Low-cost adobe structures with bamboo additives and bamboo frames. Strength tests

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ABSTRACT: The research shows the possibility to improve the resistance of adobe constructions using products of bamboo processing waste, like the bamboo powder. It can be used as additive in the mixture of the adobe bricks and can increase their resistance. A parallel research has investigated the possibility of using bamboo canes to realize an external reinforcement to the adobe structures. Under normal operating conditions, the bamboo reinforcement does not collaborate with the adobe structure, but in case of strong exceptional events is able to avoid the collapse of adobe walls. The tested solutions suits to solve many problems in difficult contexts in Latin America. In fact, this system can be built as self-construction, in environmental extremely precarious conditions, and is also part of the traditional building knowledge of the populations to which it is addressed.

1 INTRODUCTION

1.1 *Raw earth architectures*

Vernacular architecture in its many forms is able to gather and witness traditional building techniques of any time. During the centuries, these traditions achieve high levels of adaptation to the context, with solutions of considerable interest from a structural, bioclimatic, economic and environmental point of view. Among them, earth constructions play a leading role, having demonstrated a high adaptability. In fact, they spread for thousands of years throughout the world, in areas with very different environmental and social contexts.

Many construction techniques rely on the use of raw earth. The best known are adobe and rammed earth (called also *pisé* or *tapia*). Very widespread are the techniques based on earth and straw, for example the wattle and daub (called *quincha*, *bahareque*, *embarrado*, *cuje* etc. in Latin America.), and methods based on earth and wood, like the cob wall constructions (*bague* or *freemason*).

In this paper we refer to the technique of adobe. It consists of sun-dried bricks made of a mixture of clay, water and organic fibers, pressed into an open timber frame. Adobe buildings are widespread in Latin America and the Middle Eastern countries, but also in the Mediterranean Europe.

The main property of adobe is the compression resistance, but no tension resistance. Therefore, one of the most critical points of adobe buildings, and in general of earthen structures, concerns their seismic behavior. In case of horizontal loads of a certain severity, the walls tend to crumble.

This material, often considered as weak, has been regularly replaced by materials considered "modern" and "safer". Nevertheless, understand and analyze the criticalities of raw earth should be the challenge to improve both the material and the techniques, in order to design innovative solutions.

1.2 *The research on the bamboo structures*

The research analyzes the possibility of delaying the collapse of the structures of adobe using bamboo as a completion.

This material has very peculiar botanical, anatomical, physical and mechanical properties. It grows in different climates, and many species are also invasive; moreover, it is easy to work, lightweight to carry and it has an optimal tensile strength. The plant grows under the ground with a complex root system that forms a single body with the stems that protrude from the ground. The control of the cutting of the culms does not involve the death of the plant, that every year regenerates, in contrast with what happens with trees. Despite its peculiarities, the bamboo is often known as the "poor man's timber", the symbol of the precariousness in which the most disadvantaged sections of the population live. However, it is used for the construction of traditional buildings, and in various branches of the industry.

The research is divided into two parallel fronts. The first research analyzes the possibility to increase the tension resistance of earth bricks using bamboo powder and fibers from the waste of industrial processing as additive in the mixture of adobe. The second research designed an external frame of bamboo to be applied to the existing and new adobe walls, which is able to provide reinforcement in case of earthquake.

2 UNIAXIAL COMPRESSION TESTS ON ADOBE WITH BAMBOO POWDER ADDITIVE

2.1 *Materials and methods*

The bamboo species used in research is the *Phyllostachys edulis*, a type of giant bamboo that grows in different parts of the world at temperate latitudes. It is native of Taiwan and China, where it is called *moso bamboo* or *mao bamboo*, where is one of the most common species used in the textile industry. The used powder is a waste of production from an Italian company that produces accessories for the fashion industry.

For the tests, 12 specimens of adobe with bamboo powder addictive from the "bamboo burr" were prepared. The specimens are 8 × 8 × 8 cm. The number of test specimens is reported in Table 1.

