EXPERIMENTAL RESEARCH AND SEISMIC DESIGN PROPOSAL FOR CONFINED ADOBE MASONRY

A. San Bartolomé[1], D. Quiun[2]
[1] Professor, Department of Engineering, Catholic University of Peru, Av Universitaria 1801, Lima 32, Peru, asanbar@pucp.edu.pe
[2] Professor, Department of Engineering, Catholic University of Peru, Av Universitaria 1801, Lima 32, Peru, dquiun@pucp.edu.pe

ABSTRACT
The traditional constructions of unreinforced adobe are highly vulnerable to earthquakes, mostly affecting people of low income. The experimental researches to mitigate this problem have tried to reinforce adobe constructions with internal meshes of canes or external meshes of welded wires or similar. In recent years, laboratory tests have been developed to study adobe confined with reinforced concrete elements under seismic loads, with good results. The tests include cyclic lateral loads on full scale walls and shaking table tests on models of one and two stories.

Based on the results of these experiments, a seismic design proposal for confined adobe houses up to two stories was developed. The theory of the proposal uses the criteria of ultimate strength and performance-based design used in confined masonry of fired clay bricks, with acknowledge to the poor quality and low resistance of the traditional adobe masonry. The application of this theory leads to columns and beams of low resistance concrete and minimum reinforcement. In this way, the design proposal can be useful for people of low income.

KEYWORDS: Codes; Adobe; Confined Adobe; Seismic design; Experimental tests

INTRODUCTION
In Peru, a few houses of one or two stories can be found in which the adobe walls are confined by reinforced concrete elements (Figure 1). However, such constructions do not have a rational structural design, and usually they have too much steel reinforcement and become an unnecessary expensive construction. On the other hand, experimental tests carried out in the Laboratory of Structures of the Catholic University of Peru, indicate that it is possible to make a rational design of confined adobe under seismic forces.


Figure 1: Examples of confined adobe walls in Peru.

Also, there are evidences of the good behaviour exhibited by these structures under real earthquakes, like the Mexican Omotepec1995 earthquake, as shown in Figure 2. The purpose of this paper is to present a seismic design proposal for confined adobe structures. The experimental tests in which this proposal is based are previously summarized.

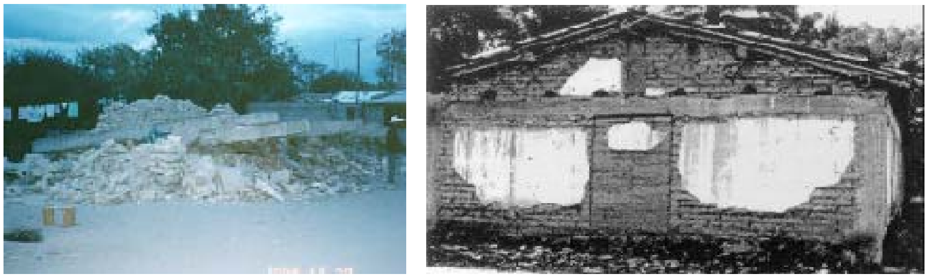


Figure 2: Unreinforced collapsed house (left) and Confined adobe house (right) after the 1995 Omotepec earthquake (EERI, 1995).

PREVIOUS EXPERIMENTAL RESEARCH ON CONFINED ADOBE

A set of experimental projects on confined adobe structures are briefly summarized. All were subjected to seismic loads at the Laboratory of Structures of the Catholic University of Peru.

The first experimental project was seismic simulation tests on a shaking table with one horizontal movement to a one story full scale model (Matos et.al., 1996). The model had four adobe walls with one door and two window openings, as shown in Figure 3.

