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Feasibility of construction of two-storey adobe buildings in Peru

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ABSTRACT: This paper demonstrates the feasibility of construction of two-story adobe buildings in Peru, by an experimental, analytical and computational studies. The analytical study shows the construction possibility in seismic Zones 1 and 2 and on some foundations soil types. Several conditions required to construct two-story adobe buildings are proposed. The Modified Distinct Element Method (MDEM) was used to show the fracture process in adobe wall. The MDEM results show a good agreement with actual seismic damage.

1. INTRODUCTION

In many developing countries such as Peru, most rural houses and some urban houses are made from adobe, and many of them are two-story houses. It is evident that the use of low cost material such as adobe will continue in developing countries. Furthermore there is no other alternative material available in some places. It is necessary for engineers to improve the behaviour of this type of housing against severe seismic forces.

Historical earthquakes have shown that most of adobe buildings collapse after severe earthquakes. However, some of one or two-story adobe buildings surprisingly could resist the earthquake forces. Therefore, there are certain conditions under which adobe buildings can behave satisfactorily during severe earthquakes. The structure should be able to resist the forces due to: a) small earthquakes without damage, b) medium earthquakes with moderate damage and c) big earthquakes without collapse.

The objectives of this research are: 1) to identify the conditions under which two-story adobe buildings can behave satisfactorily during severe earthquakes, 2) to propose a structural system composed of simple shear walls and/or coupled shear walls for two story adobe buildings, and 3) to study the feasibility of two-story adobe construction using both the Peruvian Seismic Resistant Adobe Design Code and computer simulations of fracture process of adobe walls due to earthquake forces.

To achieve the aforementioned objectives, we used results from the experimental tests done from 1971 to 1980 at the National University of Engineering, Lima, Peru (under the support from the Ministry of Housing and the International Development Agency USA). As computer simulation, we apply the Modified Distinct Element Method which was developed by Hakuno et al. (see Meguro (1989)) at the Earthquake Research Institute, The University of Tokyo.

2. REVIEW OF EXPERIMENTAL RESULTS

2.1 *Seismic behaviour of adobe structures*

Failure of adobe buildings are attributed mainly to the low tensile strength and reduced adherence between adobe and mortar. These properties are notably improved in stabilized adobe. Stabilized adobe is a block of adobe made from a mixing of mud and others materials (such as Asphaltum RC-250). It is also heavily improved in humidity resistance.

The main patterns of failure which frequently occur in combination, in both non-stabilized and stabilized adobe structures, are the following: 1) traction failure at wall corners, 2) bending failure at walls without fastening in some borders, and 3) shear failure. The shear failure occurs when the wall behaves like a shear wall and shear stresses increases excessively.

2.2 *Mechanical properties of adobe masonry and stabilized adobe block*

From the failure mechanism of adobe construction, it was known that the more important mechanical characteristics to be determined are: 1) the tensile strength, 2) the flexural strength and 3) the shear strength. Furthermore, it is also necessary to know the compressive strength of the masonry.

The strength of the adobe masonry walls was determined from full scale tests and also standard specimens. These models were made of small blocks

(26.5 cm x 26.5 cm) and big blocks (38 cm x 38 cm). Four types of mortar were used. They were (1) cement:sand:soil:asphalt (2:4:6:1), (2) cement:sand with 1% of asphalt (1:10:1%), (3) soil with 2% of asphalt (S-2) and (4) simple soil without any additive.

2.3 *Axial compression tests*

The results are shown in Table I. They were an average of 3 to 5 specimens. In the specimens with stabilized adobe, the values for compressive strength, the deformation corresponding to the maximum stress and the modulus of elasticity were greater than the model made with non-stabilized adobe. The compressive strength for stabilized adobe specimens was 25% greater than non-stabilized ones.

