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VULNERABILITY OF ADOBE BUILDINGS UNDER EARTHQUAKE LOADING

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ABSTRACT

Adobe walled buildings are used quite widely in the developing world. Recent earthquakes have caused severe damage often leading to collapse of these buildings. This paper outlines an experimental investigation undertook at the Cambridge University on the performance of adobe walls under strong earthquake loading as well as some simple improvement techniques that can improve their seismic performance. The main aims of this investigation were to; 1. Develop model scale adobe walls and joints; 2. Carry out 1g shaking table tests on the adobe walls with and without improvements; 3. Develop guidelines for improved seismic resistance of adobe buildings.

Collapse of the models had to be as realistic as possible if the improvements were to be tested effectively, therefore accurate modeling was the focus of the first part of this project. The second part of this project involved testing proposed improvements on 1:5 scale model corner joints on a 1g shaking table. The failure accelerations of the improved models were then compared to the performance of an unimproved model. There were three successful improvements tested, the use of steel reinforcing bars, the use of a wire mesh cage and the use of a mesh made of plaited plastic carrier bags.

The main conclusions drawn from this project were: Improvements must be cheap and simple as the majority of adobe buildings are found in poorer areas; and improvements must increase the tensile strength and ductility of the model not just the bonding properties of the mortar.

Keywords: Adobe walls, Earthquake loading, Physical modeling, Seismic resistance

INTRODUCTION

Earth is one of the oldest construction materials used by man and it is estimated that 50% of the populations of developing countries live in some form of earth made construction. Adobe is readily available and cheap and as such will continue to be used by the poorer populations of the world (Blondet et al, 2003).

Adobe construction performs very poorly under seismic loading. The reasons for this are four-fold:
1. Adobe has a high mass to strength ratio.
2. The brittle nature of adobe leads to a sudden and catastrophic collapse.
3. Generally engineers and architects are not involved in this type of construction.
4. There is often a lack of maintenance on these types of buildings.

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As the majority of the occupants of adobe buildings are not from wealthy backgrounds any proposed techniques to improve seismic performance must be cheap. Proposed improvements must also be simple to implement as there are not normally the use of skilled tradesmen in the construction process.

Figure 1: Typical Collapse of Adobe Buildings in the 2001 Bhuj Earthquake, Choudhary et al (2002)

Adobe construction is used throughout India and the 2001 Bhuj earthquake destroyed many buildings. Typical collapses can be seen in Figure 1.

MODEL TESTING AND SCALING LAWS

If joints were to be modeled properly and improvements tested effectively then it was critical that unimproved walls were weak enough to fail within the peak acceleration capacity of the shaking table. Thus a dimensional analysis was performed to assess a suitable scale. The variables and dimensionless groups for this problem are shown below. Where σ = stress, t = time, ρ = material density, E = Young's modulus, a = horizontal acceleration and l = length.

$$\sigma = f\left\{t \quad , \quad \rho \quad , \quad E \quad , \quad a \quad , \quad l\right\} \tag{1}$$

$$\frac{\sigma}{E} = f\left\{\frac{t}{l}\sqrt{\frac{E}{\rho}} \quad , \quad \frac{al\rho}{E}\right\} \tag{2}$$

Note that gravitational acceleration is neglected in the above analysis. Adobe buildings are nearly always single storey thus the stresses induced by gravity are assumed to be negligible when compared to the stresses induced by the lateral accelerations caused by an earthquake.

Dimensionless groups should have the same value in the model and prototype. Assuming that E and ρ are constant in the model and the prototype gives $a_r=1/l_r$, where subscript r denotes the ratio between the model and the prototype scales. This means the shaking table must have the capacity to model accelerations $1/l_r$ times greater than those experienced by the prototype. Thus it was clearly beneficial to build the model as large as possible to ensure collapse was attainable within the 1.02g acceleration capacity of the table. Model size was only constrained by the size of the table thus a 1:5 scale was chosen.

MODEL COMPOSITION

It was critical that the composition of the model was similar to real adobe buildings. In reality the collapse of adobe buildings are sudden due to the brittle nature of adobe. After collapse all blocks would come apart from the mortar as there would be no suction in the mortar once the walls had dried out. Suction is caused by negative pore pressures in the clay due to partial drying. Adding sand to the model mortar produced a drier mix and thus reduced suction in the model mortar. This led to a realistic brittle collapse.

