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Study of Bamboo Physical Properties and its Application as Reinforcement in Adobe Structures

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Abstract: ***This study is referred to the application of bamboo as a structural reinforcement in constructions with adobe. The main focus is the need of searching and using economical, safe and environment-friendly alternative construction materials because of the current environmental situation. Two adobe walls were built; one reinforced with bamboo and the other without any reinforcement. Those walls were essayed to cyclic lateral load in order to get capacity curves, displacement ductility, Young Modulus, stress distribution, dissipated energy, secant stiffness, and to compare between them. The results showed that the bamboo reinforced adobe wall has a substantially better structural behavior because its lateral load capacity was highly increased; also a higher absorption and better distribution of energy were achieved.***

Keywords: Bamboo, Adobe, Structural Reinforcement, Alternative Construction

1. Introduction

Adobe bricks have been used for millenniums. Dating as far as the 9th century B.C. earth has been one of the first construction materials employed by humankind. The first earth bricks used were probably coarse, mashed clay, air-dried, and hardened by the sun heat. Earth has a fragile behavior, therefore the main focus has always been to reinforce it. The Babylonians were the first civilization to use reed reinforcement in their adobe constructions. It is known that the Babylonians moistened earth, added chopped straw, and mashed the earth in-situ with their feet. In order to obtain a better solidity and wall cohesion, the Babylonians used bitumen or hot asphalt as mortar and reed reinforcement between rows. It could be said that this was the first time that bamboo was used as reinforcement in earth constructions. Adobe was used in many cultures. It was used in Spain and in other Mediterranean areas. Also, in the 15th Century, Spaniards found Native Americans already using it. New Mexico is another place where adobe constructions from the 18th century were found. In the seventies, the professors of The Engineering Department of PUCP (Pontificia Universidad Católica del Perú) began their research about stability of earth constructions in seismic areas. The first investigations were oriented to determine the mechanical characteristics of adobe walls through static essays. Between 1973 and 1978, several housing modules were statically essayed. These housing modules were of real size and with different reinforcement materials such as reed, wood and wire. The most efficient reinforcement was achieved through the collocation of complete vertical reeds inside the walls and tying up horizontal crushed reeds every four rows of mortar. Another study on improved construction technologies talks about the use of vertical and horizontal reinforcements. This can be done with any ductile material including reed, bamboo, rope, wood, chicken coop, barbed wire, and steel bars. The vertical reinforcement helps to maintain the walls integrity due to its connection from the foundations to the sill. The horizontal reinforcement helps to transmit inertial and bending forces. Both reinforcements must be connected among them and to other structural elements. The main focus of this research is to look for sustainable construction materials like bamboo and adobe. The main characteristic of this type of construction is the lack of research due to culture. It is not considered important to innovate but rather to base on foreign researches and models. In order to analyze this problem, it is necessary to mention its causes. First, the acknowledge and underestimation of alternative materials such as bamboo and adobe. Second, the increasing population and the consequent demand of housing in which the economic aspect is very important. However, safety, comfort, and peace, which characterize an adequate household, are not left aside. This research was done because of the interest to know and provide new alternative construction technologies that fulfill the required earthquake resistance criteria, currently there is not enough development in seismic design in Ecuador. In addition, this investigation wanted to prove that it is possible to get safe, economic and esthetic structures using bamboo and adobe. These are great options to have in mind when building. The study was based on a bibliographic compilation by taking in account those foreign countries where this technology is more advanced. The information was adapted to local conditions for testing and application. This was done through a cyclic lateral load essay of two adobe walls one with bamboo reinforcement and the other without any reinforcement.

2. Material Properties and Adobe Walls Design

The walls were designed according to the specifications listed in the Peruvian code E080 “Construction con Tierra” common dimensions of construction in Ecuador, and the conditions of the essay area at CIV- EPN (Centro de Investigación de la Vivienda – Escuela Politécnica Nacional) located in Quito, Ecuador. The earth used for construction had to fulfill certain requirements specified in the Peruvian code. First, enough clay content, which should be verified using the “Cinta de Barro” test. Second, enough dry resistance, which should be verified with the “Resistencia Seca” test. In the event of not knowing the material mechanical properties, some values of the Peruvian code can be considered. The ultimate stresses are shown in Table I.

