STRUCTURAL PROPERTIES OF ADOBE DWELLINGS IN CUSCO (PERU) FOR SEISMIC RISK ASSESSMENT

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Abstract

This paper looks at the structural properties of adobe buildings in Cusco, Peru, for use in seismic risk assessment.

The geometrical properties (typology) of adobe dwellings from Cusco have been established according to a building-by-building survey. Cusco has been chosen for this study as, according to the national census, around 80% of the building stock in this town is constructed with adobe.

Furthermore, this region of the country is relatively seismically active and thus seismic risk assessment studies are warranted. Additional structural information of adobe buildings has been obtained from experimental tests carried out at the Catholic University of Peru. These tests have allowed the inter-storey drift capacity and the period of vibration of adobe buildings to be derived.

A database containing the principal geometrical properties of 30 dwellings has been created which has allowed the mean, standard deviation and probability density functions (PDF) to be defined for each parameter such as storey height, wall length, etc.

These properties are of use in a recently proposed probabilistic displacement-based earthquake loss assessment method (DBELA) which generates random populations of buildings based on this input data. The structural capacity of each random building is then predicted based on structural mechanics principles, and by comparing this capacity with the demand from earthquakes, estimates of the probability of damage can be made.

1. INTRODUCTION

The collapse of adobe buildings due to earthquakes has caused considerable loss of life in many third world countries. Adobe buildings are constructed with dry earth which is the least expensive construction material and often the only one available to much of the world's population in rural areas (Bariola and Sozen, 1990). The high seismic vulnerability of earthen buildings is due to an undesirable combination of the mechanical properties of dry earth: 1) earthen structures are massive and thus attract large inertia forces, 2) they are weak and cannot resist these forces, and 3) they are brittle and break without warning (Blondet *et al.,* 2006). Each time a strong earthquake strikes in areas where earthen buildings are common, there is widespread damage to historical monuments and housing and tragic loss of life due to the collapse of these constructions. Recently, this has been seen in Pisco city (Peru) during the earthquake of Mw 8.0 on August 17, 2007, where more than 500 people died and more than 37 500 dwellings collapsed, where the majority of them were constructed in adobe.

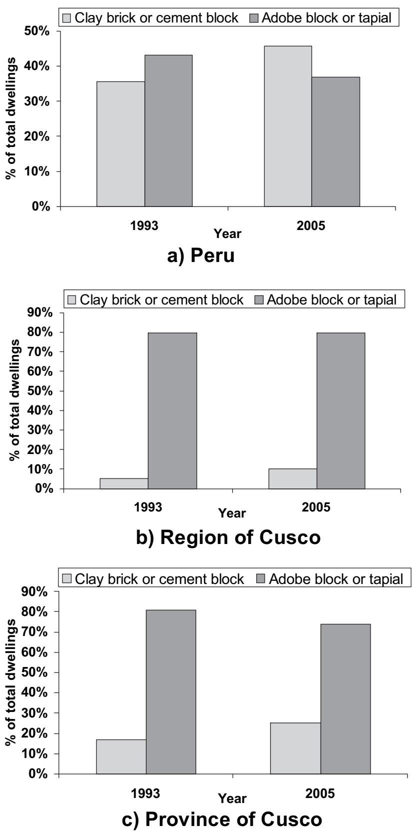

Figure 1. Percentage of adobe and clay brick masonry buildings in 1993 and 2005 (source: INEI 2005).

Adobe dwellings are widespread in the Peruvian highlands because adobe is a traditional material and low cost. Furthermore, it has good thermal properties; it retains the warmth of the environment during the day and releases it at night and thus the house remains warm even in seasons with low temperatures.
In Peru the total number of earthen dwellings (adobe and tapial) still forms an important percentage of the total number of Peruvian houses (INEI, 2005), and the authors believe that the majority of these are constructed in adobe, as opposed to tapial (rammed earth). According to the last census (INEI, 2005), earthen buildings have decreased from 43% to 37% at a national level (Figure 1a) from 1993 to 2005. However, the