Composition of the models was based on real adobe structures. Thus, gravel was used to simulate blocks and mortar was made up of kaolin clay plus sand. The exact amounts of each material was determined through a series of experimental tests:

1. Compression tests and a shear box test on samples of varying composition were used to assess the shear strength of various combinations.
2. Further to this a series of shaking table tests were carried out on 1:5 scale single walls tested in-plane and transverse to the direction of shaking. This ensured that the collapse mechanisms of the walls were accurate and that complete collapse occurred well within the capacity of the table. Realistic failure mechanisms are: shear cracking for the in-plane wall; toppling of the transverse wall.

PERFORMANCE OF THE UNIMPROVED MODEL

Before improvements were assessed a control test was carried out. The 1:5 scale model corner joint was subjected to a series of shakes at increasing ground accelerations.

The corner joint had dimensions such that it was made up exactly of the single wall tests performed. Construction took 2 days and the model was allowed to dry for 5 days. It was anticipated that the failure should be between 0.32g and 0.49g (the failure accelerations for the in-plane and transverse walls when tested alone). The transverse wall should have failed first either at the corner or by toppling if it was to mimic the behaviour of full size adobe buildings.

Table 1: Performance of unimproved joint

Displacement (mm)	**Frequency (Hz)**	**Peak Acceleration (m/s^2)**	**Comments**
2	4	0.13g	No Damage
5	4	0.32g	Total Failure of Transverse Wall

Figure 2a,b: Joint model before testing

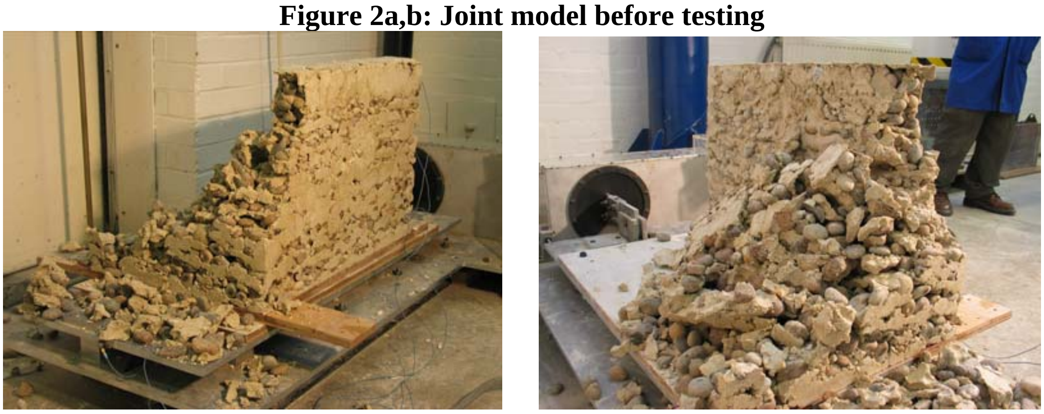


Figure 2c,d: Collapse at 0.32g

Failure occurred by the transverse wall rotating about the corner causing a vertical crack to open up. This was deemed to be total collapse even though part of the in-plane wall was still standing because if this was a full size building the roof would have inevitably collapsed at this point. Also the wall failed in such a way that it would have crushed any inhabitants of the building. The failure was at 0.32g – the same as the single transverse wall tested which failed by toppling.

PERFORMANCE OF THE IMPROVEMENTS

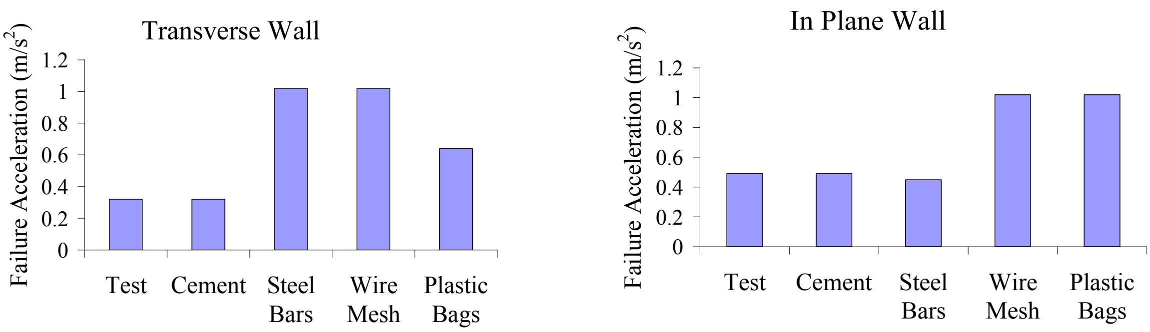


Figure 3: Summary of the performance of the improvements tested

Improvement A: the addition of 2% cement

The addition of 2% cement to the mortar was an attempt to increase the bonding properties of the mortar and thus make the model stronger.

