	7.1	12.3	26.9	84.1	64.7
XI	0	0	0	0	0.2	0.2	1	1.7	4.8	10.3	94.1	87.8
XII	0	0	0	0	0.1	0	0.3	0.5	1.9	3.6	97.7	95.9

Some of the effective seismic strengthening solutions that may be adopted in the context of adobe structures in Pakistan are listed as under:

1) Ring beams: These beams should be resistant, continuous, adequately tied to the walls floors and roof. The beams may be made of reinforced concrete, steel or wood (Arya 2000; Blondet 2003);
2) Ductile vertical and horizontal elements: These can be placed in the interior or on the surface of walls. The elements are generally made of steel, bamboo, cane or wood (Dowling 2002, Blondet et al. 2002) and should be properly connected together and to other structural elements;
3) Metallic or geosynthetic meshes: These are applied to the surfaces of walls and should be adequately tied to other structural elements (Meli et al. 1980, Blondet et al. 2003, Varum et al. 2011);
4) Buttresses and pilasters: These increase the stability and strength of the structure when used in critical areas, and are habitually made of masonry, reinforced concrete, steel or wood (Dowling 2002).

8. CONCLUSIONS

This paper presented the results of a study which was carried out to estimate damages to adobe buildings in Pakistan. Fragility curves for adobe buildings were developed. The method employed an empirical approach, as suggested in the technical literature. The results indicated that adobe buildings in Pakistan are vulnerable to low intensity earthquakes. A comparison of vulnerability of these buildings with the European adobe buildings is made. Pakistani adobe buildings were found to be slightly (10%) more vulnerable than the European adobe buildings. Possible retrofitting methods for Pakistani adobe buildings are also suggested in the paper.

AKCNOWLEDGEMENT

The authors wish to acknowledge the support provided by Earthquake Model for Middle East (EMME) for this work.

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