EMPIRICAL FLEXURAL BEHAVIOR APPROACH OF ADOBE MASONRY

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Adobe masonry is one of the most widespread low cost material used for housing in the world. Unfortunately, it shows very low mechanical strength and it is mainly used in seismic. Therefore, there is a requirement for sustainable and efficient reinforcement techniques, as well as design guidelines based on scientific research to apply them. It is necessary to build healthy and safe earthen houses, as well as to preserve earthen constructions heritage sites, which most of them are in danger of collapse.

Polymeric geogrids have proven to be an efficient reinforcement technique. The dynamic response of geogrid reinforced adobe constructions has been analyzed in dynamic seismic simulation tests. When comparing with non reinforced constructions, they significantly increase the strength of the construction and reduce the danger of collapse under a seismic load.

This paper presents an empirical approach for the assessment of the flexural behavior and flexural strength of adobe masonry, considering the effect of geogrid reinforcement. The approach is based on the analysis of experimental results of bending tests of adobe walls reinforced and non reinforced with geogrids. Analytical models for the flexural behavior were initially based on the constitutive laws of the individual materials. Then, they have been simplified and updated so they agree with experimental moment-curvature relationships.

The analytical approach show that it is necessary to consider the tensile behavior of adobe in order to obtain a realistic moment-curvature relationship. However, in the ultimate state of the wall, tensile strength of adobe can be neglected, and the ultimate flexural strength of the wall is defined by the cracking of adobe under compression or the breakage of the geogrid under tension. The paper includes a simplified method for the assessment of the ultimate strength of adobe walls, based on similar methods used for reinforced concrete.

Keywords: *adobe masonry, seismic reinforcement, flexural behavior, geogrid reinforcement*

INTRODUCTION

Earth is one of the oldest building materials used by humans. About 10% of UNESCO World Heritage Sites are earthen constructions; moreover, almost 60% of World Heritage Sites in danger of destruction or collapse are built with earth (Alejandro Alva 2001). Earthen construction is currently considered to be a low-cost technology because the materials it requires are readily available and easy to handle. According to studies by several authors (Dethier 1983; Lynne and Adams 2000), it is estimated that between 30 and 50% of the global population lives in earthen houses.

Apart from being inexpensive, earthen constructions have excellent thermal and acoustic insulation properties, aesthetic qualities and environmental sustainability. This is why certain sectors of modern architecture are paying special attention to such constructions for specific applications and their use is growing in developed countries all over the world.

The main disadvantage of earth as a building material lies in its low mechanical properties (compressive strength is in the order of 1 MPa), added to the highly heterogeneous values of such properties and particularly the difficulty to determine such values accurately, whether in cheap housing or historic buildings. To make matters worse, many of the geographical areas where earthen construction is common are precisely the areas of the planet most prone to earthquakes.

Therefore, it is obvious that adobe cannot be considered as a non-engineering material and that seismic reinfrocement techniques and guidelines are necessary for the design and analysis of structures made with this material. Moreover, it is necessary to transfer the necessary knowledge with the right format and level for each situation and obtain safe results on every occasion.

As regards housing, it is important to consider the socio-economic context . Design guidelines should be easy to understand and implement, and be accompanied by training and dissemination programs aimed at beneficiaries, local professionals, non-governmental organizations, institutions, etc. Knowledge and technology should be transferred adequately, adapting to the level of training and prior knowledge of participants in such activities, and assuming low or nonexistent technical and quality control in this type of construction. In the case of historic buildings, design guidelines and calculation models can be more complex, given that skilled professionals will probably be involved. Each case will require a specific study and course of action.

In recent years, proposals have been made to reinforce adobe walls with geogrids, a polymeric material (Blondet et al. 2006; Torrealva, Cerrón, and Espinoza 2008; Torrealva 2009) . 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 (Figure 1). This attachment method is completed by covering the geogrid with mud mortar (Figure 1). The geogrid should be anchored to the stem wall at the bottom and wrapped around the ring beam at the top.