Table I. Results from the compression test. (mean value for 3 to 5 specimens)

Mortar type	1:10 - 1%	S-2%	Simple
Strength f'_m kg/cm^2	12.8	12.8	10.3
Strain	12.3x10^{-3}	13.5x10^{-3}	9.7x10^{-3}
Modulus of Elasticity kg/cm^2	1788	2140	1600

2.4 *Shear tests*

The results agree with Coulomb's expression ($\tau = c + \mu * \sigma$) where τ is the failure shear stress, c is the adhesion stress, μ is the friction coefficient and σ is the normal confining stress. In Table II, we present the values of c and μ for each type of mortar (which was the main variable).

Table II. Adherence values (c) and friction coefficient (μ). Direct shear tests. (S:small blocks, B:big blocks)

Mortar	1:10:1%		S-2%		Simple		2:4:6:1	
Block	S	B	S	B	S	B	S	B
Adherence (c) kg/cm^2	1.40	1.30	0.90	0.75	0.55	---	1.80	1.98
Friction Coef.(μ)	0.60	0.63	0.78	0.80	0.58	---	1.06	0.98

We can point out the following: (1) the specimen with stabilized adobe showed an adherence strength c significantly greater than non-stabilized adobe specimens; (2) the specimens with stabilized adobe had a friction coefficient μ greater than the non-stabilized specimens. However the difference, in this case, was not as big as the adherence strength and (3) it had not been observed a big difference among the specimens made with big or small blocks

2.5 *Diagonal compression tests*

The experimental values for failure shear stress are shown in Table III.

Table III. Diagonal Compression Tests. Rupture shear stress in kg/cm^2.

1:10:1% Small blocks	1:10:1% Big blocks	S-2%	Simple
1.01	1.15	0.45	0.30

It was noticed that the stabilized block specimens had higher strength than that of non-stabilized ones. Furthermore, the specimens failed by shear stress.

2.6 *Mechanical properties of cane*

The Code recommend to use cane as reinforce for adobe walls. In the tests, the cane showed an non-linear elastic behaviour up to the rupture. It had been determined experimentally that the modulus of elasticity was equal to 1.52 x 10^5 kg/cm^2 (coefficient of variation 6.2%) and the mean value of tensile strength was 1350 kg/cm^2 (coefficient of variation 17.7%). The deformation capacity of the adobe walls reinforced with cane was larger that the wall without reinforcement.

2.7 *Summary of experimental results.*

a) In general, the stabilization with asphalt improved the mechanical characteristics of adobe blocks.

b) The experimental results agreed well with the Coulomb's law $\tau = c + \mu * \sigma$.

c) The adobe walls that were constructed with small blocks had mechanical properties the same as those that were made of big blocks.

3. FEASIBILITY OF CONSTRUCTION OF TWO-STORY ADOBE BUILDINGS.

We studied the feasibility to construct two story adobe buildings taking into account the seismic zone and the foundation soil type. According to the Peruvian Seismic Design Code, three seismic zone in the country are defined. They are: a) Zone 1 (high seismicity zone), b) Zone 2 (medium seismicity zone) and c) Zone 3 (low seismicity zone). The Code also define three foundation soil types: a) Soil 1 (hard soil) b) Soil 2 (medium hard soil) and c) Soil 3 (soft soil).

We used a two-story adobe building model, with a total size of 4 m x 4 m (plan view), a story height of 2.56 m, a wall thickness of 0.45 m and a wooden roof. Two dynamic model were used, the first one with concentrated mass at each story level, and the second one with uniformly distributed mass. The results had shown fundamentals period of 0.26 sec and 0.21 sec respectively. Therefore, we can use an elastic seismic coefficient (c) of 0.40. It corresponds to a natural period of vibration less than or equal to 0.33 sec.

We applied the Peruvian Seismic Resistant Design Code using U = 1.0 (type of structural use coefficient), c = 0.40 (elastic seismic coefficient), Rd = 1.5 (reduction for ductility coefficient). The design seismic coefficient was obtained for the different seismicity zones and soil types specified by the code (See Table IV)

Table IV. Values of Seismic coefficients.

