EXPERIMENTAL AND ANALYTICAL APPROACH FOR THE ASSESMENT OF FLEXURAL STRENGTH OF ADOBE MASONRY

Daniel Torrealva[1], Mario Solís[2], Patricia Santillán[1], Gonzalo Montoya[2]

[1]Engineering Department
Pontificia Universidad Católica del Perú
Avda. Universitaria 1801
San Miguel, Lima 32 Perú
Tel: 511 6262000
E-mail: *dtorrea@pucp.edu.pe*

School of Engineering
Universidad de Sevilla
Camino de los descubrimientos s/n
41092 Sevilla Spain
Tel: 0034 954487294
E-mail: *msolis@us.es*

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Abstract
This paper presents an investigation about the flexural behavior of adobe masonry. It is focused on the development of constitutive models that can serve as a basis for the establishment of new design guidelines for adobe constructions, with special emphasis on seismic reinforcements. The paper analyzes the flexural behaviour of geogrid reinforced adobe walls. The experimental seismic tests of geogrid reinforced adobe houses have proven the effectiveness of the reinforcement technique. However, additional research is needed to develop constitutive models that can be used to quantify the actual performances of the reinforced adobe. For this purpose, bending tests have been carried out to obtain experimental curvature-moment relationships for reinforced and non reinforced adobe walls. Analytical models have been developed to approach these experimental laws, using equilibrium and compatibility equations similar to those usually applied for the flexural behaviour of reinforced concrete. The constitutive models of the individual materials are previously obtained through experimental tests, and simplified constitutive models are proposed for the governing equations. The analytical models show the ductility of adobe masonry, and how ductility increases when adobe is reinforced with geogrids. The proposed mathematical models and methodology can be applied to other structural elements and reinforcement systems. They can serve as a basis for the development of new design guidelines for adobe masonry.

1. INTRODUCTION

Rammed earth exhibits well known features as a building material (low cost, sustainability, thermal and acoustuc isolation, etc). However, it exhibits low mechanical strength, and unfortunately it is most commonly used in areas where there is a high seismic risk. Therefore, it is clearly necessary to develop reinforcement systems and design guidelines to obtain adequate levels of resistance, essentially to seismic loads, both for building housing and conserving historic sites. This requires thorough and in-depth research studies on the behavior of structures built with this material. The present paper aims to take a first step towards the study of the structural behavior of adobe masonry, focusing on the bending behavior of geogrid reinforced and non reinforced walls.

Over the last few decades, various reinforcement techniques have been studied to improve the resistance properties of adobe. Types of reinforcements studied include natural materials (straw, cane, wood, etc.) (Ottazzi et al, 1988, p. 1123-1128, Bariola et al, 1988, p. 1154) as well as industrial materials such as chicken wire, electro-welded steel wire mesh, PVC pipes and other plastic materials (Zegarra et al, 1997, p. 1, Zegarra et al, 2001, p. 1, Blondet et al, 2005, p. 1-20). Although all these techniques improve the structural behavior of adobe, no mathematical models of the structural behavior of these techniques have been developed so far to quantify the positive effect of the reinforcement system.

In recent years, proposals have been made to reinforce adobe walls with geogrids, a polymeric material (Blondet et al, 2005, p. 1-20, Blondet et al, 2006, p. 1-8, Torrealva et al, 2008, p. 1-6). This reinforcement improves the resistance of adobe walls, essentially increasing its capacity to withstand tensile stress. An additional advantage to the structural benefits of this reinforcement technique is that it can be applied to existing structures without changing their external appearance. Moreover, it has good durability and resistance to corrosion and is economically affordable.

The procedure used to build houses with geogrid-reinforced adobe is explained in several booklets produced to disseminate the construction technique based on the reconstruction of the areas damaged in the Pisco earthquake in 2007 (Vargas et al, 2007, p. 22-29, GTZ, 2007, p. 37-54).

The basic idea of the geogrid reinforcement technique is to wrap the reinforcement around the walls, working jointly with them. To do so, the geogrid is tied to the wall with strings threaded through the walls during their construction. When building the walls, strands of rope or nylon should be placed between the bricks. Once the walls are built, the geogrid should be placed on both sides and tied with the strings. This attachment method is completed by covering the geogrid with mud mortar. For the geogrid to wrap the whole adobe structure effectively, the different pieces of geogrid should be placed with sufficient overlapping and attached to one another with pieces of polymer string. The geogrid should be anchored to the stem wall at the bottom and wrapped around the ring beam at the top.