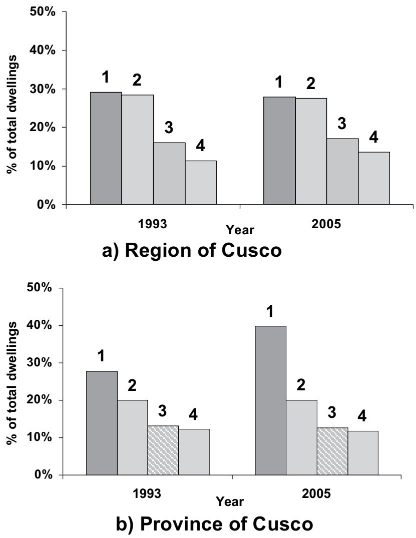

Figure 2. Number of rooms in adobe dwellings (source: INEI 2005).

region of Cusco (with more than 1 171 500 inhabitants) maintains almost 80% of earthen houses (Figure 1b), though the percentage in the province of Cusco (which has around 348 500 inhabitants) has decreased slightly from just over 80% in 1995 to around 72% in 2005 (Figure 1c). Despite this slight reduction, it is clear that in Cusco people build with adobe as a principal material and with clay bricks as a second material.

There is no statistical data about the quantity of adobe houses of one or more storeys in Cusco. However, it can be seen from Figure 2 that the majority of adobe houses has 1 or 2 rooms. Indirectly it may thus be concluded that these houses, or at least the majority of them, will have only one level. Considering this assumption, in the region of Cusco more than 50% of adobe dwellings have 1 storey (see Figure 2a). However, this number increases at a provincial level, where the value reaches almost 60% (see Figure 2b).

According to Carazas (2001) the rural zone in Cusco (*i.e.* the periphery of the city) has a huge pre-Hispanic influence. This means that the adobe dwellings have only one level, with two rooms, one of which is used for social activities, such as cooking or eating, and the other is generally used as a bedroom. The entrance is defined with an opening between the two rooms. Figure 3 shows some examples of typical rural adobe houses in Cusco.

Considering the high concentration of adobe buildings in Cusco, as well as the moderate seismic hazard (see Figure 4), this town has been selected for a building-by-building survey to determine the structural characteristics of these buildings. The seismic hazard map showed in Figure 4 has been calculated by Tarque (2008) taking into account the site conditions in Cusco, and gives the peak ground acceleration (PGA) for a return period of 475 years.

This paper looks at how the structural data required for the displacement-based earthquake loss assessment methodology (DBELA) have been derived. The DBELA

Figure 3. Rural adobe houses in Cusco (Blondet *et al.*, 2004) (figures by authors).

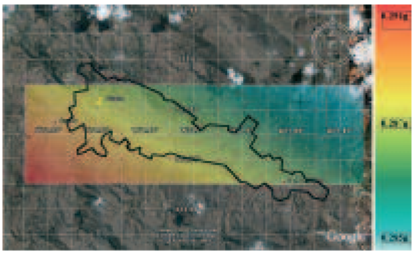

Figure 4. Seismic hazard map for Cusco – peak ground acceleration for a return period of 475 years (Tarque, 2008) (figure by authors).

method makes a comparison between the displacement demand and the displacement capacity of a random population of buildings at increasing levels of seismic intensity (Crowley *et al.*, 2004). The random population of adobe buildings used in DBELA is generated with Monte Carlo simulation based on probabilistic distributions of the geometric and material properties which are defined *a priori*.

The displacement capacity of the buildings is estimated for different damage states as a function of the failure mechanism and the geometric and material properties of the buildings. The typical geometric properties of adobe buildings in Cusco are presented in Section 2 whilst the drift capacity of adobe buildings estimated from experimental tests are presented in Section 3. The period of vibration of the buildings is also required in this methodology, as the displacement demand is function of this structural property. The equations derived to estimate the period of vibration are presented in Section 3.

2. GEOMETRICAL PROPERTIES

Blondet *et al.* (2004) carried out a building survey in Cusco and collected information from 30 adobe buildings (see Tarque, 2008 for photos of these buildings). The available data which was collected included the dimensions of walls and bricks, the height of the gable, number of rooms, number of openings, etc, were collected and then organized in tables. With that data it was possible to define the mean values and standard deviations of these geometrical properties.

