Seismic Performance of Mud Brick Structures

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Abstract

There has been no previous research that directly compares mud brick and traditional clay fired brick walls under seismic loading. Current design methods for mud bricks recommend a similar approach as for fired clay bricks; however it is possible that the materials act quite differently. This paper outlines the proposed methods for comparing the two materials based on preliminary tests that have been carried out and shows how the research can be applied in practice.

Mud bricks

Importance for Seismic Research

The use of unfired clay bricks, more commonly known as adobe construction, can be dated back to 8000BC (Houben & Guillard 1994) and it is estimated that one third of the world’s population live in mud brick structures. They are common in countries such as Latin America, Africa, Indian subcontinent, other parts of Asia, Middle East and Southern Europe, many of which are hazardous areas being in earthquake zones.

Adobe structures are typically low cost and built from readily available material by local communities. An adobe construction usually consists of sun dried mud bricks joined with a mud mortar, with the material obtained in the local vicinity. As the structures are normally built without the input of an engineer or an architect, they are described as “non-engineered” buildings. Mud brick structures are also becoming increasingly more popular in Western countries due to their green credentials and chic design.

Adobe structures are believed to have a very poor performance under seismic loading and it is coincidental that the seismic zones seem to follow the distribution of mud brick dwellings quite well. As a large proportion of the structures are located in earthquake zones, when there is an earthquake there is often massive amounts of destruction, and usually a large loss of life. At present there are few engineering design codes available for the design of mud brick structures and those that do exist are based on little published experimental evidence1. A summary of recent earthquakes affecting adobe dwellings is summarized in Table 1 below.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Fatalities</th>
<th>Adobe Buildings Collapsed</th>
<th>People Displaced</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Salvador, 2001</td>
<td>1,100</td>
<td>150,000</td>
<td>1,600,000</td>
</tr>
<tr>
<td>Peru, 2001</td>
<td>81</td>
<td>25,000</td>
<td>36,000</td>
</tr>
<tr>
<td>Bam, 2003</td>
<td>26,000</td>
<td>85%</td>
<td>60,000</td>
</tr>
</tbody>
</table>

Table 1: Earthquake Data (ref. Adobe Construction, Marcial Blondet and Gladys Villa Garcia M., 2003)

This project seeks to improve current knowledge of the seismic performance of mud brick structures, which will in turn move a step forward in improving the safety of such dwellings.

Scope of Project

Current design methods for mud bricks recommend a similar approach as for fired clay bricks. However, it is possible that adobe and traditional bricks and mortar behave quite differently under seismic loading due to different comparative strengths and stiffness’s. The main reason differences between fired bricks and mortar and unfired earth bricks, are that the strength in fired bricks is due to a fired clay matrix, while the strength of unfired earth bricks is thought to result from liquid bridges between the soil particles (Jaquin, 2009). The principle objective of the project will be to determine how the two different walls behave and if there are any similarities.

The aim of the project is to gain empirical data which will allow the development of guidelines based on sound engineering principles, modelling and physical testing, which could become the benchmark guide for this type of construction. Such guidelines would be used by field engineers and local masons in both disaster relief and long term reconstruction projects.

There has been no previous research that directly compares the behaviour of traditional clay fired bricks to mud bricks, although there have been numerous studies into the behaviour of mud brick walls under seismic loading and how to retrofit them.

1 There are currently a few basic design codes available in New Zealand, India and Australia.
The following is a list of a brief overview of projects carried out within this field which have been used to gain background information:

**Reports on Adobe Projects**

- Getty Seismic Adobe Project (Tolles et al, 1996)
  
  Between 1990 and 1996 the Getty Conservation Institute carried out an investigation into different methods that could be employed to retrofit buildings of historical or cultural importance. The project studied existing adobe structures, recent earthquake damage, experimental shaking tests and new retrofitting techniques.

- Quake Safe Adobe

A project run by Dr. D Downing of the University of Technology, Sydney, investigated the behaviour of adobe structures. The information was gathered from studies in Latin America and Pakistan and from experimental work in laboratory conditions. The main focus of the project was to find inexpensive retrofitting methods for adobe structures in developing countries.

**Previous Research Projects**

- Increasing the Collapse Time of Non-Engineered Masonry During Earthquakes

A report carried out by Redman and Smith (2009) looked into unreinforced masonry buildings. The study investigated different methods of retrofitting structures using inexpensive techniques. In order to test the different techniques Extreme Loading for Structures (ELS) was used to simulate the structures under seismic conditions.

**Construction Manuals**

- Guidelines for Earthquake Resistant Construction of Non-Engineered, Rural and Suburban Houses in Afghanistan (HABITAT, 2006)
  
  A set of guidelines written by UN-Habitat recommending effective construction methods for the construction of new structures. The guide looks into various key points such as location, size, shape and different construction methods including reinforcements.