When using the reinforcement technique on existing constructions, such as historic buildings, for example, the construction technique is essentially similar to the process described above. In these cases, however, the placement of the strings to attach the geogrid to the wall requires drilling holes in the wall.

The present paper attempts to study the behavior of this compound material formed by adobe and geogrid reinforcement. For the first time, the paper proposes analytical behavior models for earthen buildings so that in the future design procedures are not only based on experience and restricted to qualitative criteria or geometrical proportions.

The paper is organized as follows. Firstly, the experimental constitutive law of each individual material is analyzed. Then, the paper shows the experimental results of the bending tests of the reinforced and non-reinforced adobe walls. Finally, the paper presents an analytical model for the structural behavior of the walls to approach the experimental curvature-moment relationship. The last section includes conclusions and proposals for future research.

2. MATERIAL PROPERTIES

Adobe was characterized by performing compression tests on individual adobe bricks and piles of 5 bricks. The dimensions of the adobe bricks were 120x210x100 mm.
These tests showed an average resistance of 1.0 MPa for the bricks. The experimental constitutive law obtained for the adobe masonry (the brick piles) show

that adobe masonry have a maximum compression stress around 1.1MPa when the compressive strain reaches 0.4%.

To characterize the behavior of the geogrid, tensile tests were performed following the specifications of the ASTM D6631-01 standard. The geogrid exhibits a very ductile behavior. It showed an experimental average tensile strength of 25 kN/m for a maximum strain of 13%.

The experimental compression constitutive law of adobe and the tensile constitutive law of the geogrid was approached by piecewise linear functions. These linearized constitutive laws were used for the analytical models.

3. EXPERIMENTAL FLEXURAL BEHAVIOR

To characterize the bending behavior of walls, bending tests were performed at 3 points of vertical walls, as shown in Fig. 1. The walls were 1.60m high, 0.80m wide and 0.22m thick. Of the 3 walls tested, one did not have any kind of reinforcement and the other two were reinforced with geogrid.

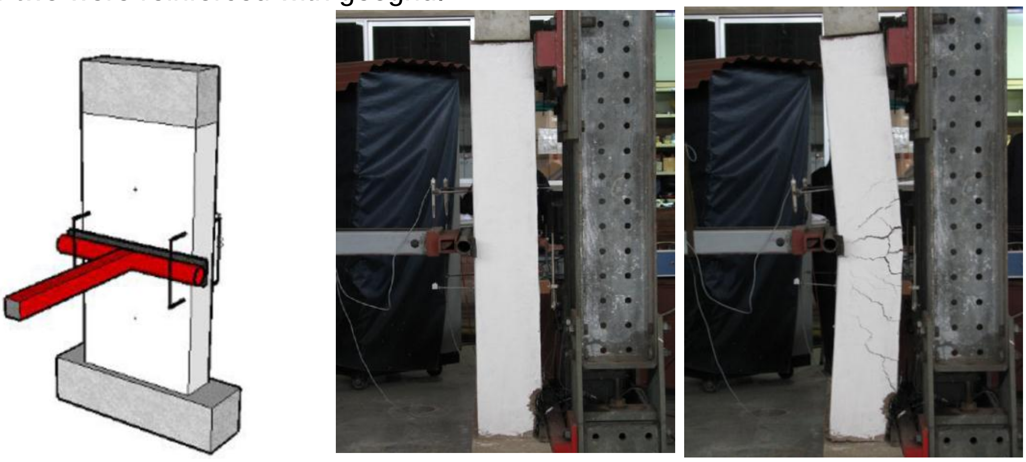

Fig. 1. Pictures of the bending tests

These tests recorded applied force, which determines the bending moment in the middle section of the wall. At the same time, strains were measured at two points of the tensile side (ε^+) and two points of the compressive side of the wall (ε^-) in its middle area, using LVDT sensors recording the relative displacement between two points 40cm apart . This yields two measurements of the curvature (χ) in the middle section, obtained from the following expression:

$$\mathrm{X} = \frac{\varepsilon^+ - \varepsilon^-}{h} \quad \text{(Eq. 1)}$$

where *h* is the thickness of the wall (h=0.22m).