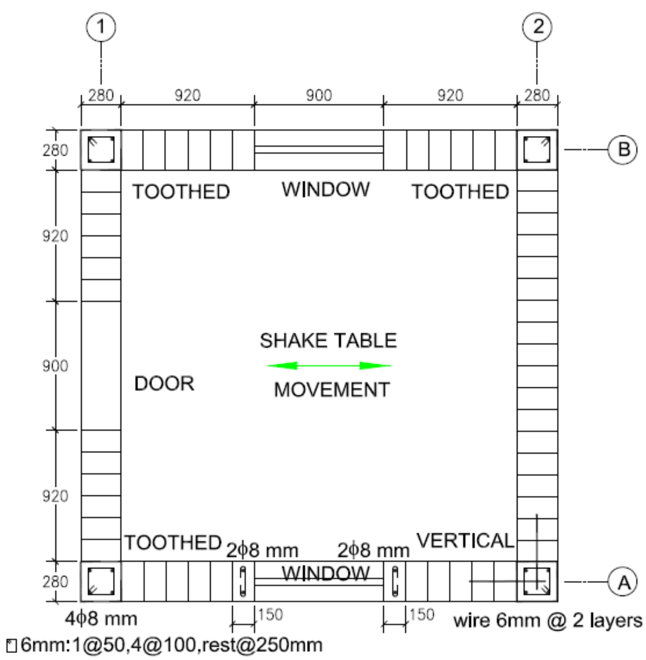
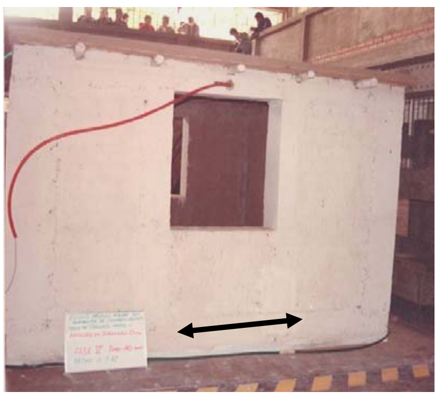


Figure 3: Confined Adobe 3D model

In each corner, a confining square concrete column was added, with 280mm side, reinforced with 4-8mm bars. Three corner connections between adobe walls and concrete columns were toothed, while one had small wires anchored in the walls in two perpendicular directions. Surrounding the window opening in the A-axis, two small RC columns were included, with 2-8mm bars. This model was subjected to the acceleration of May 31 1970 earthquake recorded in Lima, Peru, in six steps up to a peak base acceleration of 1.6g.

The confined adobe model behaved elastically without any crack (Figure 4a). After that, the adobe walls of axes A and B were removed in order to observe if the concrete columns were responsible to the high strength observed, and the specimen was again tested (Figure 4b). In this second stage, for step 2 (0.6g of peak acceleration) plastic hinges were developed in the column borders and the specimen become unstable. In Figure 4c a comparison between the confined adobe masonry walls and the RC frame is given, and it was concluded that the adobe wall was greatly responsible for the strength and rigidity.



(a)

(b)

(c)