- Adobe Reforzado (Blondet, 2007)

The manual includes a step by step guide explaining how to design and build an adobe structure. This includes how to mix the material for the bricks and the mortar mixture. This work was the result of around 30 years of work carried out by Marcial Blondet at the Catholic University in Peru and was based on shake table tests, and was updated to aid reconstruction following the Pisco earthquake of 2007.

**Case Studies**

- Collapse from the Inside Out (Langenbach, 2003)

An investigation into the 2003 earthquake in Iran. The paper looked into whether the amount of damage, to the citadel of Bam, had been increased by previous restoration works. The structure had been built around 2000 years ago and has withstood many earthquakes but it was severely affected by the 2003 earthquake.

**Test Methodology**

The following methodology for the tests has been adopted

**The Bricks**

All the bricks for use in the experiments have been supplied by Ibstock. Ibstock are a UK based brick manufacturer with a plant on the outskirts of Bristol and all the clay for the bricks is sourced in a quarry at this location. This ensures that the composition and size of all the bricks is kept constant. There were two sets supplied, a fired set and an unfired set. Before construction of the brick wall, the unfired bricks will undergo two weeks of air drying; this is to simulate the sun drying the bricks in real life. The dimensions of the bricks are 110X110X55mm which represents a quarter scale of the actual bricks.

**The Mortar**

The mortar consists of clay powder, the same as that used in the brick manufacturing process, mixed with water. The mix for each wall is ten parts powder to three parts water and each batch will be mixed for three minutes with a plaster mixer.

**The Walls**

The walls will be constructed using standard construction methods, with a Running Bond used throughout the wall. The mortar bed thicknesses will be set between 5 and 6mm with the same gap between the bricks. All the walls shall be constructed on the same base which consisted of a square steel frame made from channel section. The channel section is filled with concrete to give the base of the wall a good foundation. This roughly simulated the lightly mortared stone foundation used in the real world.
The walls will be constructed in a “U” shape as seen in Figure 1. They will be a 1:4 scale model of a wall section of a real house. In order to ensure that the results collected from the fired brick walls and the unfired walls can be compared the size of the two walls needs to be kept roughly constant. As the bricks differed in size by around 10mm, it is possible to get the overall size of the two walls within 3mm of each other by adding another brick to the fired brick wall.

**Instrumentation**

In order to collect and compare any data from the walls the instruments will need to be placed in the same location for each wall. As the walls differ in size very slightly the datum will be taken at the bottom centre of the wall. The instruments are then placed at the points show in Figure 2 measurements from the datum.

Three SETRA accelerometers will be used on the front of the wall along with three, one on each axis of the table. The SETRA’s will have their own predetermined calibration that can be used in the interpretation of results. Three Linear Variable Differential Transformers (LVDT’s) will be used on the back of the wall in order to see differential movement between the three points.

In addition to the instrumentation on the wall the experiments will be filmed with high speed cameras. This will allow frame by frame video analysis ensuring that crack propagation and failure patterns can be seen.

**Preliminary Tests**

The tests that have been carried out thus far consist of a number of exploratory tests on the shaking table on an unfired brick wall. The wall was shaken using a randomly generated signal produced by a spectrum analyser. The purpose of the exploratory shakes were to determine ‘order –of–magnitude’ values for parameters such as natural frequency and to resolve any issues found that would skew the results of any further tests.

Computer modelling software has also been used to find the theoretical value of the natural frequency, so that it can be compared with the results gained in the laboratory tests. The model was created using finite element package Oasys GSA. In order to create the model, a number of properties had to be obtained including the Young’s modulus and the density of the mud bricks, from empirical tests. An approximate value for the Young’s modulus was obtained through a compression test, with the load and displacement values plotted on a stress vs. strain graph.

**Proposed Tests**

Further tests to be carried out include;

- Sine waves shake in the X-axis. This will be carried out on a fired and unfired wall. This shake will give a clearer understanding of how the wall is reacting to the seismic activity.

- An earthquake with increasing strength over time. Again this will be carried out on a fired and unfired wall. This experiment should give insight of how the failure propagates through the walls.

- Finally a full force earthquake carried out on an unfired wall and a fired wall. This will show how the wall would react in real life situation.

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Panel Presentation: Habitat  
Author: Joseph Hardwick & Jonathan Little  
Institution: University of Bristol
Preliminary Results

The wall was constructed using the method outlined above, although cracks were visibly present on the wall and a noticeable amount of shrinking had occurred prior to testing.

*Figure 3* shows the extent of the shrinkage, with a five pence coin placed beside shrinkage gap to highlight the size. The shrinkage was a result of inadequate drying of the bricks prior to construction, which subsequently occurred once the wall had been built. As a result of this the base of the wall had generally become debonded from the concrete base thus allowing it to rock when the base input motion was applied. After an initial exploratory shake, it was evident that the wall was moving about the base so it was therefore decided to clamp the wall returns down before carrying out anymore testing. Subsequently the wall appeared to be significantly more rigid and there was no apparent sign of rocking although there may still have been some sliding between the foundations and the base of the wall.