Figure 1. Building of the tested walls

This reinforcement improves the resistance of adobe walls, essentially increasing its capacity to withstand tensile stress. Even more importantly, it increases the ductility of the building,

dissipating the energy transmitted by the earthquake, as it has been qualitatively proven in dynamic seismic simulation tests (Blondet et al. 2006).
The reinforcement technique has been disseminated in various meetings and has received great interest in the field of foreign aid and restoration and conservation of historic buildings. In fact, the technique has already being used in Peru and Chile to build new houses and restore churches and other earthen buildings damaged by the 2007 and 2010 earthquakes
In a previous paper (Torrealva et al. 2012), similar analytical models used directly the constitutive laws of the individual constituent materials and the experimental behavior was successfully approached. The present paper attempts to obtain similar results by using simplified constitutive models that could lay the basis for simplified methods for the assessment of flexural behavior and flexural strength of adobe walls.

PROPERTIES OF CONSTITUENT MATERIALS

Compressive tests of individual adobe bricks showed an average ultimate strength of 1.0MPa. Compression tests of piles of 5 bricks showed a maximum strength of 1.1 MPa when the compressive strain reaches 0.4% (Figure 2). As for the geogrid, it showed an elastoplastic behavior with an average maximum tensile strength of 25kN/m and maximum elongation of 13% (Figure 2).

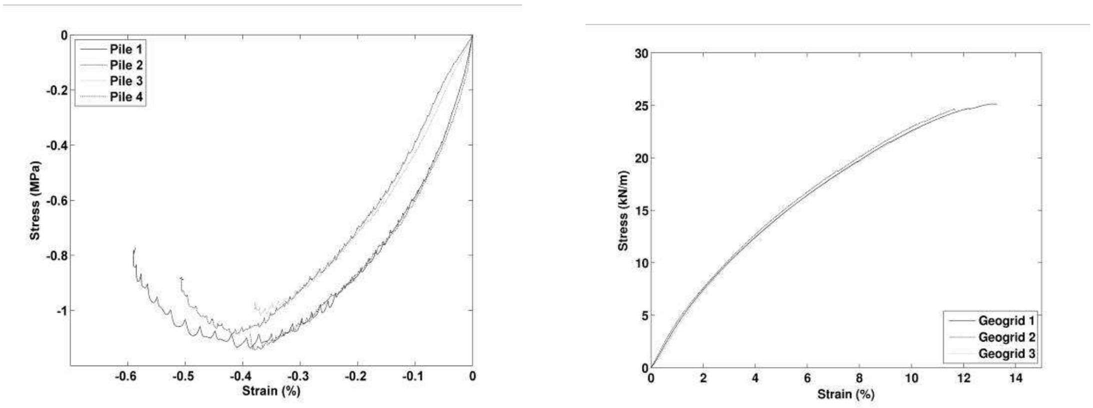

Figure 2. Experimental constitutive laws of adobe masonry (compressive) and geogrid (tensile)

These experimental constitutive laws can be approached by a piecewise linear law according to the numerical intervals shown in Table 1. In a previous work (Torrealva et al. 2012) these linearized laws were directly introduced into the governing equations. The present paper uses them as a reference, as it will be discussed in the following sections.

Table 1. Definition of interval values for the piecewise linear approach of constitutive laws of adobe in compression and geogrid in tension

Adobe Strain interval	E(MPa)	Geogrid Strain Interval	E(kN/m)
[0,-0.005)	752.5	[0,0.02)	374.4
[-0.005, -0.0015)	339.0	[0.02, 0.042)	214.1
[-0.0015,-0.0025)	225.9	[0.042, 0.07)	188.8

[-0.0025,-0.004)	99.6	[0.07, 0.106)	142.5
[-0.004,-0.005)	-59.0	[0.106, 0.1328)	71
[-0.005,-0.0056)	-284.4	-	-
[-0.0056,-0.0058)	-1649	-	-
[-0.0058,-0.047)	-0.370	-	-

EXPERIMENTAL FLEXURAL BEHAVIOR OF ADOBE WALLS

Three point bending tests were performed for 3 walls (Figure 3). The tested walls were 1.60 m high, 0.80 m wide and 0.22 m thick. Of the 3 walls tested, one did not have any kind of reinforcement and the other two were reinforced with geogrid.