Table 1a shows the properties of the walls. It was found that the mean wall thickness of adobe buildings in Cusco is 0.44 m, and the mean wall height is 2.45 m for one storey buildings and 4.88 m for two storeys buildings. These mean heights have been calculated without considering the height of the gable. The thickness of the wall is fairly uniform amongst the buildings analysed, confirmed by the low standard deviation (0.04 m). It is important to remark that in other Peruvian cities, especially those located at the Peruvian coast, the wall thickness of the adobe dwellings is around 0.25 m. This result in slenderness values (height/thickness ratio) greater than 9, which increase the probability of collapse, principally associated to out-of-plane mechanisms. The adobe houses in Cusco have slenderness ratio values around 6 and thus may be less susceptible to out-of-plane collapse. According to the Peruvian Adobe Code (NTE E.080, 2000), walls with slenderness ratio equal or less than 6 require just a top crown beam as a reinforcement. However, walls with slenderness ratio greater than 6 require horizontal and vertical reinforcement.

a) Wall dimensions

	Thickness (m)	Height (m) 1 storey	2 storey
Mean	0.44	2.45	4.88
SD	0.04	0.21	0.38

b) Adobe blocks

	Length (m)	Width (m)	Thickness (m)
Mean	0.44	0.21	0.15
SD	0.04	0.02	0.01

c) Gable, opening and room dimensions

		Openings				Room	
	Gable	Door		Window		Length	Width
	(m)	Width (m)	Height (m)	Width (m)	Height (m)	(m)	(m)
Mean	1.33	1.08	1.80	1.08	1.80	5.38	4.53
SD	0.18	0.18	0.15	0.18	0.15	1.10	0.59

Table 1. Geometrical properties (table by authors).

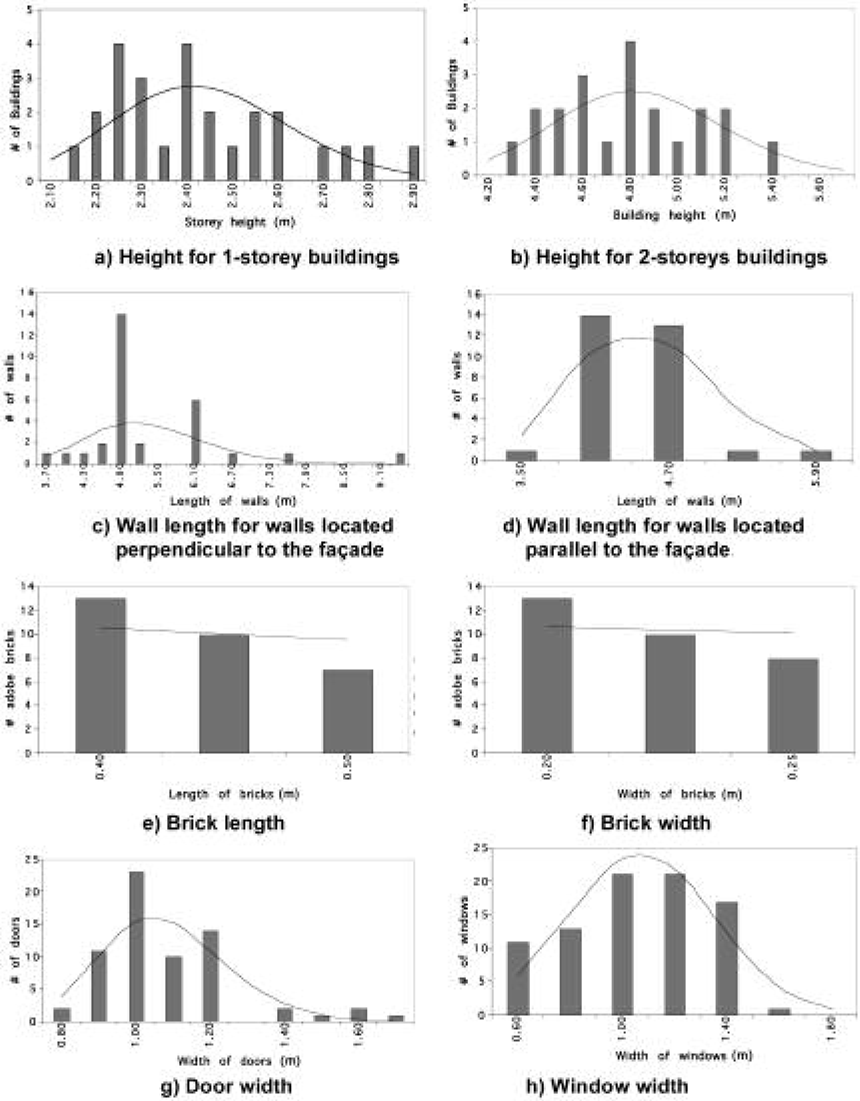

Figure 5. Histograms and PDFs of some geometrical properties (figure by authors).