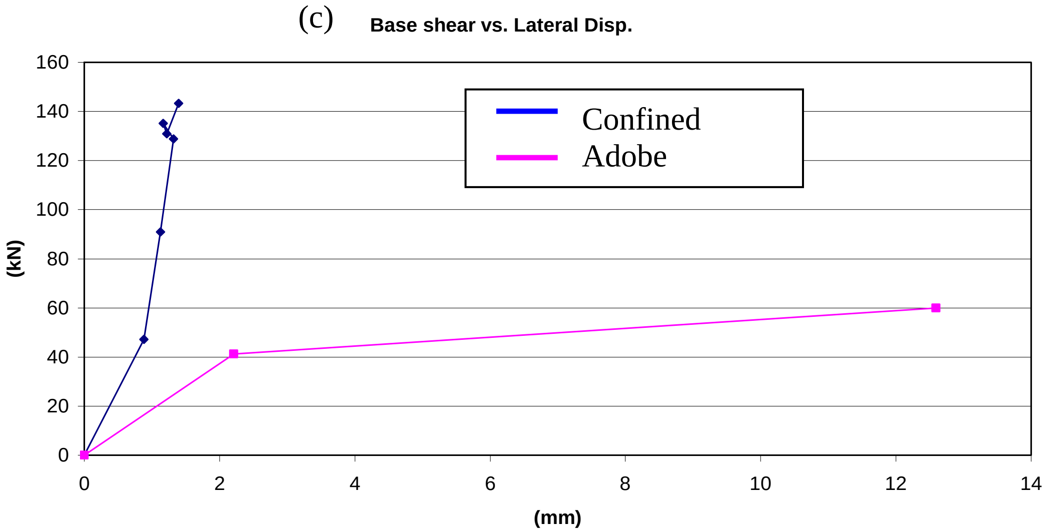


Figure 4: Confined Adobe 3D model and Concrete Frame, 1996

In the second experimental project, two confined adobe walls were subjected to cyclic lateral load (San Bartolomé, 2003). The confinement RC elements were designed to resist the diagonal cracking load, according to the procedure given hereafter in the design proposal. The design required only 2-6mm bars in each column, but in order to study the effects of the vertical reinforcement, in wall W1 4-6mm bars were used in each column, while in wall W2 only 2-6mm bars were used. In Figure 5 the hysteretic loops for both walls are displayed, in which almost no difference can be appreciated, which is attributed to the dominant shear deformation that prevailed in both walls under the cyclic loads.

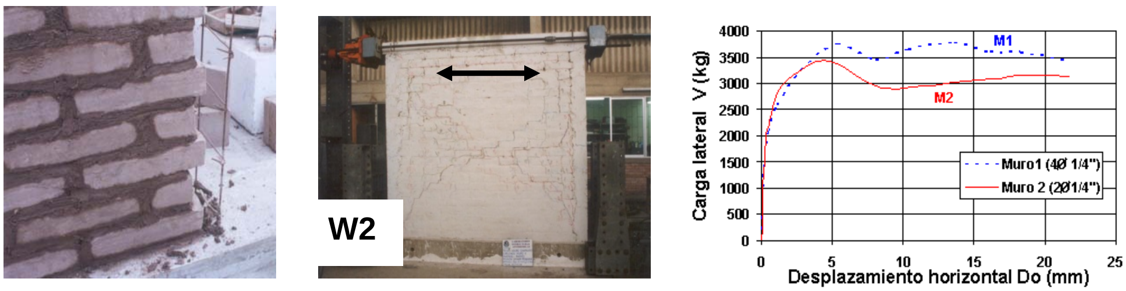


Figure 5. Lateral Load Test and Envelope V-D (Angel San Bartolomé, 2003).

For the third experimental project, a two-story model was constructed with a ¾ scale, and subjected to shaking table test (Figure 6, San Bartolomé et. al. 2009). The reinforcing bars of the confinements were obtained using the specifications shown hereafter in the proposal, except that for the second floor the horizontal reinforcement within the layers was omitted. Also, the spacing between columns was a bit larger than the proposed design. For the columns, 4-6mm (1/4”) bars were obtained and for the collar beams, 2-6mm (1/4”) bars were required. The model was subjected to the acceleration of May 31 1970 earthquake recorded in Lima, Peru, in six steps up to a peak base acceleration of 1.0g. In step 4 (0.8g) some adobe units of the flexural wall of the second story fall down, producing a “V” shape failure. In the last step, this whole wall collapsed due to the out-of-plane forces and the lack of horizontal reinforcement, while the shear walls only had a few small cracks.