Figure 3. Three point bending tests of adobe walls

Experimental moment-curvature law was obtained from the applied force (*F*) and strains at the tensile and compressive sides (ε^+ and ε^- respectively), according to equations 1 and 2

$$M = F \cdot L / 2 \qquad (1)$$

$$\mathrm{X} = \frac{\varepsilon^+ - \varepsilon^-}{h} \qquad (2)$$

where M is the bending moment, L is the height of the wall and X is the curvature at the middle section of the wall.

Figure 4 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 tests 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.

From Figure 4, 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.

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.

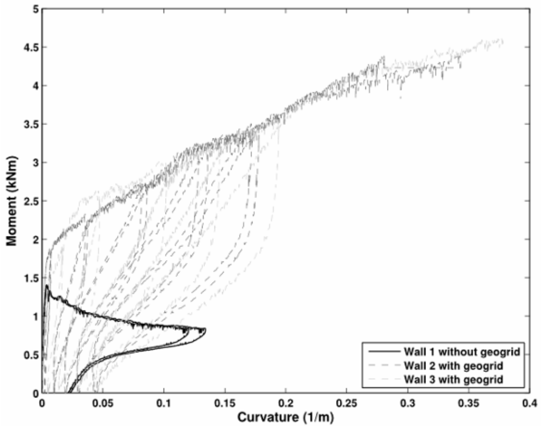

Figure 4. Experimental moment-curvature relationships

EMPIRICAL MODEL OF FLEXURAL BEHAVIOR

The bending problem is governed by compatibility and equilibrium equations in the cross-section of the wall. For the compatibility equations, it is assumed that there is a linear distribution of strains along the cross-section of the wall (Figure 5). 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}, being *h* the thickness of the wall. 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).

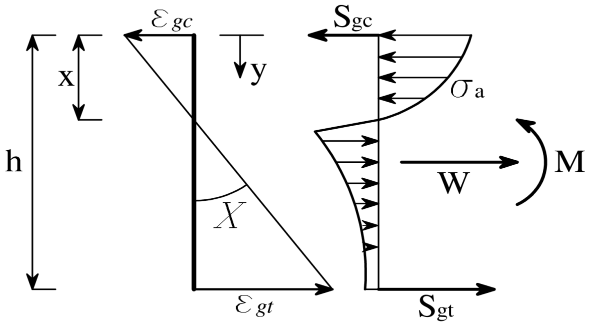

Figure 5. Stresses and strains distribution along the cross-section of the wall

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 Equations 3, 4 and 5:

$$\varepsilon_a(y,x,\mathrm{X}) = \mathrm{X}\cdot(y-x) \quad (3)$$

$$\varepsilon_{gc}(x,\mathrm{X}) = \mathrm{X}\cdot x \quad (4)$$

$$\varepsilon_{gt}(x,\mathrm{X}) = \mathrm{X}\cdot(h-x) \quad (5)$$

The force and moment equilibrium equations can therefore be written as Equations 6 and 7.

$$\int_0^h \sigma_a(\varepsilon_a(y,x,\mathrm{X})\cdot b\cdot dy + S_{gc}(\varepsilon_{gc}(x,\mathrm{X}))\cdot b + S_{gt}(\varepsilon_{gt}(x,\mathrm{X}))\cdot b = W \qquad (6)$$

$$\int_0^h \sigma_a(\varepsilon_a(y,x,\mathrm{X})\cdot b\cdot(y-h)\cdot dy - S_{gc}(\varepsilon_{gc}(x,\mathrm{X}))\cdot b\cdot h + W\cdot h/2 = M \qquad (7)$$

where $\sigma_a(\varepsilon_a)$ is the stress for the adobe, S_{gc} and S_{gt} are the geogrid tensile and compressive force per unit length, respectively, and b is the width of the wall (b=0.8m).