Foundation Soil Type	Seismic Zone 1	2	3
1	0.267	0.187	0.08
2	0.320	0.224	0.096

The Code does not allow adobe buildings on soil Type 3.

The earthquake load was calculated with the Peruvian Seismic Resistant Design Code. Then, the shear stress acting at each floor level was obtained (See Table V).

Table V. Acting shear stress in kg/cm^2. Values inside the parenthesis correspond to 2nd story, the others to the first story.

Soil Type	Seismic Zone 1	2	3
Type 1	0.39 (0.20)	0.27 (0.14)	0.12 (0.06)
Type 2	0.47 (0.24)	0.33 (0.17)	0.14 (0.07)
Type 3	0.55 (0.28)	0.38 (0.19)	0.16 (0.08)

The allowable shear stress (Vad) was also calculated at the top and bottom of each wall (see Table VI). The expression $Vad = 0.45 (c + \mu * \sigma)$ was used.

Three kind of adobe walls were considered: (a) adobe walls with mud mortar, (b) stabilized blocks with cement:sand:asphalt mortar and (c) stabilized blocks with soil:asphalt mortar.

Then, the acting shear stress was compared with the allowable shear stress. A variability of 30% of the acting shear stress for the structures locates on soil type 1 and 2, and a 50% of variability for structures on soil type 3 were considered. We present the results in the Table VII.

Two-story adobe buildings can be constructed if the foundation is soil type 1 (any seismicity zone). In the case of foundation soil type 2, two-story adobe buildings can not be constructed in Zone 1. These structures also have to fulfil the recommendation given in the following sections.

Table VI. Allowable shear stress (Vad). The values inside the parenthesis correspond to the bottom of the wall, the others to the top of the wall.

Mortar	Second Story Vad kg/cm^2	First Story Vad kg/cm^2
Simple	0.27 (0.37)	0.38 (0.49)
1:10:1%	0.64 (0.73)	0.75 (0.86)
S-2%	0.80 (0.52)	0.54 (0.69)

Table VII. Feasibility of two-story adobe constructions

Foundation Soil type	Seismic Zone 1	2	3
1	YES*	YES	YES
2	NO	YES	YES
3**	NO	NO	NO

* Only constructions with stabilized adobe.

** The Code does not allow adobe constructions on soil type 3.

4. RECOMMENDATIONS TO DESIGN TWO-STORY ADOBE BUILDINGS

The Peruvian Seismic Resistant Adobe Design Code does not allow to build two-story adobe buildings, however, they are still being constructed at several rural areas in several countries.

The design of two-story adobe buildings with the standard procedures led to relatively expensive structures, but we can obtain less expensive constructions if we use a methodology with the criteria of life safety. The objective of this kind of design is to protect the life of the habitants and to avoid the complete collapse. However, we have to recognize that this kind of structure can be damaged by a large earthquake up to a point of expensive reconstruction, but we can have a great improvement of the seismic safety of this kind of construction which are usually used by low income people.

This kind of design can be accomplished using a procedure with an allowable stress smaller than that specified by the Code, but it is compensated by providing slightly higher capacity of the system ductility. We can obtain the same level of displacements of systems with small elastic strength and high ductility requirements as of systems with high elastic strength and small ductility requirements.

Based upon of the observation of actual adobe building damage and design experience, in order to obtain two-story adobe buildings with some degree of ductility, we propose that they have to be composed of simple shear walls and/or coupled shear walls with connection beams which should fail by bending moments before the shear failure and also before the compression failure of the wall at the compression zone. The energy dissipation in the connection beams that fail by bending can be very large. It will produce a satisfactorily behaviour against severe earthquakes. Therefore, the structure will not completely collapse and save the human life.

5. SIMULATION OF BEHAVIOUR OF ADOBE WALLS

In order to understand the behaviour of the adobe walls, we perform 2-dimensional computer simulations using the MDEM.