Table I: Earth Ultimate Stresses

Parameter	Value	Units
Earth compressive stress , fo	1000,28	kPa
Earth tensile stress , ft	79,43	kPa
Earth shear stress	24,52	kPa
Mortar tensile stress	11,77	kPa

The admissible stresses are calculated dividing the ultimate stresses by 2, 5. This is done because of the variation in material quality, execution quality and loads evaluation. The Young Modulus of adobe bricks is lower than traditional masonry. The latter has an equivalent Young Modulus of its admissible compression stress multiplied by 400. For adobe, the multiplying value is 300. A lower Poisson's Ratio value than concrete was taken. This is justified by the fact that earth is more anisotropic and heterogeneous than other materials. Earth doesn't have a ductile behavior. When earth suffers longitudinal tension, there is little cross deformation before a fragile failure occurs. Because of this, a value of 0, 15 was assumed. However, it will be subjected to further investigation. Based on the researches done by it was determined that the best reinforcement alternative was bamboo. The vertical reinforcement was separated 1, 5 times the width of the wall. Three complete bamboo stems, with an exterior diameter of approximately 10 centimeters and a thickness of 8 millimeters, were used as vertical reinforcement. For horizontal reinforcement, crushed specimens of the same characteristics were collocated every three rows of adobe bricks. The vertical reinforcement was placed inside the foundations at a depth of 25 centimeters and cast-in-place together with the load transmission beam at the top of the wall. All this was done to ensure a monolithic behavior of the structure. The cyclopean concrete foundations were anchored to the reaction slab of the CIV-EPN. Moreover, two blocks of reinforced concrete were left at the sides of the wall in order to prevent bottom lateral displacement. The adobe bricks used were 40 centimeters long, 20 centimeters wide and 10 centimeters high. They were placed using the English interlocking and stuck with a mixture of earth mortar and straw. The load transmission RC beams had 4 steel bars of 2 centimeters diameter for the anchoring of a hydraulic jack, which was needed for the application of the lateral load. The beams were connected to the walls with concrete in the last two rows of the adobe walls.

The walls' schemes are shown in Figures 1 and 2.

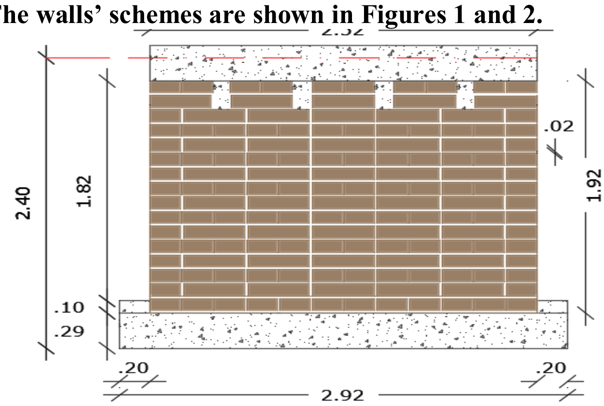

Figure 1: Unreinforced wall scheme

Figure 2: Unreinforced adobe wall at the end of the essay

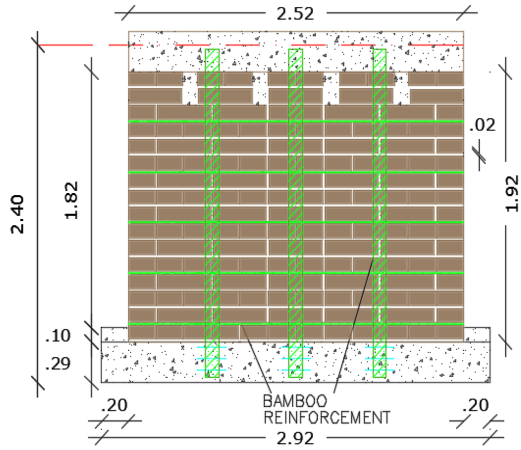

Figure 3: Reinforced wall scheme

Figure 4: Reinforced adobe wall at the end of the essay

3. Experimental Test Observations

After the preparation of the essay, the cyclic lateral load was applied in increments of 2.45 kN. Between eacycle, the load value and lateral displacement were registered and the cracks in the walls were marked.

The orientation of the cracks was diagonal in the unreinforced adobe wall, as shown in Figure 3. The failure lateral load bear was 7,306 kN with a corresponding displacement of 1, 50 millimeters.