In the Table 1 are also reported the tests from Gigliotti & Malara (2012). Those tests were conducted on earth specimens with different origin, but similar size and comparable characteristics, kneaded with calcined gypsum powder additive. The calcined gypsum (*calcium sulphate dihydrate*) reacts chemically with the clay contained in the ground of mixture, and is commonly used to stabilize earthen structures. These tests were performed in the laboratory of Materials and Structures Testing of DIDA (Unifi).

For the realization of the specimens was employed earth dried in oven at 60 °C for about 24 h, minced with mechanical grinder and passed through a sieve of diameter φ = 4.75 mm (corresponding to ASTM sieve n°4). The sieve n°4 was also employed to sift the bamboo powder. The earth was kneaded with bamboo powder in proportions equal to 3% of the weight of the earth, and mixed with water at 20%.

The mixture was manually processed and pressed into a timber mould, and removed after 2-3 days of drying. Therefore, for about a month, the specimens were seasoned with air on a wooden panel. Slow drying reduces cracking.

The test machine (Fig. 1) is composed of a hydraulic jack able to move axially, controlled by a desktop computer. The performed tests in monoaxial compression were conducted in stress-controlled mode; here, the force is increased at a given rate, and the correspondent piston's displacement is measured. The test specimen is loaded with a rounded head on a thick plate positioned on the upper surface of the specimen. The data on the displacements of the specimen along the direction parallel to the load were recorded through four displacement transducers placed on the four corners of the load plate.

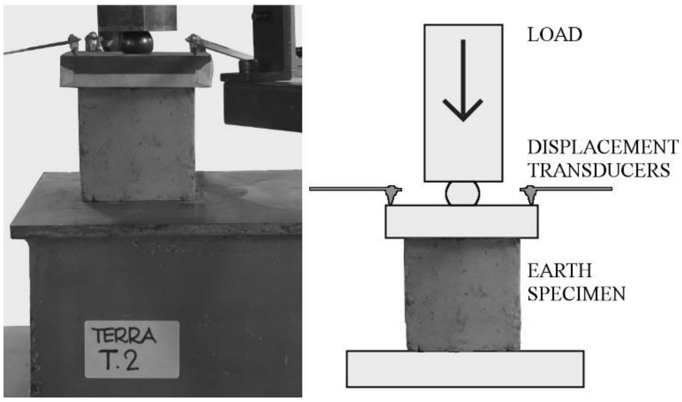

Figure 1. Loading scheme of the specimen.

Table 1. Test specimens.

Specimen	N°	Water percentage [%]	Additive	Additive percentage content*
T	3	20%	none	0%
GR	9	20%	bamboo powder	3%
TGC**	5	19%	calcined gypsum	15%

* dry weight percentage.
** Gigliotti & Malara, 2012

2.2 *Preliminary analysis on the raw earth*

The earth can have at the same time an inconsistent and monolithic texture. Therefore, in order to study earthen structures is necessary to investigate both the issues related to the soil mechanic and of the strength of materials.

In order to hypothesize the shrinkage and the behaviour during the tests, the main properties investigated (Table 2) are:

1. mineralogical composition of the soil;
2. physical properties of the soil;
3. strength of the material through mechanical properties.

The earth used for the research is from an excavation about 4 m deep in an area close to Florence.

Table 2. Physical characterization of the earth.

Property	Symbol	Value
Specific Weight	Gs	2.4707 gr/cm^3
Water content	w	15.65%
Liquid limit	Ll	23.09%
Plastic limit	Lp	19.57%
Linear shrinkage	Rl	3.15%
Linear shrinkage at cold	Rl	2.02%

2.3 *Results*

The specimens with bamboo powder additive show an increase of about 20% of the tension of failure σ_r, respect to the values obtained by the specimens without any additive. Furthermore, the specimens with the calcined gypsum additive show a similar σ_r as specimens with bamboo powder additive. The resume of the test results is proposed in Table 3.

Table 3. Comparison of the tensions of failure for adobe specimens with different additives.

Specimen number	Additive	E [N/mm²]	σr [N/mm²]
T 3	none	163.10	2.07
GR 9	bamboo powder*	166.87	2.41
TGC 5	Calcinated gypsum**	129.09	2.40

* Bamboo powder obtained from industrial processing of briar
** Gigliotti & Malara (2012)

2.4 *Conclusions*

The use of bamboo powder as well as the calcined gypsum additive increases the compressive strength of the adobe by 20%. Furthermore, the bamboo powder is a material recycled from the waste of the industrial processing. Therefore, the use of such additive is an ecological solution and does not affect the final cost of the adobe bricks.