5.1 *Theory of the MDEM*

The MDEM is a numerical method which can follow the behaviour of the media from continuous state to complete fracture. In this method, the model is composed of many circular elements (discrete elements). Each element has connections with the surrounding elements. The calculation at the contact points are done with the Voight type model which is composed of an elastic spring and a dashpot. The effect of the material present in the pores between the granules is taken into account by an additional spring (which was called pore spring) and a dashpot.The pore spring was established by Meguro and Hakuno (1989) based on Iwashita and Hakuno(1988) model.

At the initial stage, the model behaves as a continuous body, but when the forces are increased at each time step the pore springs are destroyed and the media will become discontinuous. The destruction of the pore spring show the fracture process of the structural system.

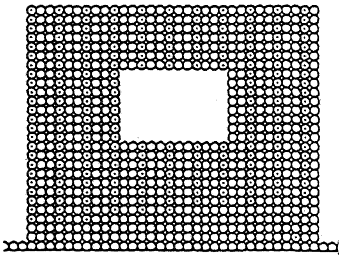
5.2 *Parameter determination*

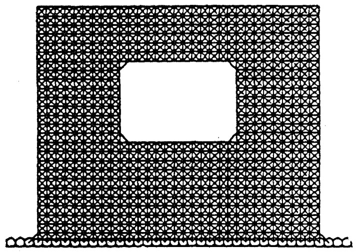
The determination of the parameters is done according to the method presented in Meguro and Hakuno(1989), and using the experimental data presented in this paper.

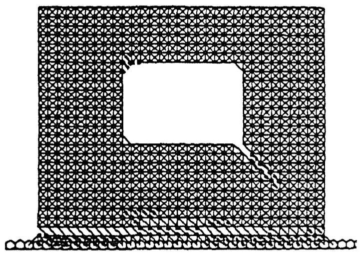
5.3 *Adobe wall models*

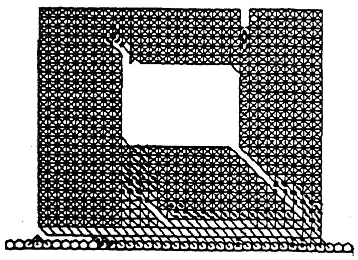
We use three adobe wall models named Model A, Model B and Model C. The same horizontal acceleration was applied to all the models using a sinusoidal function with a period of 2 sec and amplitude of 0.5 g. The horizontal acceleration that is applied has a vertical distribution of inverted triangular shape along the wall height.

The Model A was a one story adobe wall, 3.20 m length by 2.60 m height. It had an opening of 1.2 m by 0.80 m. The distribution of elements and the pore spring fracture process are shown in Fig. 1.


Initial Distribution of Elements.


Initial distribution of pore spring.


t = 0.105 sec. Initial cracks at the base and one corner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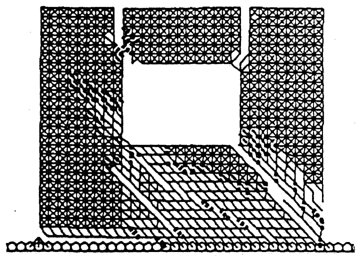
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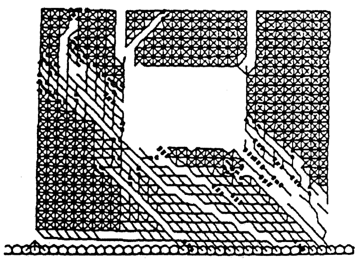
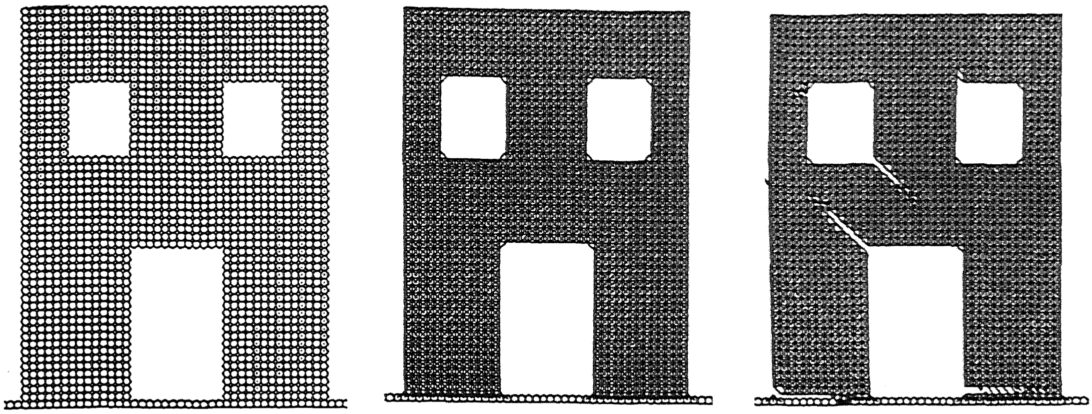