2% by weight of the mortar mixture was Ordinary Portland Cement. Other than this the composition of the model was identical to the unimproved model. The performance of the 2% cement model is summarised below. Photographs of the failure can be seen in Figure 4.

Table 2: Performance of Improvement A: Addition of 2% cement

Displacement (mm)	Frequency (Hz)	Peak Acceleration (m/s^2)	Comments
2	4	0.13g	No Damage
5	4	0.32g	Total Failure of Transverse Wall

Figure 4: Failure at 0.32g

Even though the addition of cement probably increased the strength of the mortar there was no increase in failure acceleration. This may be because there was no increase in ductility and as such the failure mechanism of the transverse wall rotating about the corner was not remedied. Thus the failure occurred in an identical way and at exactly the same acceleration as the unimproved model.

Thus is can be concluded that the addition of 2% cement does not aid the seismic performance of real adobe buildings as an increase in strength alone is insufficient to increase the failure acceleration of a building, but an increase in ductility and tensile strength is required.

Improvement B: The Use of Steel Reinforcing Bars

The addition of reinforcement is an accepted way of improving the seismic performance of adobe buildings and as such there have been several research projects in this area, for example research at the Catholic University of Peru which is discussed below. Malton (2005) also tried to improve seismic performance of adobe using reinforcement.

Figure 5: Reinforcement Details

In this test a combination of "L" bars and vertical bars were used at the corner. Bars used were 10mm in diameter, and a total of length 5.82m was required for the 1:5 scale model. It was hoped that the "L" Bars would resist the rotation of the transverse wall about the corner and that the vertical bars would resist the toppling mechanism of the transverse wall. The bars were bent and tied together first, 10mm holes were bored in to the wooden base and the straight bars hammered in, to mimic embedding in the foundations. The wall was then built up around the bars as normal.

The bars used were: 3No. 380 x 200 x 10mm Ø "L" Bars, 3No. 330 x 150 x 10mm Ø "L" Bars, 6No. 440 x 10mm Ø Bars.

Table 3: Performance of Improvement B: Use of reinforcing bars

Displacement (mm)	Frequency (Hz)	Peak Acceleration (m/s2)	Comments
3	4	0.19g	No Damage
5	4	0.32g	No Damage
6	4	0.39g	Moderate damage to unreinforced in-plane wall
7	4	0.45g	Collapse of unreinforced in-plane wall
10	4	0.64g	Very little further damage
11	4.8	1.02g	Total collapse except for parts confined by reinforcing bars

In this test only the corner of the model was reinforced as this was where previous models had failed. However this induced movement in the in-plane wall where the "L" bars were terminated, leading to the collapse of the in-plane wall at a lower acceleration than the unimproved models. The failure mechanism was the perpendicular wall trying to topple which caused the reinforcement in the in-plane wall to lift up and down leading to the formation of large cracks in the in-plane wall. Thus if this improvement is to be successful reinforcement would need to be placed throughout the structure so that large stresses are not induced where bars are terminated.

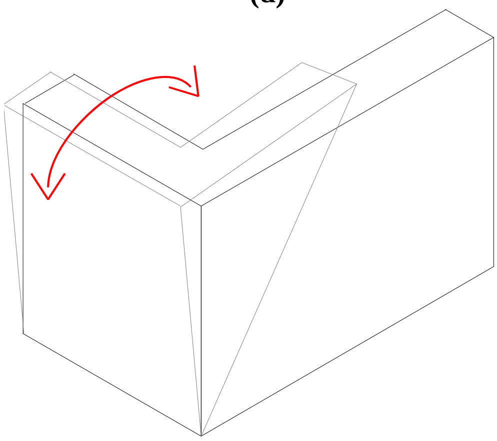
(a)

(b)

(c)

(d)

(e)



(f)

Figure 6a: Moderate damage to in-plane, unreinforced wall at 0.39g
Figure 6b: Collapse of unreinforced in-plane wall at 0.45g
Figure 6c,d,e: Parts of model confined by reinforcement still standing after 1.02g
Figure 6f: Approximation of failure mechanism for the in-plane wall

Where the reinforcement was placed it was very successful. The confinement and tensile strength provided by the reinforcing bars was enough to allow parts of the model to survive at 1.02g.