In the force equilibrium equation (Equation 6), the value of W is that of the corresponding dead load of the section under analysis. Therefore, W is negative because it is a compressive force. Given the dimensions of the walls tested and the weight of the concrete element at the top used for their handling, a value of W=-4kN was considered.

In the moment equilibrium equation (Equation 7), the origin of moments chosen was the extreme fiber corresponding to $y=h$, where the tensile geogrid was located. This origin was chosen because it was the most favorable point from a computational point of view, as happens in sections of reinforced concrete (Montoya et al. 2009). The resulting bending moment in the section was represented by M.

Provided that the constitutive laws of the materials are known, Equations 6 and 7 are a non-linear system of equations with three unknowns: x, χ and M. Equilibrium equations for given χ values are solved by introducing the constitutive law of each material in the equilibrium equations and writing the strains on the basis of parameters y, x, χ. The depth of the neutral fiber x is obtained from the force equilibrium equation (Equation 6), and the resulting moment is obtained by introducing the value of x in the moment equation (Equation 7). Thus, the bending moment M is obtained for every given value of curvature χ and the analytical moment-curvature relationship is obtained. Choosing other independent parameters different from M and x has been observed to cause greater numerical instability and difficulties in the convergence of the system’s resolution.

In a previous paper (Torrealva et al. 2012), experimental moment curvature relationships were approached analytically by using the constitutive laws of the individual materials. For doing so, the tensile behavior of adobe had to be considered in order to obtain good results. Results and conclusions obtained in that paper have been used in the present paper to explore the possibility of approaching the constitutive laws of materials using simplified models. The purpose of designing such laws is to obtain reference values that make it possible to obtain approximate results for different wall configurations and can be of practical use without the need of precise information about the constituent laws of the individual materials..

A range of constitutive models were analyzed, changing the stiffness, strength and ductility of adobe, both under compression and tension. For the geogrid, the piecewise linear constitutive model considered in the previous paper was maintained.

To illustrate the results obtained, results of four different constitutive models are presented. The behavior laws of these simplified models are shown in Figure 6. Model 1 showed an initial tensile and compressive stiffness equal to the initial compressive stiffness obtained experimentally (E=752 MPa). By contrast, stiffness in the rest of the models was E=369 MPa, which corresponds to the rigidity of the second section of the linearized experimental compression law. Models 2, 3 and 4 show growing ductility in that order, allowing the same maximum allowable strain under tension and compression.

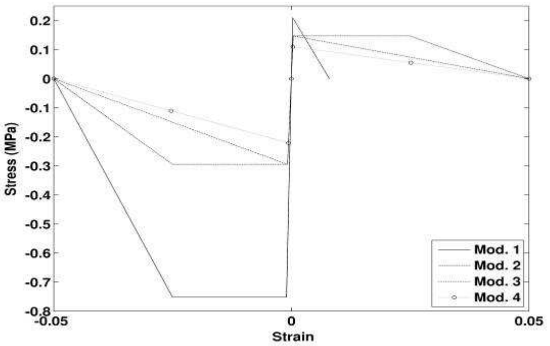

Figure 6. Simplified constitutive models for the analytical approach

Results obtained with these laws in the non-reinforced wall (Figure 7) show a qualitatively similar evolution to the experimental results, except model 1, which shows too much stiffness and strength. In the rest of the models, the approximation is better when the mechanical properties of adobe are weaker. The best results are provided by model 4, followed by model 3 and 2, in this order.