t = 0.255 sec.

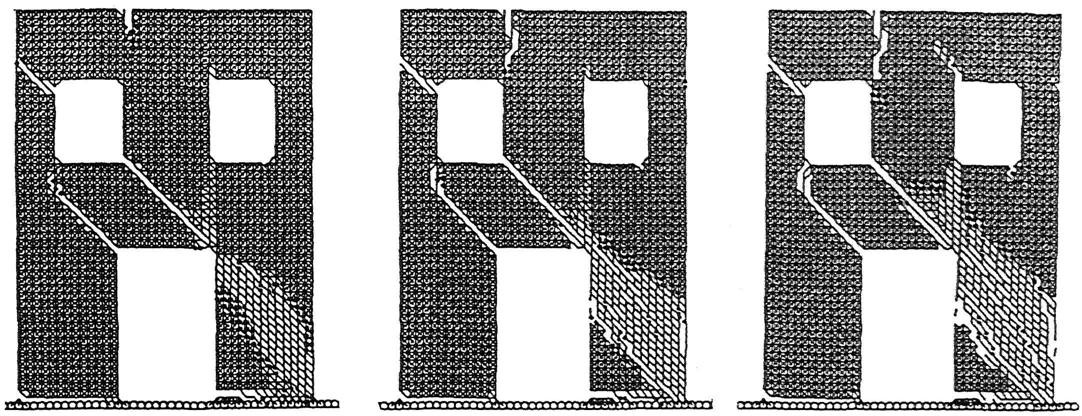
Fig. 1. Model A. One story shear wall. The applied horizontal load is from left to right.



Initial Distribution of Elements.

Initial distribution of pore spring.

t = 0.105 sec. Initial cracks at the oppening corners

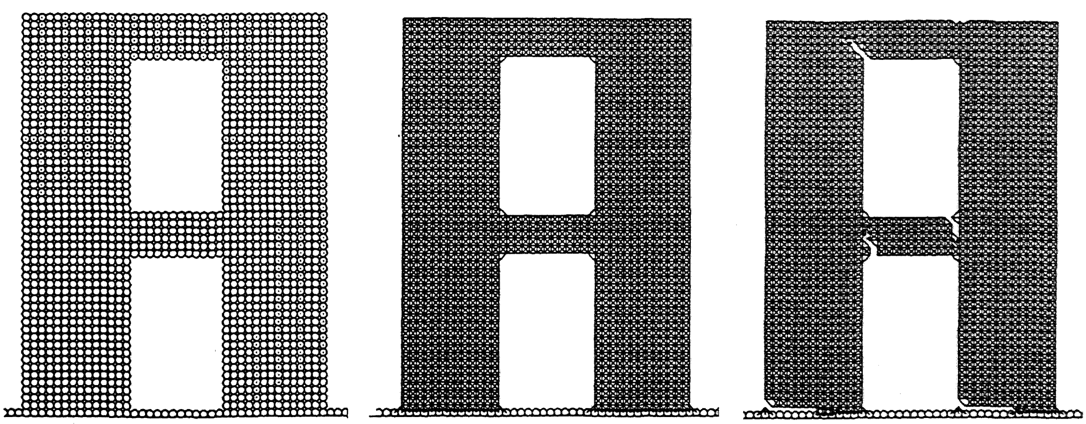


t= 0.210 sec.

t = 0.255 sec.

t= 0.300 sec.