The orientation of the cracks was mostly horizontal and vertical in the reinforced adobe wall, as shown in Figure 4. The failure lateral load bear was 28, 44 KN With a corresponding displacement of 79, 5 millimeters.

Displacement Ductility

The displacement ductility can be calculated for reinforced adobe walls, but not for unreinforced. This can be explained by its fragile behavior.

The displacement ductility was determined with the use of an elastic - plastic equivalence method, which specifies a yield limit as 0, 70 of the failure load,

$$\mu = \Delta uu / \Delta \Delta y$$

Where μ is the displacement ductility, Δu the displacement corresponding to the failure load, and Δy the yielding displacement.

The results showed that the displacement ductility in bamboo reinforced adobe walls was 3, 18 (for the pushing of the hydraulic jack phase) and 3, 58 (for the pulling of the hydraulic jack phase).

Young Modulus Determination

The Young Modulus was obtained using the mechanic of materials theory. The lateral displacement considering shear and bending effects is calculated as follows:

$$\Delta = \int_{O}^{L} . \frac{M.M}{E.I} SX + F \int_{O}^{L} . \frac{V.V}{G.A} SX$$

The parameters of the equation were calculated. Then, the equation was simplified and the variable E was isolated. The following expression was obtained:

E = 0, 0116479 P/Δ

Where E is the Young Modulus in (MPa), P is the lateral applied force in (kN), and Δ is the lateral displacement

Corresponding to the force in (meters). The results were 144, 14 MPa for the unreinforced adobe wall and 143, 08 MPa for the reinforced wall. The Young Modulus are very similar, even though one is constituted with additional bamboo elements. It could be said that bamboo does not completely modify the elastic behavior of the reinforced wall.

Unreinforced Wall Resistance

The wall bears a load of 7,305 kN before failure. With the assistance of a mathematical numerical program, a model was established using the material properties specified in Section 2. The stresses in the wall were calculated and compared with the admissible stresses specified in the Peruvian code E080 "Construction con Tierra" Finally, it was determined that the critical condition was shear stress. The results of the mathematical numerical model using the FEM (Finite Element Method) for the unreinforced wall are shown in Figure-5.

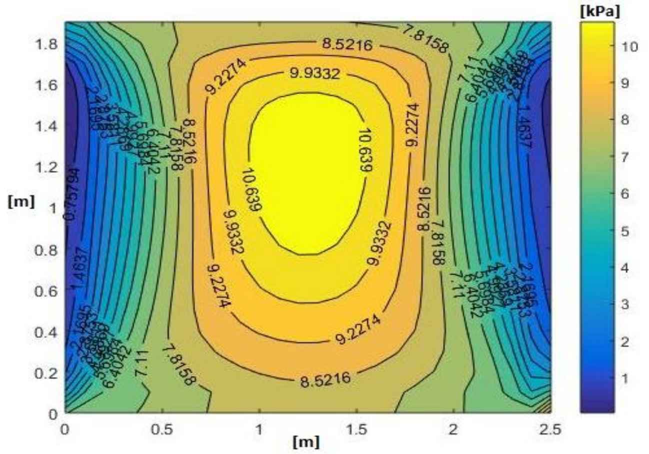

Figure 5: Experimental Shear Stresses in the unreinforced adobe wall

The maximum shear stress for the failure load of 7,305 kN was 10,639kPa, which is approximately 1 kPa higher compared to the value admitted by the code (9.807 kPa). This shows that the used material properties in the mathematical model and the design for the unreinforced wall were correct.

Hysteretic Capacity Curves

A hysteretic capacity curve indicates the lateral load force against the structure's displacement. The bounded area represents the dissipated energy of the system. Both walls hysteretic curves are shown in Figures 6 and 7.