Fig. 2 shows the combined results of the moment-curvature law for the tested walls. This law was obtained from two points of each wall, producing 6 curves (2 for wall 1, without geogrid, and the remaining 4 for walls 2 and 3, with geogrid).

During the trials with the reinforced walls, load and unload cycles were performed to study the ductile behavior of the wall and its ability to recover from the load and strain level after each cycle. The behavior observed was similar to that of a reinforced concrete beam.

As shown in the Fig. 2, all the experimental curves obtained were very similar. Hence, it can be concluded that the geogrid reinforced adobe walls show a ultimate strength (4.4kNm) three times higher than a non-reinforced wall (1.4kNm). In addition, the ductility of the reinforced walls is much higher. The maximum curvature is also three times higher than the non-reinforced one. The behavior after the elastic first stage is also different. The non-reinforced wall show a softening process (bending moment decreases for higher deformation) whereas the reinforced wall still increasing its bearing load for increasing deformation.

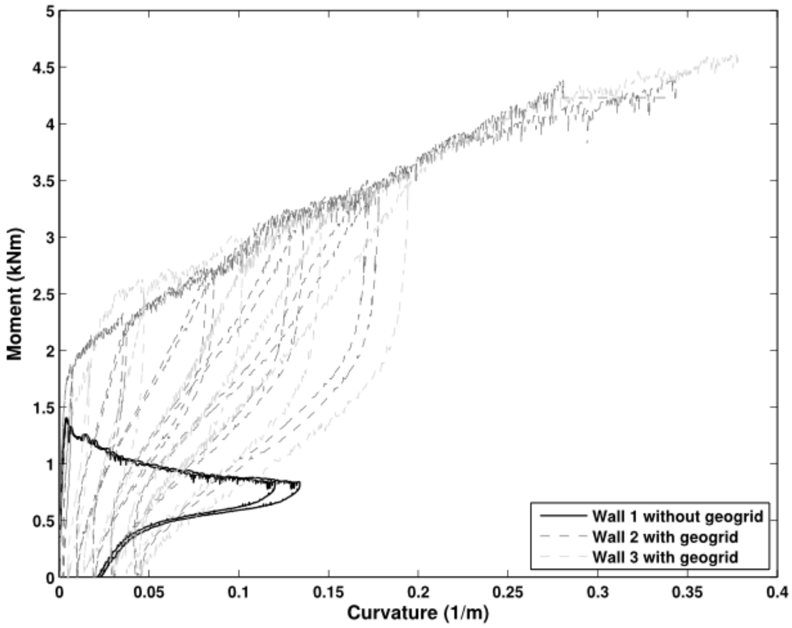

Fig.2. Experimental moment-curvature relationships

The curvature-moment relationships and the load and unload cycles show that the geogrid reinforcement significantly increases the amount of energy that can be dissipated during a shaking excitation. This is a major enhancement of the seismic response of the wall.

4. ANALYTICAL APPROACH

This paper proposes the use of similar equations to those used for the reinforced concrete. The governing equations of the bending problem for the cross-section are used to predict analytically a moment-curvature relationship.

The bending problem is governed by compatibility and equilibrium equations in the cross-section of the wall. The present research assumes that the wall behaves like an Euler-Bernoulli beam, with small displacements, small strains and flat sections remaining flat, with negligible shear strain.

Thus, a linear distribution of strains was defined along the cross-section of the wall (thickness h=0.22 m for the tested walls). Fig. 3 shows the strains along the cross-section, as a function of a *y* coordinate defined along the section. The extreme compression fiber is located at the *y=0* coordinate, which corresponds to the geogrid's strain under compression ε_{gc}, whereas the extreme tensile fiber is located at *y=h*, which corresponds to the geogrid's strain under tension ε_{gt}. The neutral axis is located at the *y=x* coordinate, and the angle formed by this strain profile with the undeformed position is the curvature of the wall's transverse deflection (χ).