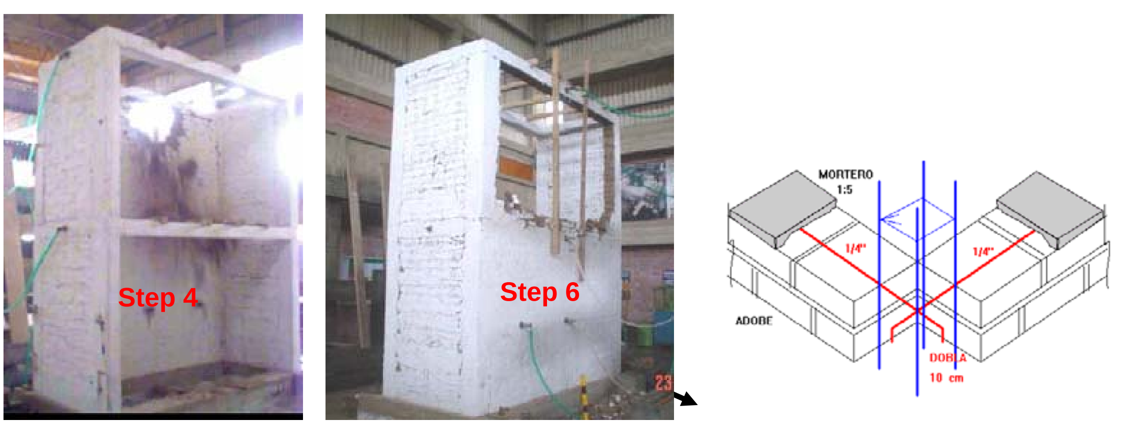


Figure 6. Shaking table test and horizontal reinforcement proposed

In the fourth and last experimental research completed, the effects of horizontal reinforcement in two confined adobe walls subjected to cyclic lateral loads were studied (Torres, 2011).

The two walls had RC confinements with the columns and collar beams reinforced with 2-6mm bars (1/4”). Wall W1 had no horizontal reinforcement. Wall W2 had one horizontal 6mm bar every 5 layers, anchored in the columns and placed in a cement-sand 1:8 mortar, while the rest of the layers had mud mortar (Figure 7, up left). The hysteretic curves (Figure 7 below left) show that in the negative branch of the envelopes the influence of the reinforcement is negligible over the shear resistance, but in the other positive branch it increased. In terms of the overall behavior, the horizontal reinforcement controlled the cracks to be very thin in wall W2, keeping the wall integrity. For a horizontal displacement D=20mm, the vertical cracks in the column-wall intersection had a maximum width of 3.5mm in W1 and 0.5 mm in W2.