**Natural Frequency**

*Figure 4* shows the values of natural frequency obtained for the wall. *Figure 4a* shows that the natural frequency obtained without the wall clamped down is 22.0Hz. *Figure 4b* shows the natural frequency of the wall with the back clamped increased to 43.8Hz. *Figure 4c* shows how the natural frequency of the wall increased further with an increase of amplitude from 2mm/V to 5 mm/V to 63.5Hz.

As expected the natural frequency of the wall increased when the wall returns were clamped down. However the increase in natural frequency with the increase in amplitude was not expected. The variation in the results could be due to variable boundary conditions of this wall and a sensitivity of this material to amplitude of excitation and these possibilities will be explored more in future tests. Initial data from FE modelling of the walls has suggested that the natural frequency of the wall should be about 38.4Hz.

*Figure 3: Shrinkage of wall (Photo taken by J. Hardwick)*

*Figure 4: Graphs showing natural frequency (Graphs produced using Matlab)*

A: Unclamped Wall
B: Clamped 2mm/V
C: Clamped 5mm/V
Failure Pattern

As shown in Figure 5 the wall has failed in a typical ‘V’ shape following the lines of the mortar. The ‘V’ shape pattern would suggest that the wall is behaving like a homogeneous unit. This was further reinforced by a number of cases where the bricks had cracked in half rather than following the mortar lines, as a traditional masonry wall would behave.

Figure 5: Photo of V shape failure pattern (Photo taken by J. Little)

Conclusion

The results gained from the tests have given a preliminary insight into how the mud brick walls are behaving and that they possibly do behave as a homogenous unit. However, the results may have been affected by a number of factors, such as the cracking outlined earlier, which may have influenced the behaviour of the walls. As a result of this, no firm conclusions can be made from the data obtained to date.

Putting the Research into Practice

Modelling

The research is being carried out on scale models taken from advice given in a number of construction manuals for mud brick housing. This means that the model should behave in a similar manner to the real life structures. In order for the results to be applied to full scale models, they need to undergo scaling factors that have been determined in the past using experimental testing and rigorous mathematical derivation. This process used is outlined by Harris and Sabnis (1999).

Tests will be carried out on both the fired and unfired walls, to allow a direct comparison to be made. This will mean that any difference due to scaling factors should be eliminated.

Limitations

There are a number of limitations using this research to give guidelines for real world construction. These include:

- The way in which the bricks are dried in the lab may differ to reality. The drying of the unfired bricks is at a constant rate as the temperature and humidity in the lab is well regulated and the dry time is kept to 2 weeks. To compare, in practice the drying will all depend on the weather and timings could differ for different bricks.

- In the lab tests the construction of the wall is done with small tolerances as the bed thicknesses are checked during the construction process along with the brick spacing. This is unlikely to be carried out so rigorously in the field as it can be very time consuming.

- The unfired bricks that are used in all the experiments have uniform properties as they have been mass produced in a controlled environment by Ibstock. The bricks used in the field may have different properties as they are generally made by hand using locally sourced materials.

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2 Dimensions of the wall were taken from Neumann, J.V. Torrealva, D. And Blondet, M. (2007), Adobe Reforzado, Fondo Editorial. Catholic University, Peru.
Acknowledgements

Financial support has been provided by the IStructE and their contribution of £500 has helped with the purchase of construction materials and equipment required for the walls. Ibstock (UK brick manufacturer) have very kindly donated a mixture of approximately 2000 fired and unfired clay bricks, as well as providing us with some raw clay material to produce the mortar with. This generosity has enabled us to save a large amount of time which can be used effectively, rather than slowly producing the bricks through a traditional method. Furthermore, as the bricks were all manufactured by machine, they are therefore of roughly the same size, material, density and moisture content allowing consistency throughout the project. This project also builds on PhD work by Dr Paul Jaquin who has undertaken a large amount of work on rammed earth structure and is now acting as an advisor for the project along with Dr James Norman. Finally we thank Dr Adam Crewe for his guidance throughout the project and for the use of Bristol University shaking table facilities.

References

Blondet, M. and Garcia, G.V. 2003, Adobe Construction, Catholic University of Peru, Peru
Langenbach, R. 2004, The impact of the 2003 bam, Iran earthquake on the earthen architecture of the arg-e Bam, Earthquake Spectra, EERI, Oakland, California
Redman, T. and Smith, A. 2009, Increasing the Collapse Time of Non-Engineered Masonry During Earthquakes, Research Project, Bristol University UK
United Nations Human Settlements Programme (HABITAT) 2006, Guidelines for Earthquake Resistant Construction of Non-Engineered, Rural and Suburban Houses in Afghanistan, Kabul