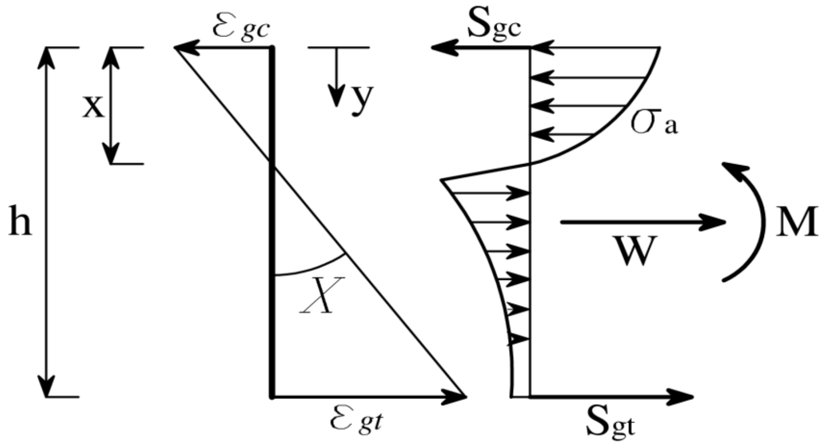

Fig. 3. Distribution of strains and stresses in the cross-section of the wall

The strains of each point can be written as a function of the *y* coordinate, of the depth of neutral fiber *x* and of curvature χ , according to the following expressions:

$\varepsilon_a(y,x,\mathrm{X}) = \mathrm{X}\cdot(y-x)$ (Eq.2)

$\varepsilon_{gc}(x,\mathrm{X}) = \mathrm{X}\cdot x$ (Eq.3)

$\varepsilon_{gt}(x,\mathrm{X}) = \mathrm{X}\cdot(h-x)$ (Eq.4)

Provided that the constitutive laws of the material are known, the distribution of strains can be used to assess the resulting stress sustained by each material (Fig. 3), knowing that equilibrium must be reached in the section. In these equilibrium equations, the resulting force sustained by the adobe is given by the integral of the stress distribution $\sigma_a(\varepsilon_a)$ along the section (the width of the wall is given by parameter b=0.8 m). These stresses can be compressive or tensile and are defined by the constitutive law of the material. Such stresses are zero for strains greater than those acceptable under tension and compression. The resulting forces of the geogrid under tension and compression are defined by its stress per unit of length (S_{gt} and S_{gc} respectively). The authors considered that the presence of mortar around the compression geogrid allows it to work under compression, since this seemed logical. However, future trials will be necessary to verify whether this hypothesis is correct or not.

The force and moment equilibrium equations can therefore be written as follows:

$$\int_0^h \sigma_a(\varepsilon_a(y,x,\mathrm{X})\cdot b\cdot dy + S_{gc}(\varepsilon_{gc}(x,\mathrm{X}))\cdot b + S_{gt}(\varepsilon_{gt}(x,\mathrm{X}))\cdot b = W \qquad \text{(Eq. 5)}$$

$$\int_0^h \sigma_a(\varepsilon_a(y,x,\mathrm{X})\cdot b\cdot(y-h)\cdot dy - S_{gc}(\varepsilon_{gc}(x,\mathrm{X}))\cdot b\cdot h + W\cdot h/2 = M \qquad \text{(Eq. 6)}$$

In the force equilibrium equation (Eq. 5), the value of W is that of the corresponding dead load of the section under analysis. Given the dimensions of the walls tested and the weight of the concrete element at the top used for their handling, an approximate value of *W=-4kN* was considered.

In the moment equilibrium equation (Eq. 6), the origin of moments chosen was the extreme fiber corresponding to *y=h,* where the tensile geogrid was located.

By introducing the constitutive law for each individual material in the equilibrium equations, one can obtain the profile of strains in the section that corresponds for every value of bending moment. Hence, the analytical curvature-moment relationship is obtained.

5. ANALYTICAL RESULTS

The first analytical approach to bending behavior is based on introducing material constitutive laws based on those obtained in the individual tests of the materials into the equations of the problem. As it was stated above, these experimental laws were approached by means of a piecewise linear law to simplify numerical calculations.
In order to analyze and understand the real behavior of the walls observed experimentally, various constitutive models of adobe under tension were considered. This paper shows the values resulting from considering a few characteristic models, called A, B, C and D. The laws of these models under tension are shown in Fig. 4.