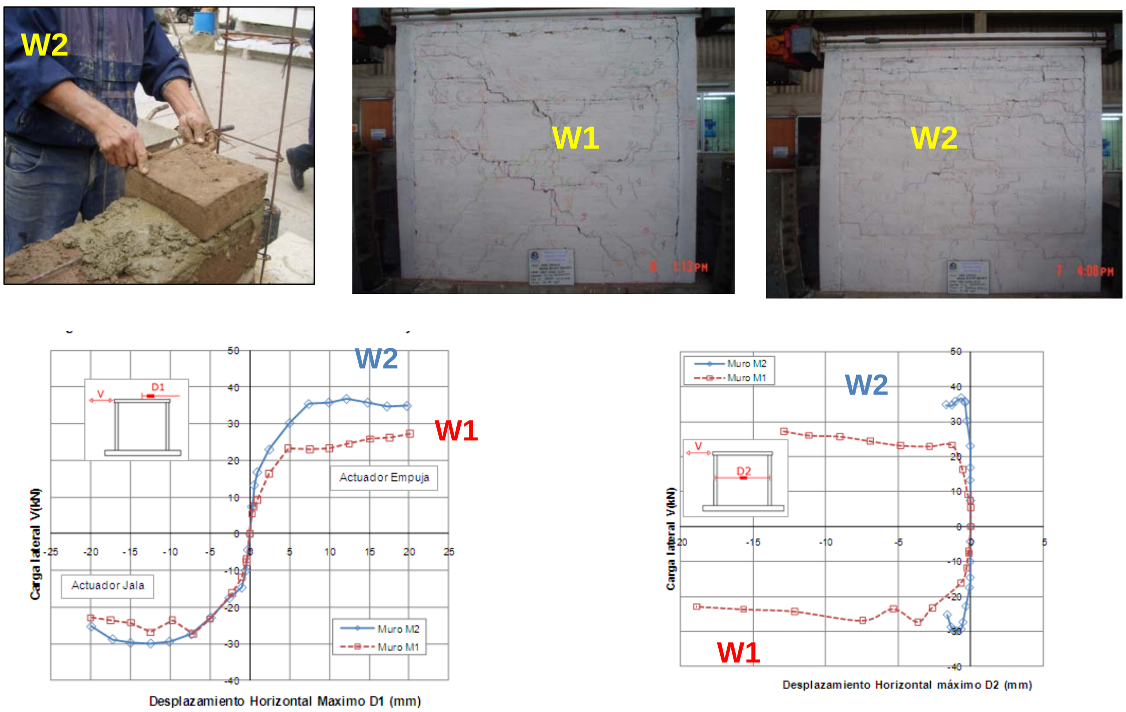


Figure 7. Cyclic lateral load in Walls W1 (unreinforced) and W2 (with horizontal reinfrocement); hysteretic envelope V-D; and relative displacement between columns

SEISMIC DESIGN PROPOSAL FOR CONFINED ADOBE

The following seismic design proposal is based on the experimental tests performed, in the observations that confined adobe walls have a seismic behaviour similar to clay brick masonry with a low strength, a predominant shear deformation under in-plane loads, while for out-of-plane loads the weakness are in the wall-confinement connections. The equations are similar to those used in the Peruvian Masonry Code (San Bartolome and Quiun, 2007; SENCICO Norma E.070 “Albañilería”, 2006).

GENERAL CONSIDERATIONS FOR CONFINED ADOBE

The confined adobe buildings may have a height up to two stories or 6m. In this proposal, an adobe wall is considered to be confined by RC elements whenever it meets the following specifications:

a) The masonry adobe wall must be completely surrounded by RC elements cast after the masonry was built;

b) For the first story, if the foundation is made of plain concrete, it can be considered as a horizontal confinement; the height of the foundation should be enough to let a proper anchorage of the vertical column bars plus a 75 mm cover.

c) The distance between confinement columns shall not exceed twice the distance between the horizontal confinements (collar beams) nor 3.5m.

d) The openings for doors and windows wider than 1m, must be surrounded by RC columns. The lintel beams in such openings must be of reinforced concrete with a cross section similar to that of the collar beams over the walls.

e) The minimum width of the wall shall be of 250 mm. The confinement width ("t") shall be equal or greater than the wall width. The minimum area of the confinement cross sections shall be 100 t (in mm2).

f) The connection wall to columns shall be vertical.

g) All the walls must have continuous horizontal reinforcement, consisting in al least 1 deformed 6mm bar every 5 layers, placed in the wall axis over a mortar bed of 1:8 cement-coarse sand (in volume), during the adobe masonry construction. The bars should enter 120 mm into the column core with a 90° bend of 100mm. In the case that the column dimension is larger than 150 mm, the anchorage of these bars can be mechanically, bent over a stirrup or hook.

h) The concrete of the confinements shall have a compressive strength f'c of 10 MPa or more. The concrete should be compacted with a 12mm bar or a vibrator. If voids are detected, the lose particles will be discarded, the affected area will be watered, and filled manually with 1:4 cement-sand mortar.

i) The reinforcement in the confinements should be ductile steel deformed bars, with diameters equal or larger than 6mm, and have a yield stress of 420 MPa. The cover of the bars should be 20mm if a overall cement cover is applied, or 30 mm otherwise.

j) The minimum longitudinal reinforcement in the confinements shall be two 6mm bars, while the minimum stirrups should be 6mm hooks, 1 at 50mm, 4 at 100mm, and the rest at 250 mm. The hooks shall be bent 180° over the longitudinal bars.