There have been several areas of research in to the addition of reinforcement to adobe buildings, not just using steel. Most noteworthy is the research at the Catholic University of Peru where bamboo was used as reinforcement. Here full scale buildings were tested on tilting and shaking tables. "The main conclusion was that an interior reinforcement made of vertical cane, combined with the placement of horizontal crushed cane every forth row of adobe blocks noticeably increased the seismic strength of the housing modules. The cane reinforcement almost doubled the maximum horizontal load capacity and, most importantly, increased almost 6 times the lateral deformation of the reinforced walls. The cane reinforcement thus provided strength and ductility to the adobe masonry." (Blondet et al, 2003). This is in good agreement with the results found here as where the reinforcement was placed there was a 2-3 fold increase in collapse acceleration was viewed (i.e. a 2-3 fold increase in horizontal load capacity).

It has been clearly demonstrated that the addition of steel reinforcing bars is an effective way of improving the seismic performance of adobe buildings but the other criteria for a successful improvement was that it must be cheap and simple to implement. In a full size building, to be equivalent to these model tests, 50mm diameter bars would be required and as mentioned previously reinforcement would need to be provided throughout the building, this would be very expensive. Another point worth noting is that the use of specialist bar bending equipment would be required which is not ideal as this would be expensive and difficult to implement in rural areas. Thus coming up with other arrangements of rebar that does not require bending or the use of so many large diameter bars may be a focus for future research.

A final problem worth noting with the use of steel reinforcement is the high level corrosion. In this test 20mm cover was used, but the level of corrosion after only 5 days was high, indicated by the red-brown rust stains in the mortar at the surface of the wall. The effectiveness of the improvement would thus deteriorate at an unknown rate as time progressed. For this reason it may be better to use some other ductile, non-ferrous material for the reinforcement, such as the bamboo used in the Catholic University of Peru research.

Improvement C: The Use of Steel Reinforcing Mesh Cage

In this test a cage that fully encased the wall was constructed out of 13mm$\times$13mm steel mesh. Mesh was fixed to the base with simple tacks, to mimic either burying in the foundations or pegging into the ground. It was hoped that the mesh would have two benefits; firstly to increase the ductility and tensile strength of the model; secondly to contain the collapse when it occurred.

(a) **(b)**

Figure 7 a: Part of Mesh Cage in Mould

Figure 7b: Wall Built Up in Cage before Plastering

The cage was constructed from flat sheets of mesh and the wall built up inside the cage. Once complete the adobe mortar was used to plaster the mesh to the surface of the wall. The wire mesh used here scales to 65mm square at prototype scale.

Table 4: Performance of Improvement C: Use of reinforcing mesh cage			
Displacement (mm)	**Frequency (Hz)**	**Peak Acceleration (m/s^2)**	**Comments**
3	4	0.19g	No Damage
5	4	0.32g	No Damage
7	4	0.45g	Ends of walls vibrate, large deformations, but no damage
10	4	0.64g	Extreme deformations as transverse wall tried to rotate about corner. Some plaster lost from surface of wall, but very little damage
11	4.8	1.02g	Complete Collapse – Caused by mesh coming unattached from the base

Figure 8 Failure mechanism at 1.02g of Test C with wire mesh reinforcement

This improvement was very successful and increased the ultimate capacity of the model by more than three times. The eventual failure was due to the mesh becoming detached from the base. A repeat test would be required to investigate the level of fixing required to prevent failure at 1.02g.

Research at the Catholic University of Peru indicated that wire mesh nailed in to the walls of existing adobe buildings and covered with sand and cement mortar was highly effective in delaying collapse.[3]

[3] Based on Zegarra et al (1997) and Zegarra et al (2001) but are taken directly from Blondet et al (2003)

Unfortunately there are no figures for this claim as the technique was used on real buildings which then went on to perform better in comparison to unimproved buildings in the 2001 Arequipa Earthquake. The improvement seen is in agreement with the results found here.