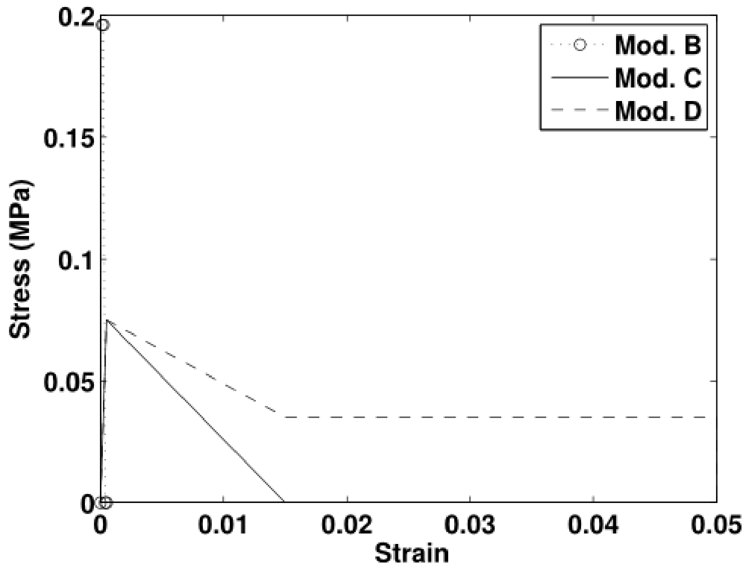

Fig. 4. Tensile constitutive laws of adobe considered for the analytical models

Law A considers that adobe does not offer any resistance to tension. Law B supposes an equal initial tensile and compressive stiffness (752.5 Mpa), which is equal to the initial experimental compressive stiffness. It assumes a maximum tensile stress of 0.196 MPa. This value corresponds to the tensile crack stress obtained by assuming a cracking moment of 1.4kN.m, which is the maximum moment obtained experimentally for the wall without geogrid, and subtracting the stress caused by dead load. This yields an approximate value of tensile strength in adobe.

Law C supposes a lower initial tensile stiffness (369 MPa), reaching a maximum tension of 0.075 MPa. It also offers greater ductility, by means of progressive softening to reach a maximum strain of 1.5%.

Finally, model D differs from C in its softening and has even higher ductility. Softening occurs first, reaching a stress of 0.035 MPa, and it is followed by a perfect elasto-plastic behavior, reaching a strain of 5%.

Fig. 5 shows the curvature-moment relationships obtained for each model for the non reinforced wall. Results for model A shows that if tensions in adobe are not considered, the wall can only withstand the moment thanks to the pre-compression caused by the dead load, and its higher value (0.4 kNm) is much lower than the real value. This illustrates the fact that, in non-reinforced adobe constructions, the material's tensile resistance must be considered to estimate its bending resistance, except in those cases in which the dead load borne by the wall is much higher than its tensile resistance. This is not the case in rural adobe houses but may occur in historic buildings, where walls are thicker and the weight of ceilings or roofs can be greater.

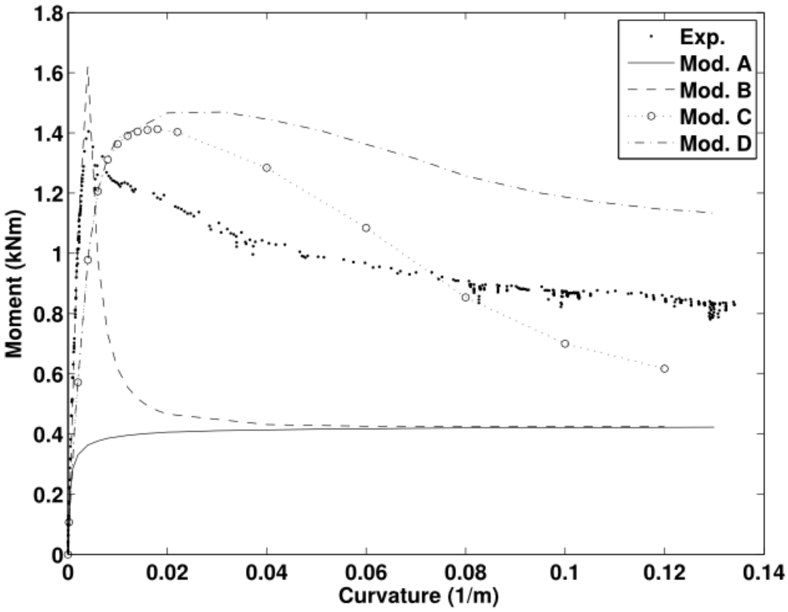

Fig. 5. Analytical and experimental moment-curvature laws for a non reinforced wall.

