A Study into the Earthquake Resistance of Circular Adobe Buildings using Static Tilt Tests

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Abstract

Many unreinforced adobe or mud-brick structures have in the past suffered severe damage from seismic forces and have caused a vast number of deaths. However, some adobe buildings located in seismic regions have performed well under several seismic events. Most of these traditional buildings are symmetrical in shape which has significant bearing on the performance of the buildings during strong earthquakes. Most existing and typical circular adobe houses have performed well in withstanding earthquakes even though some did not have any additional ductile reinforcement.

This paper presents the first series of tests conducted to study the performance of unreinforced circular adobe buildings subjected to earthquake forces. Nine small-scale models (1:3 scale) of adobe structures were built with a variety of configurations and roof loads. Static tilt tests were carried out to evaluate the seismic performance of this type of structure. The adobe house models were subjected to a constant acceleration when tilted on a tilt-up table. The lateral component of model weight was used as a parameter to quantify the maximum seismic force for each model. The results were then used to develop a methodology for designing circular adobe buildings to resist earthquakes in specific seismic zones and for specific site conditions.

Keywords: Adobe construction, mud-brick, earthquake resistance, circular building, tilt table test.

1. INTRODUCTION

Adobe or mud brick construction or sun-dried earth block is one earthen technique that has been known for more than nine thousand years (Minke 2000). However, the earthquake performance of this type construction is generally poor and has caused a vast number of deaths. The low tensile strength of the earth material is the primary cause of building damage which results in both shear and flexural cracking. A high likelihood of serious injuries and loss of life in earthquakes usually accompanies local or general collapse of the adobe structures (E. Leroy Tolles, et al. 2000).

Comprehensive earthquake damage statistics from around the world serve as clear reminders that research to improve the earthquake performance of adobe buildings is urgently needed. On the other hand, there are some historical earthen buildings which had withstood several seismic attacks in recent centuries such as the Hakka houses in China, the Bhunga houses in India, the Yomata houses in Malawi, and rammed earth buildings in Argentina. These existing earthen houses used different construction techniques and they were all of a circular shape. It seems that the building proportions may also be a significant determining factor of the seismic resistance of a building. Mauro Sassu (n.d.) states that the circular floor plan of vernacular buildings offers the best resistance to seismic forces, however, a box shape building creates troubles with out-of-plane forces and separation at the wall corners. Minke (2001) indicated that building with a square plan had better seismic performance than a rectangular one, and the circular plan had better seismic resistance than the square one. There is also a similar outcome from part of this research indicating a circular plan had better seismic performance that a square plan when tested using the tilt-up method.

Therefore, this study focuses on exploring the seismic resistance of circular adobe structures. Static tilt-table tests were carried out to investigate the failure modes of circular adobe structure and its failure mechanism. The aim is to gain better understanding of the earthquake performance of circular adobe building, to predict the performance of existing circular adobe houses in seismic regions, and to provide design recommendations for circular structures located in specific seismic zones and in specific site conditions. This research contributes to reducing the vulnerability of adobe houses from earthquake activities.

2. CONSTRUCTION DETAILS OF ADOBE TEST WALLS

Nine small-scale circular models (1:3 scale) adobe structures were built with a variety of configurations and roof loads. The bricks and mortar were made of the same raw material using combinations of raw soil, rice husk and sand with the selected mix of 2:2:1, respectively (Uthai Phat Ra Kun 2004). Bricks were laid in stretcher bond with

10-12 mm thick mortar joints. Compressive strength test was carried out to determine unconfined compressive strength of adobe specimens (Walker & Standards Australia 2002). The average unconfined compressive strength was found to be 667 kPa. The tested specimens were unreinforced. The specifications of all specimens are shown in Table 1.

Table 1: Small scale adobe models: specifications

Model set	*Wall thickness (mm)*	*Diameter (m)*	*Wall height (m)*	*Roof height (m)*	*Roof load pressure (kN/m^2)*	*Total roof load (kN)*	*Total wall load (kN)*
1A	31	1.2	0.82	0.94	2	2.25	1.56
2A	31	1.2	0.82	1.00	3	3.38	1.55
3A	31	1.2	0.82	1.06	4	4.51	1.55
2B	45	1.2	0.82	0.94	2	2.25	2.23
3B	60	1.2	0.82	0.94	2	2.25	2.93
2C	31	1.4	0.82	0.94	2	2.25	1.82
3C	31	1.0	0.82	0.94	2	2.25	1.29
2D	31	1.2	0.96	1.08	2	2.25	1.82
3D	31	1.2	0.67	0.79	2	2.25	1.27

3. STATIC TILT TABLE TESTING

A static tilt-table was set up to evaluate the seismic performance of this type of structure. The static tilt table was constructed with 5 mm steel plate of dimensions 1.5 x 1.5 metres with checker plate floor surface on top. A hydraulic floor jack was installed in order to lift the tilt table with the maximum model load of 2,000 kg.