The addition of mesh resulted in an increase in strength and a significant increase in ductility indicated by the large deformations viewed without damage occurring. If the mesh were better fixed to the base then it could be possible to prevent loss of life by containing the collapsed wall inside the cage.

A possible problem with using these thin wires to reinforce would be that any corrosion could penetrate all the way through the wire, rendering it totally ineffective. Future research may be better focused by using plastic meshes which do not have the associated corrosion problems.

Improvement D (21/03/2006): The Use Plastic Carrier Bag Mesh
Clearly the use of reinforcement is successful in improving seismic performance of adobe buildings but it has been recognised that the use of steel is problematic as it is expensive and susceptible to corrosion problems. Thus an innovative new method was tested, using ordinary plastic carrier bags made into a mesh to reinforce the model.
Plastic bags were cut in to 20mm strips, these were then plaited together to make “ropes”. These plaited ropes were then knotted together to make 50mm × 50mm mesh.

The mesh was wrapped around the wall in one continuous piece and fixed to the base using tacks to

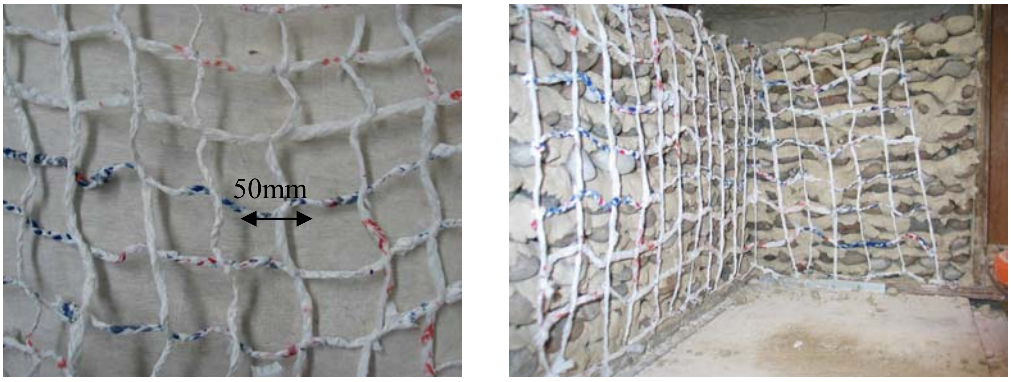


Figure 9: Details of carrier bag mesh

mimic pegging to the ground. Three further layers of the wall were built on top of the mesh to keep it in place and the surface of the mesh was plastered with the adobe mortar mixture, this was to hold it in place and for aesthetics. See Figure 9.

The performance of the carrier bag mesh is summarised below. Photos of the test can be seen in Figure 10.

Table 5: Performance of Improvement D: Use of reinforcing carrier bag mesh

Displacement (mm)	**Frequency (Hz)**	**Peak Acceleration (m/s^2)**	**Comments**
3	4	0.19g	No Damage
5	4	0.32g	No Damage
7	4	0.45g	Transverse wall tries to rotate about corner but carrier bag mesh resists – Minor Damage
10	4	0.64g	Collapse of transverse wall
11	4.8	1.02g	Complete Collapse – Caused by shear cracking of the in-plane wall

(a)

(b)

(c)

(d)

(e)

(f)

Figure 10a: Improvement D: Use of carrier bag mesh- No damage up to 0.32g
Figure 10b,c: Damage restrained by mesh at 0.45g
Figure 10d,e: Collapse of transverse wall at 0.64g, in-plane wall undamaged
Figure 10f: Complete collapse at 1.02g

The addition of the carrier bags clearly made the model more ductile and there was also an increase in strength. The transverse wall failed at 0.64g, double the acceleration at failure of the unimproved model. Similarly the in-plane wall totally collapsed at 1.02g, double the collapse acceleration the unimproved in-plane wall.

The ductile failure mechanism would mean there would be advance warning of the collapse, which would improve the fatality rates in earthquakes. Also the collapse of the transverse wall was much more contained and the wall did not topple inwards, again this would represent an improvement in anticipated fatality rates in real earthquakes.