PROPOSAL FOR SEISMIC ANALYSIS OF CONFINED ADOBE

The proposal for the seismic analysis of confined adobe buildings has the following specifications.

a) The strength design force for seismic design (V for severe earthquakes) shall be given by the Seismic Code (In Peru, the Seismic Code is given by SENCICO E.030, 2003). The reduction factor for the elastic forces will be 3.

b) It is accepted that continuous RC beams and lintels provide a rigid diaphragm in each level. Wood or steel roofs can be used properly connected to the beams. Besides, a plan ratio of length to width for the building must be less than 4.

c) The plan and elevation irregularities shall be avoided. If such a case, the building should be divided into several blocks by seismic joints, and each separate block should be analyzed independently.
d) The walls that carry seismic loads must have vertical continuity and their length should not be less than 1.2m.
e) The elastic modulus for adobe masonry can be taken as Em=650 MPa, and the shear modulus can be taken as Gm=0.4 Em. The elastic modulus of the concrete (normal weight) shall be given by the expression Ec = 4700 $\sqrt{f'c}$ (in MPa).
f) To determine the lateral stiffness of confined adobe walls, the confining RC columns shall be transformed to equivalent adobe using the ratio of elastic modulus Ec/Ea. In addition, the transverse walls shall be included using an effective width of 4 times the thickness of the transverse wall. If small walls under windows openings are not isolated from the main structure, they must be considered in the analysis.
g) The internal forces in each wall under severe earthquakes are called the flexural moment Mu and shear force Vu. For the determination of Vu and Mu, rational calculations are required (manually or computational) taking into account the eccentricities of the seismic forces specified by the Seismic Code.
h) The maximum inelastic story drifts shall not exceed the value of 0.005. If this limit is surpassed, the stiffness of the building must be increased.

PROPOSED SEISMIC DESIGN FOR CONFINED ADOBE WALLS UNDER IN PLANE FORCES

The proposal for the in plane seismic design of confined adobe walls has the following specifications.

For step a) the Shear Strength VR, for the ultimate strength condition of adobe units laid with mud mortar shall be obtained using Equation 1:

$$VR = 0.5L\,t + 0.2P \qquad (1)$$

In which: L is the total wall length including the columns; t is the wall width without cover, and P is the accumulated gravity load.

In case the adobe units were laid using cement mortar, VR shall be increased by a 1.3 factor. If a cement cover is placed with a mesh properly connected to the masonry, the width "t" can include the cover thickness.

In step b) the wall density, in each direction of the building and in each floor, shall be calculated through the sum of shear force strength (Σ VR) for all the walls that carry seismic loads in the direction of the analysis. The sum of these wall shear capacities should be equal or greater than the actual seismic load acting in the story under analysis (Equation 2), specified by the Seismic Code.

$$\sum VR \geq V \qquad (2)$$

In the case that Σ VR > R V, in which R=3, the walls will behave elastically under severe earthquakes. Such walls will be designed according to step "e" of this section.

Step c) is the Check for Moderate Earthquakes. It is assumed that moderate earthquakes produce a lateral force equal to 50% of that of severe earthquakes. Using equation 3 it will be verified that under moderate earthquakes none of the walls exceeds 60% of their shear resistance. This means that for moderate earthquakes none of the walls should have shear cracks.

$$0.5Vu \leq 0.6\,VR \tag{3}$$

Step d) is the design of the walls with shear cracking. Under severe earthquakes, it is assumed that all the walls reach their shear capacity VR, except when Σ VR > R V (see step b of this section). For the walls that develop shear cracking, the RC confinements shall be designed with the following procedure.

The internal forces in the RC confinements are three: Tension (T), Compression (C) and Shear (Vc). There is no flexure moment as the column cannot bend as it is connected to the wall. For design purposes, the compression C may be neglected, due that the walls are relatively low (up to two stories), and the cross section of the columns is large enough to take this compression. For the Tension and Shear Forces, the expressions given in Table 1 are proposed.