Considering a tensile law like that of model B, it can be observed that the stiffness reached in the initial stretch of the moment-curvature law is too high. The maximum moment, reached when the extreme tensile fiber reaches its maximum allowable strain (0.0005), is also too high. From that point, the moment falls sharply and converges to the curve of the model without tensile resistance (model A). This means that, when subjected to tension, adobe presumably has a lower tensile resistance than that estimated from the cracking moment, a lower stiffness to compression than that obtained experimentally and particularly higher ductility.

Models C and D are aimed at illustrating this fact. As can be seen, model C adapts to the experimental behavior with a high degree of approximation and has a slightly less stiff and ductile behavior than the real behavior. The opposite is true for model D, which is more distant from the experimental behavior than model C.

For a reinforced wall (Fig. 6) model A is also unable to simulate the cracking phenomenon (which happens approximately at a moment of 1.8kNm). It does not make it possible to estimate the value of the maximum moment correctly either. Yet, once its cracking moment is reached and the geogrids start to work significantly, the chart shows a similar slope to the experimental conditions (similar stiffness) and shows a certain convergence towards the maximum moment obtained experimentally. This is because in this situation stiffness is determined by the geogrids and, to a lesser extent, to adobe under compression, and the tension of adobe plays a negligible role in a situation close to breaking.

Model B shows good behavior until the cracking moment. Yet, resistance drops sharply after this and rapidly tends towards type A behavior (without tensions in adobe).

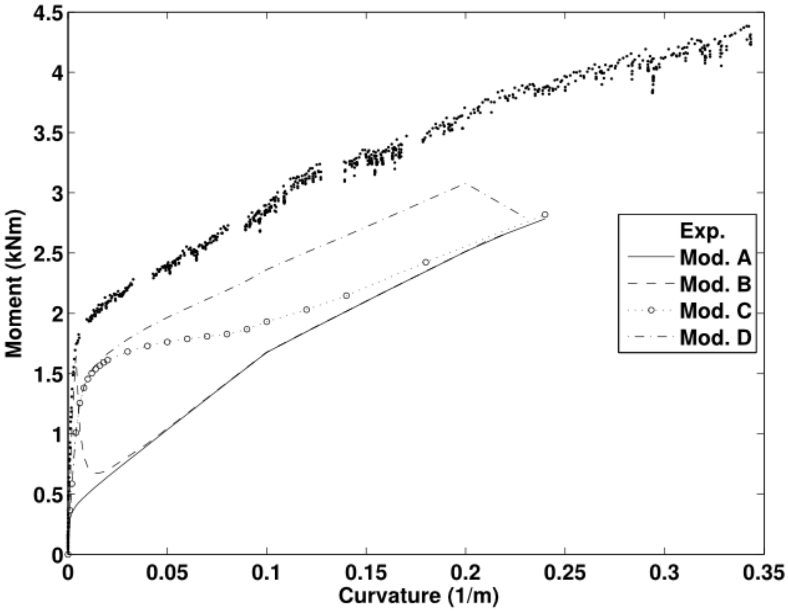

Fig. 6. Analytical and experimental moment-curvature laws for a reinforced wall.

Again, models C and D reproduce real behavior quite closely, although model D is closer to reality. A comparison between this situation and that of the non-reinforced wall suggests that the geogrid itself not only increases the resistance of the wall but also brings cohesion to adobe that contributes to improving its properties, increasing its resistance and ductility.

The results obtained show that the relationship between the tensile and compressive resistance of adobe masonry is relatively high if compared with the usual values found in concrete. However, considering a compressive resistance of 1 MPa in adobe and applying the approximate correlations commonly used to infer the tensile strength of concrete from its compression strength (Calavera, 1992, p. 24 EHE Standard, 2008, p. 114), the values of tensile strength obtained would be about 30% of those of compression; in concrete, however, the typical value for this would be 10-15%. This is because, as happens with concrete, it can be understood that a lower resistance to compression leads to a higher relationship between tensile and compressive strength.