3 BAMBOO FRAME FOR THE REINFORCEMENT OF ADOBE WALLS

A parallel line of research tested the effectiveness of a bamboo external frame for adobe walls, to install on existing and new structures. The designed reinforcement is formed by a grid of orthogonal bamboo canes, tied together by means of vegetal ropes. The frames, juxtaposed on both sides of the adobe wall are anchored each other by transversal elements, in order to form an external cage that stands on independent foundations (Fig. 2).

In service conditions, the bamboo grid does not collaborate with the bamboo wall, but the frame activates in case of earthquake, avoiding the risk of crumble of the wall; in fact, the elastic bamboo grid dissipates the seismic energy.

The reason why the reinforcement is installed on both sides of the wall is that the seismic force can have different directions. Nevertheless, the tests were performed considering the presence of the frame on only one side of the wall. In fact, the tests are aimed to evaluate the resistance of the canes and the lashed connections under the wall's self-weight on the most loaded side. If the wall were loaded on the opposite side, the second grid activates. The tests were performed considering the anchoring of the bamboo frame to the ground, and the rest of the highly resistant structure. This very complex aspect of the connection among the structural elements needs to be further investigated.

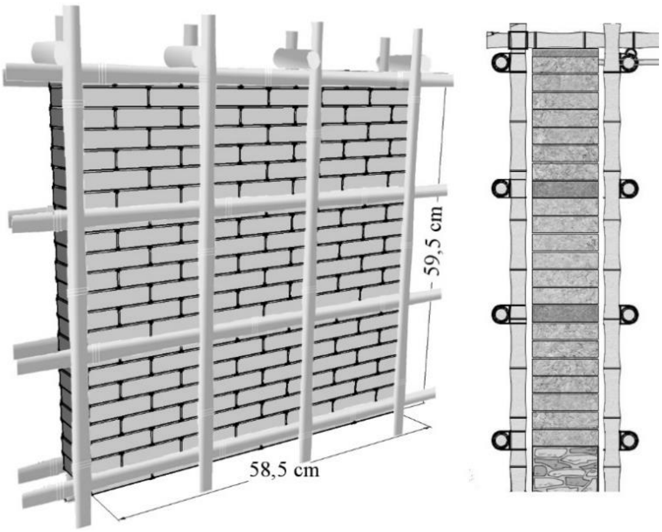

Figure 2. Scheme and section of the bamboo frame on the adobe wall.

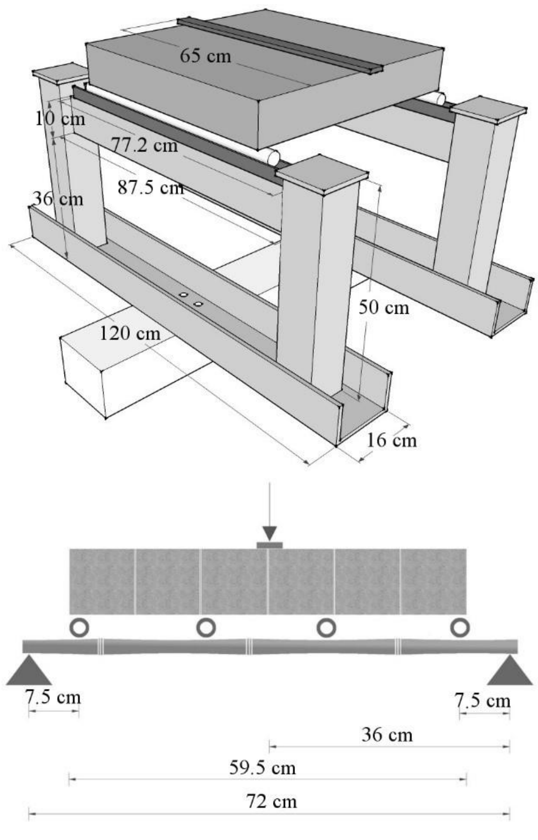

Figure 3. Scheme of the tests.