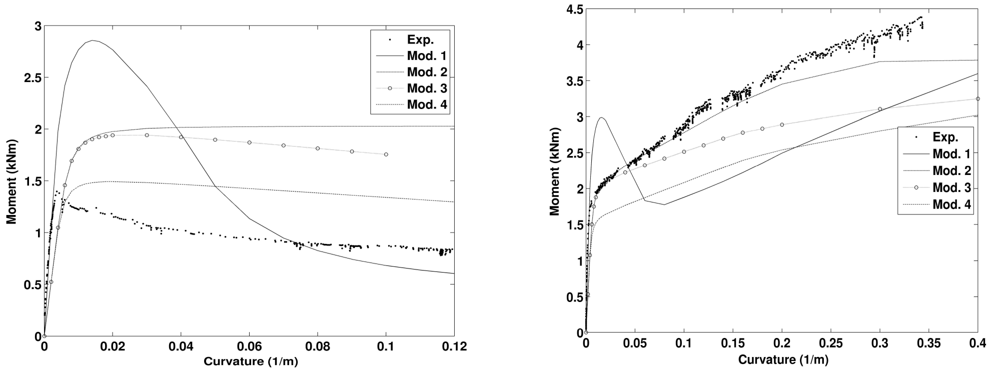

Figure 7. Analytical moment-curvature relationships for non-reinforced (left) and reinforced (right) walls

However, in the reinforced wall, the order of these 3 models classified according to the level of approximation to the experimental case is exactly the opposite. In this case, model 2 provides an accurate approximation, while the other two show a slight deviation. In this case, model 1 is again too stiff and strong.

As it was concluded in a previous work (Torrealva et al. 2012), these findings show the need to take into account the tensile strength of adobe and consider high levels of ductility under both tension and compression to obtain an appropriate bending behavior law. Moreover, it is once again observed that the strength and ductility of adobe increase when it is confined by the geogrid, producing a similar effect to that of reinforced concrete.

In summary, it can be concluded as an approximation that, with no reinforcement, adobe can be modeled as a material whose initial stiffness is about 50% of the initial modulus of elasticity obtained in a column compression test. Compressive and tensile strength can be in the order of 25% and 10%, respectively, of the resistance obtained in such a compression test. These levels of strength would lead to softening that can reach strain levels of 5%.

With geogrid reinforcement, compressive and tensile strength can increase by 50% compared to the previous case. Reinforcement also increases ductility of adobe, which can be modeled as a perfect elasto-plastic behavior, reaching a strain of 2.5% and subsequent softening reaching a strain of 5%.In both cases, the cracking moment can be considered as the moment at which the maximum tensile stress is reached.

These are obviously approximate values, which make it possible to obtain the bending behavior law of the wall with enough approximation and analyze its ductility and eventually its ability to withstand an earthquake. However, more experimental tests are necessary to confirm these approximate values and establish more reliable calculation models.

SIMPLIFIED METHOD TO ESTIMATE THE ULTIMATE MOMENT

The previous section tried to reproduce the bending behavior of walls with and without reinforcement. It has shown the importance of considering the tensile strength of adobe and its ductility. These data can be used to analyze the ability of walls to dissipate energy in the event of an earthquake. Yet, from a practical point of view and in the absence of advanced calculation methods, it can be interesting to calculate the wall's ultimate moment, regardless of its evolution up to the moment of breaking.

To do so, this paper proposes a simplified diagram of adobe under compression, similar to the rectangular diagram commonly used in conventional sections of reinforced concrete (European Committee for Standardization 1992; EHE08 2008; Montoya et al. 2009). The parameters defining this diagram are the uniform compression stress value and the portion of the compressive area where this distribution of stresses is considered to act upon.

In view of the constitutive laws used in the previous sections and the results obtained, the present study proposes considering a maximum stress equal to 30% of the characteristic compressive strength of adobe (0.30.fca), and a depth of the compression area encompassing the whole area compressed. The equilibrium of forces of the section could thus be represented as shown in Figure 8.

A linear elastic behavior law is assumed for the geogrid, with a modulus of elasticity estimated from the quotient between its ultimate strength (25kN/m) and strain (0.13), which leads to an equivalent modulus of elasticity Eg=190kN/m.