The influence of this tensile behavior is obviously negligible when calculating the ultimate bending moment of the wall. However, results show that it provides high ductility and is essential to obtain an approximate law of its behavior before breaking. Such behavior ultimately defines and characterizes the wall's ability to dissipate energy and defend itself in the event of an earthquake.

6. CONCLUSIONS AND FUTURE RESEARCH

This paper aims to contribute to the development of calculation models for earthen constructions. Such models are essential to respond to the need to define design and calculation criteria in this type of constructions, whether the purpose is to build inexpensive earthquake-resistant houses or to conserve historic buildings.

The present study has developed models of the bending behavior of geogrid-reinforced adobe walls. It proves that it is possible to obtain and apply such models in this building technique, in spite of the fact that earth is usually considered as a "non-engineering" material.

The models developed prove that, contrary to the general belief, adobe masonry has relatively high ductility, in spite of its low tensile strength. Moreover, the ductility of adobe considerably improves when geogrid reinforcement is used. Thus, the geogrid reinforcement contributes to dissipate the energy transmitted by an earthquake, and contains the adobe masonry avoiding the collapse of the structure even when it is subjected to great displacements. Moreover, from an engineering viewpoint, the geogrid reinforcement provides controlled mechanical properties that can be used to make safer and more reliable predictions about the structural behavior of reinforced adobe masonry.

The paper also proves the need to consider the tensile behavior of adobe when exploring the bending behavior laws of the walls analyzed. Such laws define the walls' capacity to dissipate energy of the material in load and unload cycles, as happens in an earthquake. However, as can be expected, this tensile strength is negligible in the calculation of the ultimate collapse moment under a static load.

Yet, new experimental tests are needed to validate, complete and improve the models proposed in this paper. To do so, we suggest to start by performing bending trials at 4 points, with different reinforcement conditions in the area between the points where the load is applied (area of constant bending moment). This would make it possible to test walls with differences in this area: no union mortar between adobe blocks, no mud covering the geogrid, or neither of them. These tests will shed more light on the importance of these elements on the global behavior of the compound adobe-geogrid material with greater accuracy. This is relevant, first of all, because these are the components whose properties are subject to the highest variability depending on the skills and performance of the people doing the work. Secondly, the mud cover may fall off in an earthquake. These tests would help to quantify the contribution of each component of the compound adobe-geogrid material with greater accuracy and lead to more reliable models yielding practical calculation values that are on the safe side.

More progress is also needed to develop shear behavior models for this type of walls to complete knowledge about their structural behavior. In these shear tests, as in the bending tests mentioned above, it will be necessary to study walls of different thickness to check the validity of the models developed.

Once models of bending and shear behavior are obtained, it will be possible to develop finite element models to model the behavior of constructions made with this material, at least approximately. This would be a great step forward in structural integrity analysis and the design of reinforcement systems for these constructions.

The authors will appreciate any contributions made by other researchers in the areas of research proposed here, trusting that cooperation between different research groups and laboratories will lead to the greatest progress in this field.

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Curriculum

Daniel Torrealva, Civil Engineer, Professor at the Catholic University of Peru (PUCP). Earth constructions in seismic areas researcher since 1980.Member of the International Scientific Comittee of Earth Architectural Heritage of ICOMOS. Dean of the Engineering Faculty of the PUCP.

Mario Solís, Mechanical Engineer. Assistant Professor at the Engineering School of the University of Sevilla. PhD on Continuum Mechanics at the Univ. of Sevilla. Research topics: structural and soil dynamics, structural health monitoring. Member of the NGO Engineering Without Borders (Ingeniería Sin Fronteras)

Patricia Santillán, Civil Engineer since 2003. Assistant Professor at the PUCP. Master of Science at the PUCP. Master thesis about the structural behavior of geogrid reinforced adobe walls.

Gonzalo Montoya. Mechanical Engineer since 2010. Graduation Thesis about mechanical models of reinforced and non reinforced adobe masonry.