3.1 *Materials and methods*

In order to test the effectiveness of the proposed system, laboratory tests were done on the adobe panel, on the bamboo frame and the adobe wall reinforced with the frame. The structures (the adobe wall, the bamboo frame and composed structure) were tested in horizontal position (Fig. 3).

The tests performed are static tests, that do not intended to quantify the failure resistance of the structure, but only to assess the collaboration of the two materials in the situation in which the adobe panel is subjected to out of plane stresses.

The line of interaction of the load is perpendicular to the rows of bricks. The load was applied manually with the consecutive addition of weights of 5 kg each. The distributed load, perpendicular to the surface of the wall, is positioned along the central part of the same on a metal bar of 4 cm in width. The surface of the metal bar on the panel side was coated with polyethylene to adapt to the surface irregularities of the adobe wall.

The measuring apparatus consists of graduated rulers integrated in the wall. The vertical displacement of the specimen at the point of application of the load is measured with respect to a fixed horizontal line, constituted by a nylon wire hold in tension between the two supports.

3.2 *Adobe wall*

To carry out the tests, 1,200 bricks of dimensions 10 × 10 × 2.5 cm (scale 1:4) were made by hand. The procedure of the production of the adobe bricks is analogous to the one described in the paragraph 2.1. The bricks were left drying for 24-48 hours inside the moulds. After removing them from the mould, the bricks were left one more day in the air; finally, they were turned on edge to finish drying one last day. Then they were stored well aerated and non-overlapped for at least 15 days. The adobe bricks were completely dried and ready for use after about a month. The water content was measured in the mixture that presented limit characteristics (most particularly malleable or dry mixture) and varied between 19.6% and 22.8%. For the realization of the bricks, no additives were used in the mixture.

The bricks were afterwards assembled in scaled walls (scale 1:4) of dimensions 60 × 60 × 10 cm. The bricks were in rows of 6 elements, fixed with mortar of sieved earth ASTM 10 (φ = 2.00 mm), mixed with water in proportion of 2.5 liters of water every 7 kg of earth. Each wall is composed of 22 rows and 132 blocks (including 22 special pieces and 111 bricks). After a few days, the formwork is disassembled, and the wall seasoned for a month.

Table 4. Characterization of the culms of *Phyllostachys viridiglaucescens**.

Property	**Unit**	**N° of specim. tested**	**Value**
Diameter min	mm		46.0
Diameter max	mm		67.0
Thickness min	mm		4.1
Thickness max	mm		7.2
Area min	mm²		578.2
Area max	mm²		1,347.0
MC	% (dev.st.)	12	24.9 (5.8)
σc	Mpa (dev.st.)	12	56.8 (7.6)
Ec	Mpa (dev.st.)	12	3,100 (520)
σt	Mpa (dev.st.)	4	159.0 (13.0)
Et	Mpa (dev.st.)	4	22,500 (8,000)

* Mechanical characterization of bamboo culms carried out by Fabiani, M. (2014).

3.3 *Bamboo frame*

The bamboo used is *Phyllostachys viridiglaucescens*, an Italian species that grows in Camaiore, Lucca. The preservative treatment is with the method of vertical diffusion for transpiration of the foliage, using a solution of borax and boric acid. The mechanical characterization of the bamboo culms is in Table 4.

Since the *guadua* (*Guadua angustifolia*) culms used for structural uses in Colombia have diameters between 8 and 12 cm, a scaled diameter comprised between 2 and 3 cm was chosen. The canes with less imperfections were chosen. The length of the canes is about 1 m.

The bamboo structure consists of 4 horizontal and 4 vertical canes joined together at 90 degrees angles. The spacing between the canes is about 19 cm, which corresponds to a real spacing of 75-80 cm (scale model 1:4). The lashing is made following the traditional technique of lashing with ropes (*uniones amarradas* in Hidalgo López, 1980). In particular, the *square lashing*, optimal for joining two perpendicular elements was chosen. This type of joint, as it is completely external to the culm, avoids to drill the bamboo fiber; it is simple to perform, and is realized with readily available on-site materials.