Table 1b shows the average dimensions of the adobe blocks. The mean length, width and thickness of the blocks calculated are 0.44, 0.21 and 0.15 m, respectively. Table 1c shows the mean and standard deviation values for the gables and the dimensions of the openings. Also, the average values of the length and width measurements for a typical adobe room are shown. The mean gable height has been found to be around 1.33 m, the dimensions of the doors are 1.08 m (width) and 1.80 m (height) and the dimensions of the windows are 1.07 m (width) and 1 m (height). Typically the rooms have dimensions in plan of 4.53 x 5.38 m^2. The variability of each of the parameters in this study (i.e. walls length, adobe bricks dimensions, etc.) can be represented by histogram plots which can then be fit to a probability density function (PDF). Figure 5 shows the histograms and the best-fit PDF for some of the geometrical parameters presented previously.

From the 30 adobe dwellings, there were 25 buildings of two-storeys and 5 buildings of one-story. The building height of 4 of the two-storey buildings was missing; this meant that data from only 21 buildings was used to produce Figure 5b. To evaluate the mean and standard deviation values for the height of the walls of the one storey-buildings, data from the 2 storey-buildings was added; this resulted in 26 values of height used to produce Figure 5a.

It seems that normal or lognormal probability density distributions can represent fairly well the height of the buildings. The width of the windows and doors whilst the brick length and width probability distributions are fairly uniform. Neither the normal nor the lognormal distribution fit well the length of the walls in the direction perpendicular to the façade (Figure 5c), or the length of the walls placed parallel to the façade (Figure 5d). However, it is noted that a different histogram may be obtained if the data are grouped considering different interval sizes.

3. MATERIAL AND DYNAMIC PROPERTIES

In 2005, a displacement controlled cyclic test (push and pull test) was carried out on an adobe wall at the Catholic University of Peru (PUCP) by Blondet *et al.* (2005). The

a) Cyclic test (Blondet et al., 2005) **b) Dynamic test (Blondet et al., 2006)**

Figure 6. Tests carried out at the Catholic University of Peru (figure by authors).

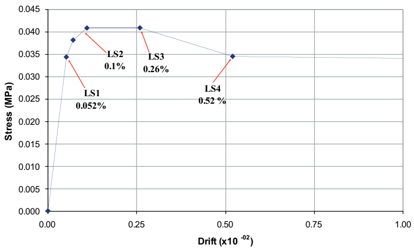

Figure 7. Capacity curve derived for the adobe wall subjected to in-plane forces (figure by authors).

wall had an I-shape configuration (see Figure 6a) and it was built over a reinforced concrete foundation beam. At the top, a reinforced concrete crown beam was built to provide the gravity loading corresponding to the roof of a typical dwelling. In 2006, a dynamic test was performed over the unidirectional shaking table of the PUCP on a full-scale adobe module (Blondet *et al.*, 2006, see Figure 6b), as with the previous test, the module was built over a reinforced concrete foundation beam.

Based on the cyclic test performed on the wall specimen shown in Figure 6a, four limit states of damage have been obtained (Figure 7). Until 0.05% drift, the structure can be considered as elastic (LS1), which means fully operational. After that level of drift, the structure can have some cracks but is still functional (LS2) until 0.1% of drift. Then, the life-safety performance (LS3) is reached at 0.26% of drift and, finally, the structure is considered near to collapse or collapsed at 0.52% of drift.

Additionally, the elastic stiffness *k* was obtained from the capacity curve (Figure 7) and with this parameter it was possible to calculate the elasticity modulus *E*. The Young modulus was found to be around 135 MPa. With the weight of the wall (135 kN) and with the elastic stiffness it was calculated the elastic period of vibration, based on the equation of a SDOF system. The period estimated is T_y= 0.15 s. From the dynamic test (Figure 6b), a period of vibration of around 0.16 s was obtained directly from a free vibration test.