Table 1: Internal Forces in Columns

COLUMN	V_c (shear force)	T (tension)
Interior	$\dfrac{VR.L_m}{L(N_c+1)}$	$VR\dfrac{h}{L}-P_t$
Border	$1{,}5\dfrac{VR.L_m}{L(N_c+1)}$	$F-P_t$

In which:
F = M / L = axial load in border columns produced by M.
M = Mu1 (VR / Vu) = flexural moment at shear cracking.
Lm = length of the longer span or 0.5 L, whichever is larger.
L = total wall length, including the columns
Nc = total number of columns in the wall under analysis
h = story height under analysis
Pt = vertical load coming from the transverse wall into the column
In walls of only one span, there are two border columns, Nc = 2, and Lm=L.

The confinement column design deals with the cross section area (Ac) and the longitudinal reinforcing steel area (As). The confinement column should be able to resist the combined tension T and shear friction Vc, for which equations 4 are used.

$$Ac = \frac{Vc}{0.2 f'c\phi} \geq 100t \ (in\ mm^2) \qquad A_{sf} = \frac{V_c}{f_y.\mu.\phi} \qquad A_{st} = \frac{T}{f_y.\phi} \tag{4}$$

$$As = A_{sf} + A_{st} \geq \frac{0.1 \cdot f'_c A_c}{f_y} \qquad \text{(4) continued}$$

In which the minimum column reinforcement A_s is 2-6mm bars.
ϕ = 0.85 for the combined action of tension T and shear Vc
μ=0.80 is the friction coefficient for concrete-concrete
The column stirrups shall be closed ties or hooks of 6mm bars, spacing 1 at 50mm, 4 at 100mm, and the rest at 250 mm.

The collar beam reinforcement shall be calculated using equation 5. The concrete area of the collar beam A_{cs}, shall be a minimum given by 100 t (in mm^2). The stirrups shall be closed ties or hooks of 6mm bars, spaced 1 at 50mm, 4 at 100mm, and the rest at 250 mm.

$$T_s = VR \frac{L_m}{2L} \qquad A_s = \frac{T}{\phi f_y} \geq \frac{0{,}1 f'_c A_{cs}}{f_y} \tag{5}$$

In the collar beam design, ϕ=0.9. The minimum reinforcement A_s shall be 2-6mm bars. The longitudinal beam bars shall be anchored in the nodes; also, additional hooks can be used in the vertical bars to bend 90° the beam bars.

In the cracked walls, continuous horizontal reinforcement should be placed, anchored into the columns. This should be placed on horizontal joints filled with cement mortar. The amount of horizontal reinforcement, A_{sh}, shall be calculated using equation 6, in which “s” is the vertical spacing between horizontal bars. The minimum reinforcement in any story either cracked or not, shall be 1-6mm bar every 5 layers.

$$A_{sh} = \frac{VR \ .s}{f_y .L} \tag{6}$$

The design of non-cracked walls shall be done whenever the building has enough shear resistance, that is when Σ VR > R V. In the interior columns and in the collar beams of non-cracked walls, a minimum reinforcement may be used. Also, in such walls, it is not necessary to add shear friction reinforcement in the columns. Only the border columns need to be designed, using equation 7.

$$T = F - P_t \qquad A_s = \frac{T}{\phi f_y} \geq \frac{0{,}1 f'_c A_c}{f_y} \tag{7}$$

In which, ϕ=0.9, and F = Mu / L, is the axial force in the border columns, produced by moment Mu. Also, the minimum reinforcement A_s shall be 2-6mm bars.

The lintel beams shall be designed to a combined action of gravity loads and seismic loads. Such beams should be designed in a ductile manner, so that a flexural failure is dominant, as specified in the Peruvian Reinforced Concrete Code ("Norma E.060", SENCICO 2009).