The analysis of the mechanical behavior of the lashes showed that it has a static behavior similar to that of a hinge. The resistance of this type of unions is linked to the mechanical characteristics of the material used for lashings. The rope used is the Cabuya, a processed product extracted from the fibers of *Furcraea Andean* plant, traditionally used in the *Eje cafetero* region (Colombia). The tension of failure in traction was measured of the order of about σr = 54 Mpa.

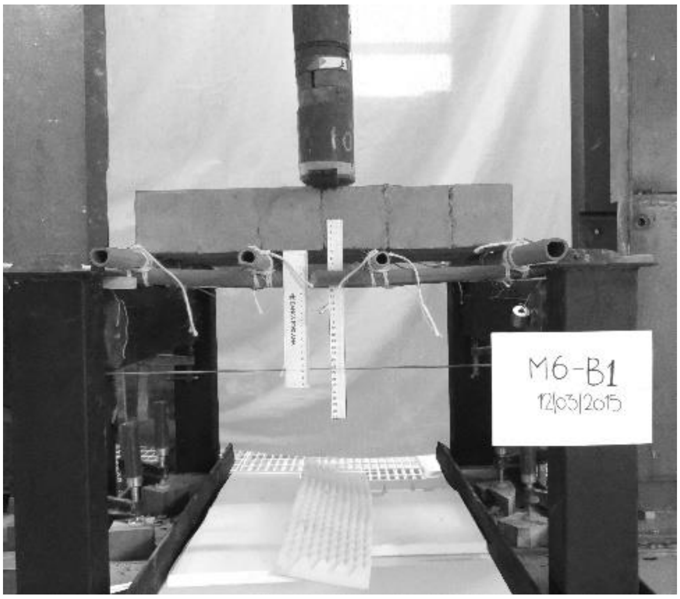

Figure 4. Bending tests on the adobe wall reinforced with bamboo frame.

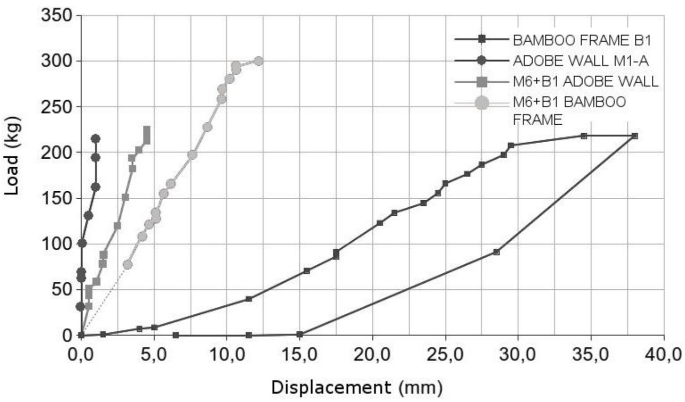

Figure 5. Load-displacement diagrams of the tests.

3.4 *Tests on the flexural test on the adobe panel reinforced with bamboo frame*

The adobe walls were loaded until the collapse, that happened at a ultimate load of Fu = 220 kg. The test results are shown in the load – displacement (σ-ε) diagram in Figure 5.

The bamboo frame was not brought to rupture, as the available instrumentation for the test was not able to apply the adequate load for the failure. The tests showed that the bamboo is able to withstand without damage to loads that determine the collapse in the adobe structure. Besides, once the load is removed, the structure goes back to its initial configuration with minimum left deformation.

Concluding, the results verified that the presence of the bamboo frame improves the stability of the adobe panel, when the panel exceeds the tension of failure. The bamboo structure, which under normal conditions of use does not cooperate with the adobe wall, is triggered in case of horizontal loads, avoiding the collapse of the wall (Fig. 6 and Fig. 7).