Carrier bags are incredibly cheap and are normally sent to landfill in the UK; only around ten standard carrier bags were needed to reinforce this model.

There has been no other research in to the reinforcement of adobe using plaited carrier bags so there is no data for these results to be compared to. Many further tests would be required before an exact figure can be placed on the value of this improvement technique.

CONCLUSIONS

The first part of this paper focused on accurate modeling of the collapse of adobe walls. The findings from this research were:

1. A realistic collapse mechanism for walls subject to in-plane shaking is shear cracking.
2. A realistic collapse mechanism for walls subject to transverse shaking is toppling.
3. A realistic collapse mechanism for a corner joint is a combination of the above two mechanisms plus vertical cracking at the corner.
4. To accurately assess the success of the proposed improvements these mechanisms had to be mobilised in the model corner joint.
5. Using as large a scale as possible enabled lower accelerations to be used to initiate failure. Thus a 1:5 scale was chosen as size was limited only by the size of the shaking table.

The second and most substantial part of the paper was concerned with testing proposed techniques to improve the seismic performance of an isolated corner joint. The conclusions from this part of the project were:

1. To increase the failure acceleration of the corner joint the failure mechanisms outlined above had to be prevented. Thus an increase in ductility and tensile strength was required, not just an increase in compressive strength or bonding properties of the mortar.
2. For the reason outlined in 1 the addition of 2% cement to the mortar did not provide any increase in failure acceleration or change the failure mechanism.
3. The use of steel reinforcing bars at the corner provided an increase in failure acceleration where they were placed. The confinement and tensile strength provided by the rebars allowed parts of the model to survive past 1.02g, three times the unimproved failure acceleration. However the unreinforced part of the wall failed at a lower acceleration than the unimproved model, this was due to stresses building up where the rebars were terminated. Thus, if this technique is to be successful reinforcement must be placed throughout the structure not just at the corner.
4. The use of a steel mesh cage around the wall had two benefits: firstly it increased the ductility of the model and secondly it contained the collapse. The increase in ductility was clearly visible during the test when large displacements were viewed without damage occurring. The eventual failure was at three times the failure acceleration of the unimproved model and was due to the mesh becoming detached from the base.
5. Major problems with using steel for reinforcement are corrosion and its high cost. The level of corrosion was high in the rebar test and evidence of rust could be seen after just 5 days.

6. The use of plastic carrier bags made in to a mesh increased the ductility of the model and delayed failure to around 0.64g. Although this was not as large an improvement as the steel reinforcement this method has other benefits; carrier bags are significantly cheaper than steel and suffers none of the corrosion problems.

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REFERENCES

Blondet, M., Garcia, M. and Brzev, S., (2003), "Earthquake-Resistant Construction of Adobe Buildings: A Tutorial", Retrieved from www.world-housing.net.

Choudhary, M., Jaiswal, K. and Sinha, R., (2002), "World Housing Report: India Traditional House in the Kutch Region of India (Bhonga)" Retrieved from EERI World Housing Encyclopedia Website, www.world-housing.net.

Houben, H. and Guillaud, H., (1994), "Earth Construction - A Comprehensive Guide" ITDG Publishing, London, UK.

Malton, J., (2005), "Earthquake Resistance of Adobe Buildings", Fourth Year Project, Group D CUED.

Tolles, E. and Krawinkler, H., (1990), "Seismic Studies on Small-Scale Models on Adobe Houses", PhD Dissertation Stanford University, USA, Retrieved from http://blume.stanford.edu/Blume/TRList.htm.

Zegarra L., Quiun, D., San Bartlome A. and Gisecke, A., (1997), "Reforzamiento de Vivendas de Adobe Existentes. 2da Parte: Ensayos Sismicos de Modulos" (Reinforcement of Existing Adobe Houses. 2nd Part: Seismic Tests of Housing Modules), Summary of a research project sponsored by CERESIS-GTZ-PUCP, XI CONIC, Trujillo, Peru.

Zegarra L., Quiun, D., San Bartlome A. and Gisecke, A., (2001), "Comportmiento Ante er Terremoto del 23-06-2001 de las Viviendas de Adobe Reforzadas en Moquegua. Tacna y Arica" (Behaviour of Reinforced Adobe Housees in Moquegua, Tecna an Arica during the 23-06-2001 Earthquake), XIII CONIC, Puno, Peru.