The compatibility and equilibrium equations can be written now as Equations 8, 9 and 10.

$$0.3 \cdot f_{ca} \cdot x \cdot b + E_g \cdot \varepsilon_{gc} \cdot b + E_g \cdot \varepsilon_{gt} \cdot b = W \tag{8}$$

$$0.3 \cdot f_{ca} \cdot x \cdot b \cdot (h - 0.5x) - E_g \cdot \varepsilon_{gc} \cdot b \cdot h + W \cdot h/2 = M \tag{9}$$

$$\varepsilon_{gc} = \frac{\varepsilon_{gt}}{x - h} \cdot x \tag{10}$$

These equations are dealt with at the breaking moment, imposing a failure in the tensile area (imposing the ultimate Strain of the geogrid as 0.13) or the failure of the adobe, imposing a strain of 0.05 (the maximum allowable strain in the simplified diagrams of the previous sections) as the compressive strain. Imposing one of them, the other can be written as a function of the position of the neutral axis *x* (Equation 10), and the value of *x* can be obtained directly from the force equilibrium equation . After obtaining *x*, it is necessary to check that the breaking mechanism matches the assumption made, that is, that the maximum allowable strains are not exceeded. Finally, the moment equilibrium equation makes it possible to calculate the ultimate moment of the section.

For the dimensions and properties of the wall analyzed for this paper, the value of the ultimate moment obtained for the reinforced wall is 4.1 kNm, a similar value to the experimental value of 4.4 kNm.

In the non-reinforced wall, the terms corresponding to forces in the geogrid were eliminated. It was considered that the only limitation was that the position of the neutral axis cannot be outside the thickness of the section. This leads to an ultimate moment of 0.41 kNm. This value is considerably lower than the maximum value obtained experimentally. However, it must be considered that there is a significant contribution of adobe under tension in that situation. The situation that the present study aims to represent here is that of breaking, in which the moment obtained experimentally was 0.8 kNm, approximately.

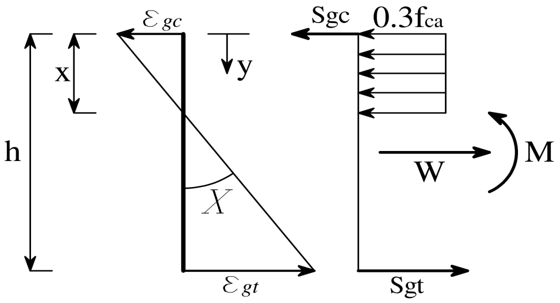

Figure 8. Strain, stress and forces in the cross-section of the wall assuming a rectagular stress block for adobe

The values obtained with this calculation methodology are adequate from a practical calculation approach, since the method yields approximate and conservative values. This leads to a more comprehensive and advanced model than that proposed in (Torrealva 2009), which is based on a hypothesis of failure of the geogrid and the calculation of the ultimate moment as that produced by the tension of the geogrid with regard to the extreme compression fiber, applying a series of safety coefficients. Results obtained for the tested walls are similar between both methods.

In any case, the methodology proposed in the present paper is aimed at establishing the basis of a simplified calculation method for adobe walls with and without reinforcement rather than providing accurate values for the type of wall studied in this research. It is obvious that more experimental studies are needed to validate the method and determine the parameters involved in it with greater rigor.

CONCLUSIONS

The present paper presents a thorough analysis of the bending behavior of adobe walls. It gives a quantitative analysis of the structural performance enhancement when adobe masonry is reinforced with geogrids.

On the other hand, simplified analytical methods are proposed for the assessment of the flexural behavior of reinforced and non-reinforced adobe walls. These methods are based on compatibility and equilibrium equations, and show how adobe masonry can be accurately modeled and therefore it should not be considered a non-engineering material.

One of the proposed methods tries to approach the bending behavior of the adobe wall when it monotonically loaded, so strains can be obtained from any applied force and vice versa. This method assumes a simplified constitutive law for the adobe masonry and the geogrid.

The paper also presents a simplified method to asses the ultimate bending moment of the adobe wall. This empirical method gives only information of the ultimate state of the wall.

The paper aims to contribute to the development of reliable guidelines based on scientific research for earthen constructions. This is a key issue for building safe and healthy low-cost houses as well as for preserving many heritage sites. Future experimental research is needed to validate the proposed methodologies and to gain knowledge about the structural behavior of adobe masonry and seismic reinforcement techniques. This goal is not only of great technical interest but also of high social interest.

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