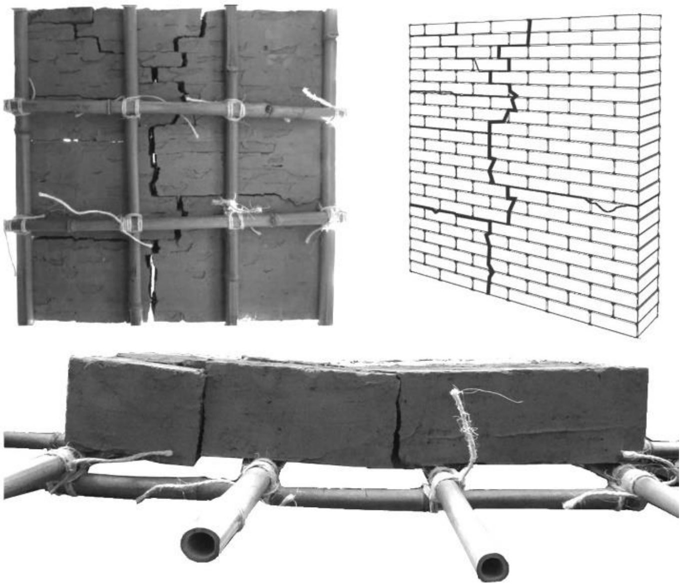

Figure 6. Failure of the test specimens.

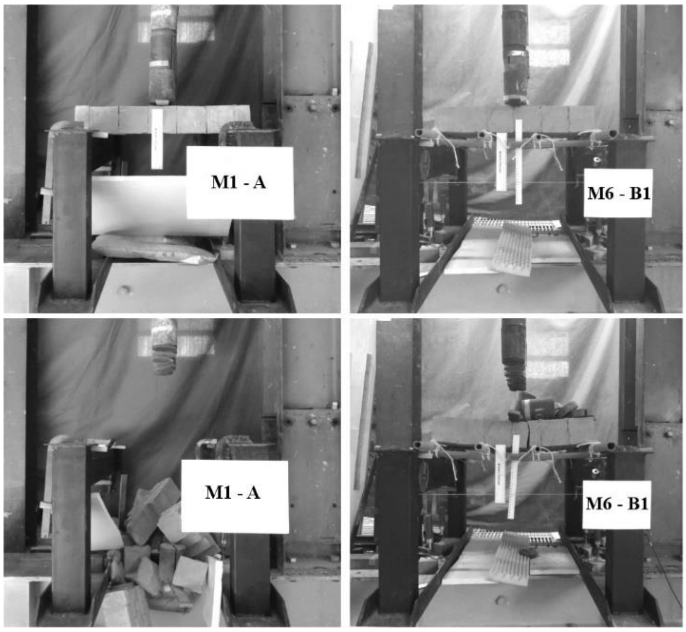

Figure 7. Comparison between the unreinforced wall (M1) and the wall reinforced with bamboo frame (M6-B1).

3.5 *Conclusions*

In Figure 5 is shown the load-displacement diagram of the tests. Here, is possible to do a direct comparison among the bending tests of the different solutions (the adobe wall, the bamboo frame and composed structure). The adobe panel and the bamboo frame have a very different behavior. On one side, the adobe wall has not yield phase and reaches abruptly the collapse (see test M1, Figure 7), on the other side, the bamboo tends to significantly deform. The specimen B1 in Figure 7 is an example of the above described behaviour. Despite the different behavior of the two materials under loading, they have shown a good collaboration. In fact, as shown by the test specimen M6-B1 in Figure 8, the tests on the reinforced adobe wall demonstrated the ability of the bamboo frame to support the adobe panel, and prevent its collapse. In fact, when the adobe structure exceeds the tension of failure and fails, the adjacent bamboo frame prevents the crumbling of the already damaged parts (Fig.6). The efficiency of the proposed solution is also evident from the comparison of the test specimens with and without reinforcement, as shown in Figure 7.

4 CONCLUSIONS

The research has shown the ability to increase the resistance of the adobe structures using various products from the bamboo cane.

• The bamboo powder, waste of the industrial processing. Produced in large quantities, it can be used as additive in the mixture of the adobe bricks. In small percentage of weight (3% of the weight of the used earth) the tested specimens' compressive strength increases up to 20%.

• The bamboo frame. Bamboo canes for the realization of an external reinforcement in existing and new adobe structures. In presence of horizontal stresses that could cause the collapse of the adobe structure, the bamboo frame is crucial to prevent the collapse. Furthermore, the great flexibility of the element in bamboo absorbs seismic energy incident on the structure by reducing a further increasing of the deformation of the adjacent adobe wall.