The periods of vibration obtained from the experimental test results were compared

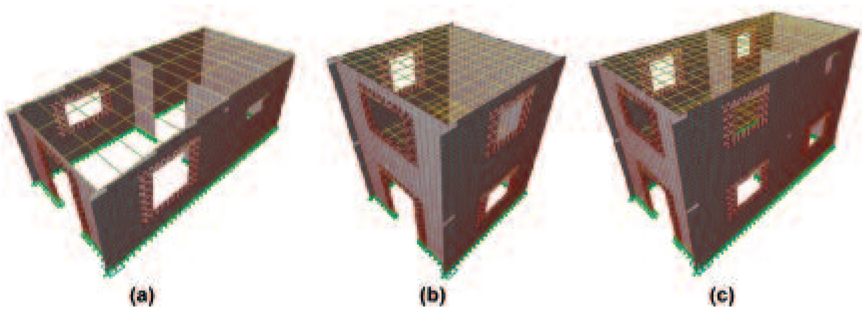

Figure 8. Analytical model for (a) 1-storey building with two rooms (b) 2-storey building with two rooms and (c) two storeys building with four rooms (figure by authors).

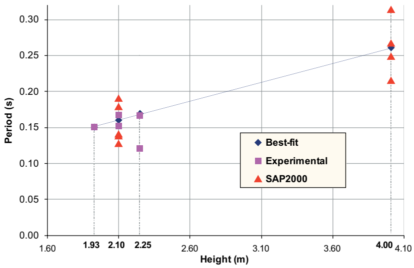

Figure 9. Vibration period versus building height (experimental and analytical data and best-fit regression curve) (figure by authors).

with the results of numerical analyses performed with the structural program SAP2000, for different configurations of adobe buildings (see Figure 8). A reduced Young modulus, *0.6E*, was used for the computation of elastic vibration periods, considering that at the first limit state the adobe walls were already cracked due to shrinkage, changes in environmental conditions, lack of maintenance, etc. Analytical models with different heights and with different configurations (considering the data obtained in Section 2) were developed to study the influence of these parameters in the variation of the vibration period. The vibration periods obtained with the experimental tests and with the analytical models are plotted in Figure 9, as function of the building height. As can be observed from the analysis of Figure 9, a strong correlation between the period of vibration and the building height was observed.

A best-fit regression analysis was applied to the data shown in Figure 9 to obtain a vibration period versus building height, H, formula of the form $T=\alpha H^{\beta}$, which led to the following expression: $T_y=0.09H^{3/4}$. The values of vibration period given by the correlation founded is higher than the formula proposed in many codes around the world for masonry buildings (which is often taken as $T=0.05H^{3/4}$), because this formula was obtained from the measured vibration periods of load-bearing wall buildings at low levels of ground shaking and has been calibrated to underestimate the period by 10-20% so that higher forces will be predicted from the design acceleration spectrum, which is inversely proportionally to period (Goel and Chopra, 1998). However, the period of vibration which has been derived in the current study is a cracked period of vibration which is to be used for assessment, and thus a realistic prediction of the expected period of vibration is required.

4. CONCLUSIONS

This paper has looked at the structural properties of 30 adobe dwellings in Cusco, Peru, as well as, the experimental results of adobe building specimens constructed and tested on a reaction floor/frame system and on a shaking table at the Catholic University of Peru. The data from these buildings have been used to create representative values (mean, standard deviation and probabilistic distribution) of various structural parameters (such as storey height, wall length, brick dimensions) to describe how they vary within a population of adobe buildings. These statistics can then be used to create random hypothetical populations of adobe buildings for use in seismic vulnerability assessment.

Some interesting data which has arisen from this study includes the slenderness value of adobe walls from buildings located in Cusco, which is close to 6 and thus much lower than the values found in typical adobe buildings at the Peruvian coast region. Hence, the out-of-plane vulnerability of these adobe buildings should be less than that which was observed in the recent earthquake in Pisco, in 2007.

Results from experimental tests and from analytical models of adobe buildings have also been used to study the period of vibration of adobe buildings, as a function of its height, H, leading to the following relationship: $T_y=0.09H^{3/4}$. This relation gives vibration periods of vibration of around 0.15s for 1 storey adobe buildings, and around 0.25s for 2 storey adobe buildings.

The geometrical data derived herein and the period of vibration equation has been applied in a seismic risk assessment for Cusco region, carried out by Tarque (2008). The results show a moderate risk to out-of-plane damage (a mean annual probability of significant damage of approximately 0.6%) with a higher risk from in-plane failure (a mean annual probability of significant damage of approximately 3%). Future studies should consider cost-benefit analysis where the cost of repairing such damage is outweighed by the cost of retrofitting.

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Curriculum

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