3.1. The relationship between the static load method and tilt table

In the tilt-table method the structure is subjected to a constant acceleration (due to gravity load) when tilted-up by a tilt table. The horizontal force in this case (*HF*) is equal to the weight of the structure times the sine of the tilt angle as given by the following equation:

$$HF = \sin\theta \times W \tag{1}$$

Figure 1 shows the weight of the model (W) transforming to lateral force (HF) when tilted at θ angle.

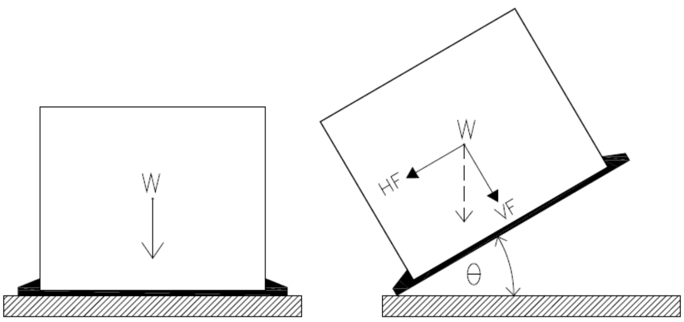

Figure 1: Concept scheme of the static testing.

Therefore, the failure angle from the tilt tests can be indicated as the ultimate horizontal force for each model.

3.2. Procedures of the static tilt-table tests

The test began once the constructed specimen was totally dry. The roof cover made from ply wood was installed on which sand bags were placed to reach the required load on the model's wall. All sand bags were laid in the same direction. The test was recorded by a number of video recorders. The table was slowly and smoothly raised by a hydraulic jack until the adobe model collapsed. The collapse angle was recorded in order to compare the results with other model tests.

Figure 2: Roof and sand bags installation.

Figure 3: Tilting the specimen until cracking and subsequent failure.

4. RESULTS

The tilt-table testing confirmed a typical failure pattern of the circular adobe structures of cracking through the mortar and brick interface causing a transverse tensile failure in-plane of its wall, which should happen to the structure in a real earthquake. The tests also enabled a comparison between the various configurations of circular specimens. The angle of the tilt table at which the first cracking appears is used to calculate the maximum lateral force. Table 2 gives the results of the static tilt-table tests.

Table 2: Results of the static tilt testing

	CASE #1A	*CASE #2A*	*CASE #3A*	*CASE #2B*	*CASE #3B*	*CASE #2C*	*CASE #3C*	*CASE #2D*	*CASE #3D*
First crack Angle (degrees)	29	25	21	30	32	31	29	28	34
Percentage of the max. horizontal force compared to model own weight	45.4	42.2	37.4	49.9	52.9	52.9	43.8	42.2	54.5

It can be seen from Table 2 that the configurations and roof loads of circular adobe buildings had a significant effect on their earthquake resistance. The specimen with lighter roof load has shown better earthquake resistance than the heavier one, as expected. The specimen with smaller height-to-thickness ratio also showed better earthquake resistance than those with greater height-to-thickness ratio.

It was clear from observations that most of the first shear cracking appeared at the side of the wall, starting from the top of the wall. The other cracks occurred when the table was further tilted. The model rapidly collapsed when the front part of the wall tended to rotate about X’ and separated from the rest of the model (Figure 4). The typical failure mechanism of the circular models in the static tests can be summarized as: the failure starts from the top of the wall and then rotates about point X’ at the bottom of the front wall, the front wall collapses, followed by the rest of the wall. Based on this observation, the failure criteria can be set up by taking moments of all forces about point *X’*.

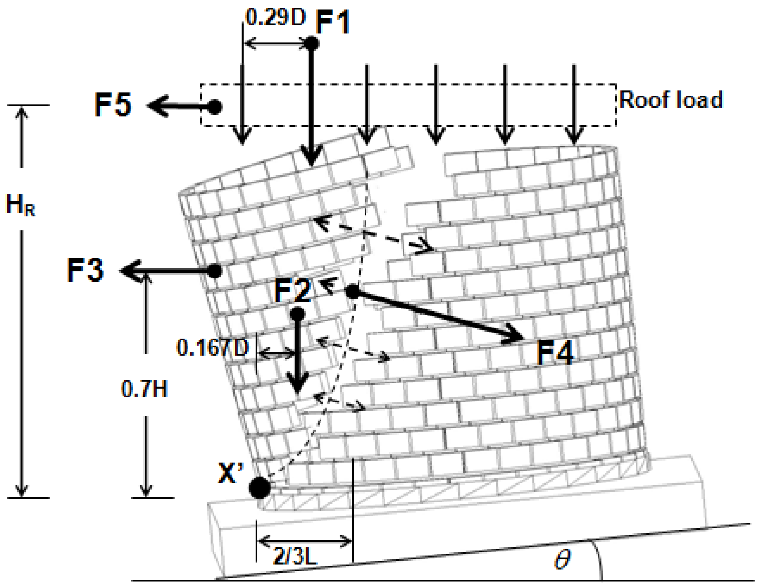

Figure 4: Failure analysis of the circular adobe specimen

Referring to Figure 4, taking moments of forces F1, F2, F3, F4 and F5 about X' gives the following equation:

$$\frac{W_W}{3}\sin\theta \times 0.7H + W_R \sin\theta \times H_R = \frac{1}{2}W_R \cos\theta \times 0.29D + \frac{W_W}{3}\cos\theta \times 0.167H + \frac{2}{3}\left[(\frac{D}{2})^2 + H^2\right] \times f_t \times t \quad (2)$$

Where

f_t = tensile strength of blocks corresponding to the thickness of wall. f_t = 35 kPa, 27 kPa and 25 kPa for the 31mm, 45mm and 60mm of the wall thickness respectively. According to the scaling effects, the increase in mortar strength and bond strength between the mortar and brick compared to the prototype behaviour.

t = thickness of the wall

D = Diameter of the model wall

H = Height of the wall

W_W = Weight of the model wall

W_R = Weight of the roof load

H_R = Height from the base of model to the centre of roof load

Using Equation (2), the predicted failure angle can be calculated, and they are compared with actual "first-cracking" angle in Table 3.

Table 3: Results of predicted angle compared to the first cracking angle

	CASE #1A	*CASE #2A*	*CASE #3A*	*CASE #2B*	*CASE #3B*	*CASE #2C*	*CASE #3C*	*CASE #2D*	*CASE #3D*
First crack	29	25	21	30	32	31	29	28	34
Predicted Angle	28.5	21.7	17.9	29.8	33.4	31.8	25.5	28.6	29.4

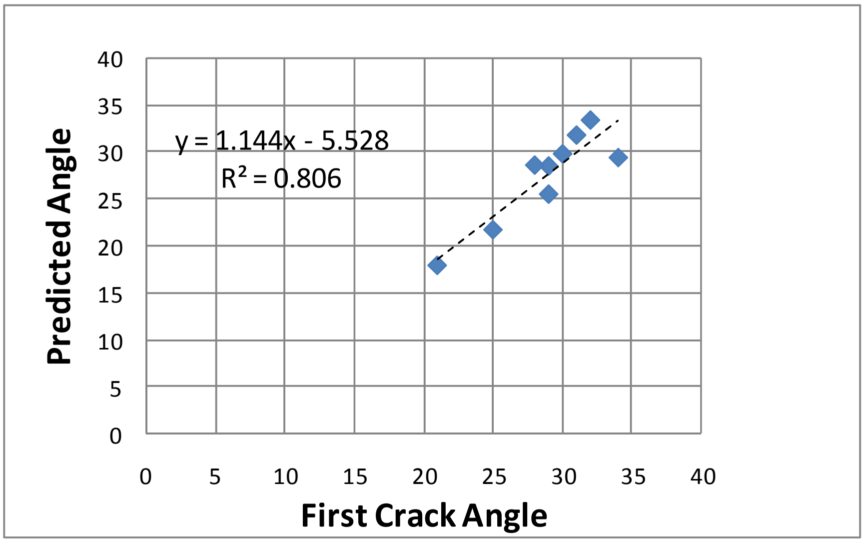

Figure 5: Variation between the first crack angle and the predicted angle.

Figure 5 is a plot of data from Table 3 which shows a good correlation between the first cracking angle of the specimens and the predicted angle from the calculation. The correlation coefficient is 0.806. The failure mechanism of circular adobe structures was clear for shear cracking depending on its tensile stress. The tilting test provided detailed information for the seismic behaviour of circular adobe models at relatively low cost and in a short time frame compared to dynamic testing methods. Therefore, it is reasonable to use this simple methodology to evaluate the seismic resistance of circular adobe structures.

5. CONCLUSIONS

The static tests presented above have shown that the assumed failure mechanism is a relatively good predictor of actual performance under static horizontal loading. This research finds that buildings with a heavier roof load and higher aspect ratios were more vulnerable to earthquake forces. The result of this research can be used to evaluate the existing circular adobe houses and can give design recommendations of suitable configurations for new circular adobe buildings.

Further research is being developed to link this to equivalent static design loads for various earthquake scenarios in order to provide a simple design methodology for circular adobe structures in earthquake regions. The accuracy of this approach will be examined by dynamic testing of a number of scale models later in 2010 using a shake table in order to reproduce the dynamic conditions of a real earthquake.

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