The advantages of the use of such products are many. First of all, the bamboo is able to increase the resistance of existing and new construction to prevent their collapse in case of exceptional events; second, it is a renewable resource.

5 OUTLOOKS

Future research will concern the possibility of unifying the two researches presented in this paper. The resistance of the adobe constructions can be further improved by the use of walls built with adobe bricks with bamboo powder additive, and with the external bamboo three-dimensional frame.

A first development of the idea is the design of a home prototype in adobe and bamboo of one level (Fig. 8). The seismic risk to which the construction is subjected is also reduced thanks to the regularity of the structure in plan and in elevation, internal small spaces, and the positioning of openings far from the corners. Furthermore, in case of damage, the bamboo frame can be locally removed and the adobe brickwork can be fixed.

The strength of this solution is based primarily on the ease of execution, the low materials costs, and the use of renewable resources. Furthermore, the proposed building can be built as self-construction, in environmental extremely precarious conditions, and is also part of the traditional building knowledge of the populations to which it is addressed. Finally, it increases the resistance of these structures without changing the construction technique. Thus, it could help solve the precarious housing situation in large urban areas of many southern America's cities.

REFERENCES

Arcila Losada, J.H. & Flórez, R. G. 1988. *Guadua y madera aplicada a nuevas tecnologías de vivienda popular en Caldas*, Universidad Nacional de Colombia seccional Manizales, Manizales.

Asociación Colombiana De Ingeniería Sísmica, Fondo para la Reconstrucción y Desarrollo social del Eje Cafetero – FOREC, 2005. *Manual para la rehabilitación de viviendas construidas en adobe y tapia pisada*, Manizales.

Briccoli Bati, S. 2001. Terra: caratteristiche costruttive e caratteristiche meccaniche del materiale e delle strutture, in Forlani M.C. (eds.), *Costruzioni e uso della terra*., Rimini.

Bizzeti, F. 2015. *Analisi sperimentale di pannelli in adobe e bambù: un esempio di recupero di antiche tecniche costruttive latinoamericane.* Tesi di laurea magistrale in Architettura, relatori Paradiso M., Briccoli Bati S., Università degli Studi di Firenze, Firenze.

Muñoz Robledo, J.F. 2007. *Sistemas Constructivos - Arquitecturas de Baja Altura en Manizales*., Manizales.

Fabiani, M. 2014. *Proprietà fisiche e meccaniche di bambù di origine italiana*, Dipartimento di Ingegneria Civile, Edile ed Architettura, Università Politecnica delle Marche.

Gigliotti, M. & Malara, A. 2012. *Prove di resistenza meccanica su elementi strutturali in terra cruda*, Tesi di Laurea, relatrice Briccoli Bati S., Università degli Studi di Firenze, Firenze.

Hidalgo López, O. 1981. *Manual de construcción con bambú*, Universidad Nacional de Colombia, Bogotá.

NTE, 2000. Reglamento nacional de construcciones - Norma técnica de edificación E.080, Adobe, Lima.

Raviolo, P.L. 1993. *Il laboratorio geotecnico*, Editrice Controls, Milano.

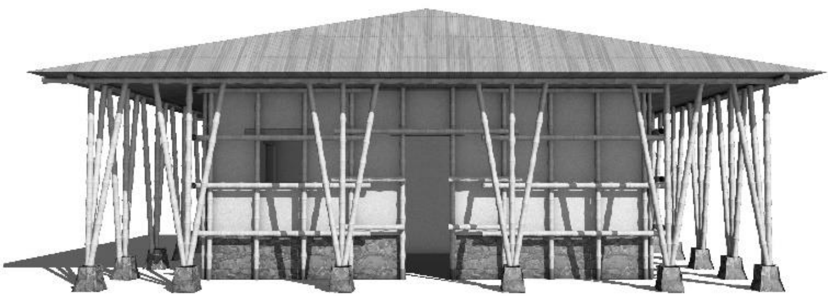

Figure 8. Prototype of building in adobe and bamboo.