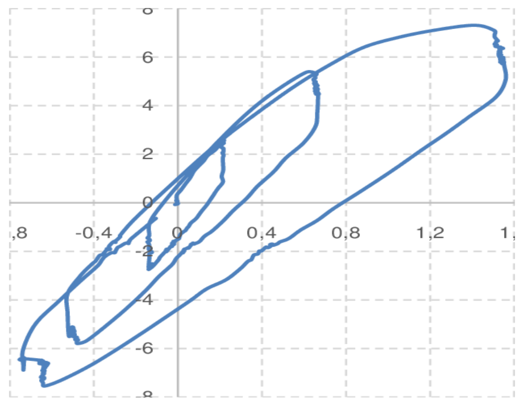

Figure 6: Hysteretic Curve for Unreinforced Wall

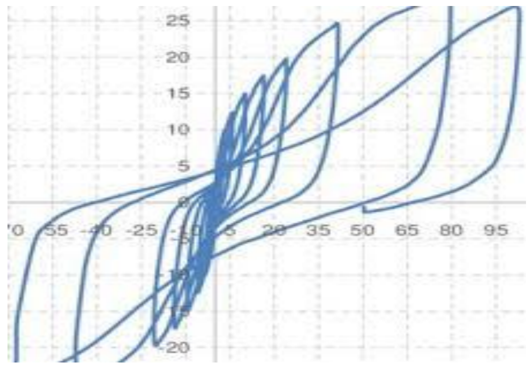

Figure 7: Hysteretic Curve for Reinforced Wall

An overlapping graphic was done in order to visually compare both walls' hysteretic curves. The result is shown in Figure 8.

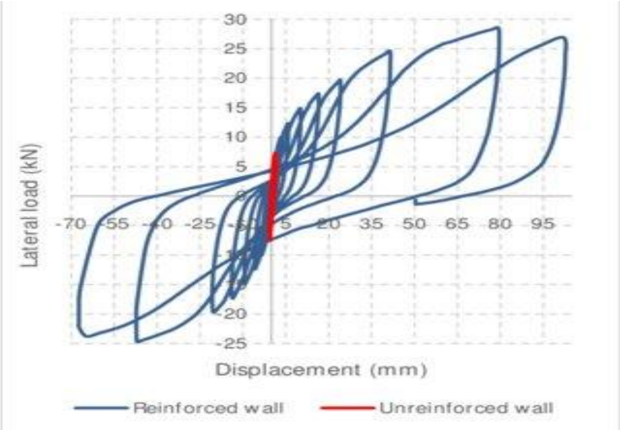

Figure 8: Overlapping Hysteretic Curves

The unreinforced wall's capacity curve is very small compared to the one of the reinforced wall. Therefore, the use of the bamboo reinforcement completely changes an adobe wall's behaviour under lateral load application.

DISSIPATED ENERGY

As stated in Section 7, the bounded area of a hysteretic curve represents the dissipated energy of the system. The energy dissipated in each cycle for the unreinforced and the reinforced walls is shown in Tables II and III respectively.

Table II: Unreinforced Wall Dissipated Energy

Cycle and Lateral Load	Value	Units
Cycle 1: 2,45 kN	0,67	J
Cycle 2: 4,90 kN	3,71	J
Cycle 3: 7,35 kN	10,80	J
Total	15,18	J

Table III: Reinforced Wall Dissipated Energy

Lateral Load	Value	Units
Cycle 1: 2,45 kN	0.81	J
Cycle 2: 4.90 kN	4.83	J
Cycle 3: 7.35 kN	11.62	J
Cycle 4: 9.81kN	34.39	J
Cycle 5: 12.26 kN	75.74	J
Cycle 6:14.71 kN	150.94	J
Cycle 7: 17.16 kN	256.08	J
Cycle 8: 19.61 kN	426.45	J
Cycle 9: 24.52kN	1249.93	J
Cycle 10: 29.42kN	24.67.97	J
Total	4678.74	J

The dissipated energy of the reinforced wall was approximately 308 times greater than in the unreinforced wall.

Secant Stiffness

The Secant stiffness (Ks) is defined as the slope of the line that connects the two edge points, maximum displacement and corresponding load with minimum displacement and corresponding load, in each cycle of the hysteretic curve. Under this concept, the secant stiffness in each load cycle was calculated for both walls. The results are shown in Figures 9 and 10.