PROPOSAL DESIGN FOR OUT-OF-PLANE SEISMIC LOADS

The confined adobe masonry and with horizontal reinforcement, does not need any further design for out-of-plane seismic loads. Only the braces need to be designed, for which the following specifications shall be used.

The seismic out-of-plane load w, shall be calculated using equation 8, according to the Peruvian Seismic Code (in Peru, "Norma E.030").

$$w = Z.U.C_1 \; \gamma \; e \tag{8}$$

Z, U = zone factor and Importance factor, specified in the Seismic Code.
C1 = seismic coefficient specified in the Seismic Code.
e = gross width of the wall, including the covers if any.
γ = volumetric unit weight of adobe masonry, which can be assumed as160 kN/m^3.

The RC confinements act in this case as braces for the adobe wall. The load that goes from the wall "w" to the braces can be obtained using the envelope rule, consistent in lines with a 45° slope from the wall vertices that intercept a horizontal line drawn at mid height of the wall.

Braces that can have flexure deformations are for example a collar beam without a roof connection, and a column at a free border of the wall. In such braces with flexure deformations, the loads (either triangular or trapezoidal distributed), will produce flexure moments and shear forces, that must be resisted by the cross section and its reinforcement, as specified in the Reinforced Concrete Codes ("Norma E.060" in Peru).

The cross section requirements or its reinforcement obtained in the RC elements acting as braces, need not be added to those values when this elements act as confinements. Only the larger values should be adopted.

CONCLUSIONS

A rational design proposal for the seismic design of confined adobe buildings has been presented, limited to two stories high. The proposal is based on several experimental static and dynamic tests on full scale models, and the knowledge of brick confined wall seismic behavior. In order to improve the confined adobe design proposal presented in this paper, some more experimental research must be done. For instance, an important research pending is the verification under out-of-plane seismic loads of adobe walls located on a second story, with the reinforcement specified in this proposal. Up to date, the observed seismic behavior under real earthquakes and in the lab tests indicates that it is possible to use this proposal safely.

ACKNOWLEDGEMENTS
The authors want to thank the students that worked in the researches described in this paper; they studied at the Catholic University of Peru. Also, a special acknowledge to the personnel at the Structures Laboratory of the University, where the experimental tests were performed.

REFERENCES
1. EERI (1995) "The September 14, 1995, Ometepec, Mexico, Earthquake". EERI Special Earthquake Report–December 1995. http://www.eeri.org/site/reconnaissance-activities/76-mexico (Read: 8/08/2011).
2. Matos, G., Quiun, D. and San Bartolomé, A. (1997) "Seismic Simulation test of one adobe model confined by reinforced concrete elements" (in Spanish) XI Peruvian Conference on Civil Engineering, Colegio de Ingenieros del Peru, Trujillo, Peru.
3. San Bartolomé, A. and Pehovaz, H. (2003) "Behavior under cyclic lateral load of confined adobe walls" (in Spanish), in Albañilería de Tierra Cruda, http://blog.pucp.edu.pe/albanileria.
4. San Bartolomé, A., Delgado, E. and Quiun D. (2009) "Seismic Behavior of a two story model of Confined Adobe Masonry" 11th Canadian Masonry Symposium, Toronto, Canada, on CD-ROM.
5. Torres, A. (2012) "Seismic Behavior of Confined Adobe, Variation: horizontal reinforcement" (in Spanish) Civil Engineering Thesis advised by A. San Bartolome, Faculty of Science and Engineering, Catholic University of Peru, Lima, Peru.
6. San Bartolomé, A. and Quiun D. (2007) "Design Proposal of Confined Masonry Buildings" 10th North American Masonry Conference, St. Louis, Missouri, USA, on CD-ROM.
7. SENCICO (2006) "Norma E.070 Albañilería", Lima, Perú (in Spanish).
8. SENCICO (2006) "Norma E.030 Diseño Sismorrresistente", Lima, Perú (in Spanish).
9. SENCICO (2009) "Norma E.060 Concreto Armado", Lima, Perú (in Spanish).