Fig. 2. Model B. Two-story adobe wall. Effect of the oppenings in the crack propagation.

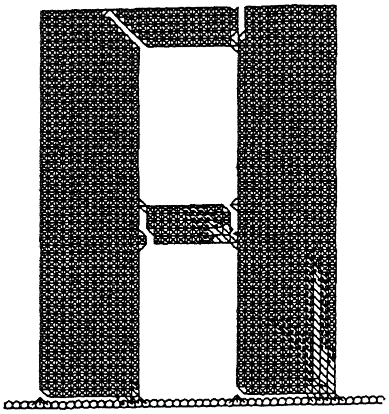


Initial Distribution of Elements.

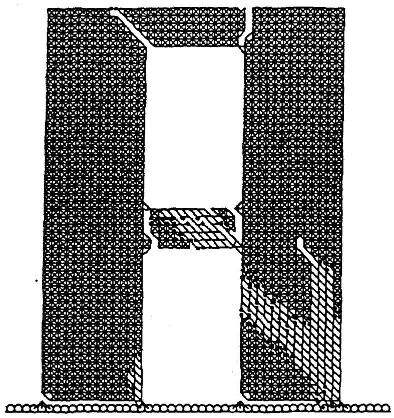
Initial distribution of pore spring.

t = 0.105 sec. Initial cracks at the connection beams

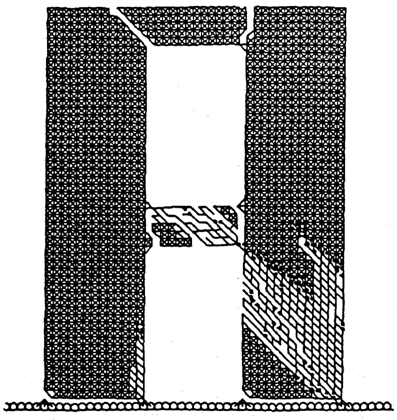
Fig. 3. Model C. Two-story adobe wall. Coupled shear wall.



t= 0.210 sec. Failure of connection beams.



t = 0.255 sec.



t= 0.300 sec.

Fig. 3(cont). Model C. Two-story adobe wall. Coupled shear wall.

The Model B was a two-story adobe wall, 4.00 m length by 5.20 m height. The door was 1.20 m x 2.00 m and the windows were 0.80 m x 1.00 (See Fig.2). Propagation of cracks start at the corners of the openings. This type of distribution is not recommended.

The Model C was also a two-story adobe wall (See Fig 3). It was almost same as Model B but it has only one opening on the second floor (1.20 m by 2.00). The fracture process is shown in Fig. 3. We can see that the connection beams fails before the failure of the wall. This case illustrate the behaviour of the recommended couple shear wall with connection beams which fails before the failure of the wall. the energy dissipation can be very large.

6. CONCLUSIONS

It is possible to construct two-story adobe buildings under the following conditions.

a) The foundation is on soil type one. If the foundation is on soil type 2, we can construct only in seismicity zone 2 and 3. Adobe constructions on soil type 3 are not allowed by the code.

b) The structural system is composed of shear walls and/or with coupled shear walls with ductile beams that fail before the failure of the wall.

c) The collar beam is used at the top of each floor. The walls are reinforced by cane in both horizontal and vertical directions.

d) In high seismicity zone, the minimum thickness of the walls is 0.60 m and in the other seismic zones, it is 0.50 m. In general, the thickness of the second floor walls can be reduced in 0.10 m.

The MDEM can be applied to study the cracks propagation in adobe walls and it can follow the complete fracture process even after the medium becomes discontinuous. Therefore it can help to the designers to clarify the behaviour of the structural system. The computer simulation show a good agreement with seismic damage observed during past earthquakes. Considering recent improvement of hardware and software of the computer systems, this method has a great applicability.

7. REFERENCES

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