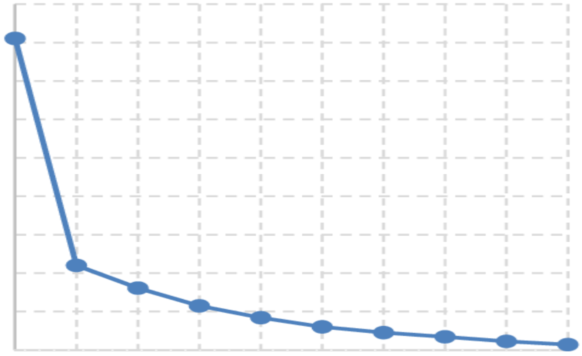

Figure 9: Secant Stiffness variation for Unreinforced Wall

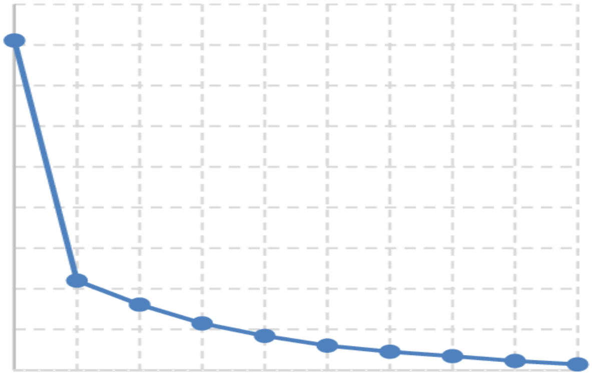

Figure 10: Secant Stiffness variation for Reinforced Wall

The variation percentage in secant stiffness between the first load cycle and the failure load cycle was 61,35% for the unreinforced wall, and 98,29% for the reinforced wall. The difference between both walls was 36, 94%, which indicates that the bamboo reinforcement considerably increases stiffness degradation.

Bamboo Reinforced Adobe Walls Design Criteria

Three parameters were considered important for construction with bamboo reinforced adobe. Lateral Load Capacity It is proposed to increase the lateral load capacity of a bamboo reinforced adobe wall. Based on the results of the wall's lateral load capacity, a range of magnification values from 3 to 4 was determined. For example, if an unreinforced adobe wall of defined geometry bears a lateral load of 10 kN, then a bamboo reinforced adobe wall with the same geometry could bear a lateral load of approximately 30 to 40 kN. Weight Percentage. This parameter was calculated with the walls' weight and the maximum lateral load each wall bears. The results are shown in Table IV.

Table IV: Base Shear Weight Percentage

Wall	Failure Lateral Load (kN	Weight (kN)	Load / Weight Percentage (%)
Unreinforced	7.31	43.48	16.80
Reinforced	28.44	43.31	65.66

It is proposed to design bamboo reinforced adobe walls with a base shear of approximately 50% of the structure weight.

Drifts

For this parameter, drift ratios were calculated. The elastic limit was considered:- For the unreinforced wall, as the load point where it failed (7,35 kN). - For the reinforced wall, as the load point where it did not suffer substantial damage

(6,86 kN). The ultimate limit was considered as the load that made the walls fail. The results obtained are shown in

Table V: Drifts Ratios

Drift	Value
Unreinforced Wall in elastic range	0,00071
Reinforced wall in elastic range	0,00083
Unreinforced Wall ultimate drift	0,00071
Reinforced wall ultimate drift	0,0377
Elastic Ratio:	1,17
Ultimate Ratio:	53,03

The elastic ratio is slightly higher than 1, however, the ultimate ratio is greater than 50. This shows that bamboo provides adobe walls with a plastic behavior.

4. Conclusion

Geographic location, dry time, straw content, organic content, construction technique, protection against weather, and insects are multiple factors than can affect an earth structure behavior. That is why the Peruvian code recommends a safety factor of 2, 5. The orientation of the cracks was different in each adobe wall. Diagonal for the unreinforced wall, and mostly horizontal and vertical for the reinforced wall. The lateral load capacity of the reinforced adobe wall was approximately four times the unreinforced. The ductility displacement was in a range of 3, 18 to 3,58 for the reinforced wall. Even though the Young Modulus of both walls was very similar, the reinforced wall had approximately 300 times more energy dissipation capacity than the unreinforced wall. With the obtained results, it can be assured that the use of alternative materials is able to create earthquake resistant, cheap, and esthetic conditions for households. It is suggested to increase the lateral load capacity by 3 to 4 times when using bamboo as reinforcement. In order to predict the maximum lateral load in an unreinforced adobe wall, it is advisable to use the one that makes 50% of the wall surpass its admissible shear stress.

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