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Analysis of the Mechanical Behavior of Prefabricated Wattle and Daub Walls

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Abstract: This paper summarizes an extensive research about mechanical strength of wattle and daub walls, employed in natural construction. Prefabricated wattle and daub walls, corresponds to the constructive system of frameworks, the perimeter of the walls of enclosures are composed of a wooden frame and the interior is a framework of Castilla canes, to eventually be covered with a mud mixture with clay, sand and vegetable fiber. Building with wattle and daub, is used worldwide, nevertheless, scant information is available about the strength of the walls against compressive and cutting loads. To gather more information about this, prefabricated wattle and daub walls were built in real scale 1:1, and tested in the University structures laboratory. Was obtained that walls have a ultimate compressive strength of $1.56MPa$ and the average shear strength is $0.13MPa$, these values are higher than adobe's values and is recommended this natural construction in areas with earthquakes because its flexibility instead of adobe. These data are valuable for structural calculations of wattle and daub houses and make safer homes.

Keywords: Earth material buildings, wattle and daub, compression resistance, shear strength

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1 INTRODUCTION

There are different techniques for building with earth, “Framework” or “Mixed technique” is one, where wood is mainly used as a supporting structure, and next is covered with earth as a plaster. This “framework”, acquires many different names in Latin American countries. For example, in Andean region (Ecuador, Peru, Bolivia) reaching north of Argentina is called “quincha” (“wattle and daub”), in Brazil is called “tapia” and in other countries this building technic is called: palo pique, estaqueo, French wall or estanteo (Octavio Flores 2003). In Quechua vocabulary the term wattle and daub is associated with the use of the cane for supporting structure of building walls (Proterra 2003) and then it is completed backfilling and plastering with earth.

The prefabricated wattle and daub that refers this paper, corresponds to the constructive system of walls, that they have a resistant frame of poplar wood (*Populus alba*) in such, and has a Castile cane (*Arundo donax*) framework in the interior, and then it is covered with mud fabricated with clay, sand and vegetable fiber in appropriate proportion. Wattle and daub technics have properties: from strength point of view are lightweight, flexible construction and seismic resistant wall; from thermal behavior is better than masonry with bricks, its materials are completely naturals, renewable and sustainable, and is a cheap technic, appropriate to self-construction for people in rural or marginal cities areas, with scarce resources. Also, thermal behavior has been studied and is possible to know thermal transmittance of wattle and daub with different fillers (Cuitiño et al. 2009).

Historically, mud buildings have been located in any region, regardless whether or not they were seismic. The regions located on the ring of fire are prone to earthquakes, therefore must be evaluated the resistance of buildings against these actions.

Prefabricated homes built with wattle and daub, are very ductile and lightweight, due to the framing canes. These two factors benefits their behavior against earthquakes.

According to tests carried out by Nakao and Yamaza-

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ki (2008), walls with different widths and thicknesses, similar to prefabricated wattle and daub, wherein the frame is wood, the interior is a frame with bamboo and mud coating with straw. They were subjected to a series of static lateral loads at the top of the wall. During the test, the rotation angle and the horizontal load applied was measured and the ultimate strength values were between $0.09MPa$ and $0.14MPa$.

Yamada (2008), in his work's proposed, a method of numerical analysis to calculate the restoration of the wall, the mathematical modeling was based on experimental tests, performed on walls with the same structural characteristics as those in Nakao, and lateral maximum resistant capacity obtained was between $0.117MPa$ and $0.125MPa$.

However, there is no experimental information about structural strength of prefabricated wattle and daub walls. In this paper, structural testing and analysis of seismic behavior are determined accurate and systematically ways, in which buildings should be made to reach a safe level of life. Some tests, has been carry out in order to know under compression and shear loads, elasticity's modulus, shear modulus and deformation capacity in wattle and daub walls, so they can be employed in the resistant design of houses built with wattle and daub. To complement the experimental work, walls were computationally simulated using the Abaqus/CAE v6.11 Software, to observe the damage occurred during the load range.

2 METHODOLOGY

2.1 Description of Wall Construction

The ASTM 7268 test (Norma IRAM 11.585 1991) for wall panels and partitions in buildings to the compressive strength for vertical load is applied; and for shear test is used the "Cantilever beam" tests in 1:1 scale (Michelini et al. 2000).

Par For mechanical tests eight walls of $1.20m$ wide, $1.80m$ height and $0.10m$ thick (Figure 1) were built. Four walls for vertical load testing and four walls to the horizontal load testing were carried out. The structures of walls are built with eucalyptus wood each $1.35m$ for roof and walls support. In each vain it is built a wattle and daub panel.

The wattle and daub panels are made up of a wooden frame of brushed poplar battens of 2" × 4" (4" gives the thickness of the panel) in the entire perimeter, then a diagonal batten is incorporated and two intermediate horizontal stiffeners, generating a panel divided in six parts. In each junction between battens were used spiral nails 3" and it were reinforced with adhesive vinyl. Inside each part was placed a batten 1.5" × 0.5" attached to the frame with drawers nails 2" and adhesive vinyl, it serves to support the cane nail (Figure 2). The canes were set at a wheelbase of $0.08m$, both horizontally and vertically. Finally at the bottom of each panel, was available a roundwood with edged boards on two opposite sides, and the final thickness is $0.10m$ between opposite sides. This facilitates the support of the walls in the testing machine. The assembly process of walls are shown in Figure 4(a) - 4(c).

On walls proposed for shear load tested, around the walls perimeter it was placed a poplar trunks edged on two opposite sides, in order to be consistent with the fact in construction. The poplar roundwoods are $0.1m$ of mean diameter and they are placed keeping distance of $0.10m$ between faces (Figure 2). They were attached to the frame with spiral nails 4", each $0.2m$ away and vinyl adhesive. For a better bond, they are fixed on a slant so that provides the greatest resistance to pull-out of the nails during test. The joint between round woods are materialized by nails with T form, manufactured with a ribbed iron of $8mm$ in diameter and approximately $0.20m$ long (Figure 3).

Once armed the structure of the panel, it was backfilled and plastered on both sides with the mixture of mud and vegetable fiber, and allowed to dry for a period of a month and then were painted with white syn-

Figure 1. Wattle and daub constructions parts

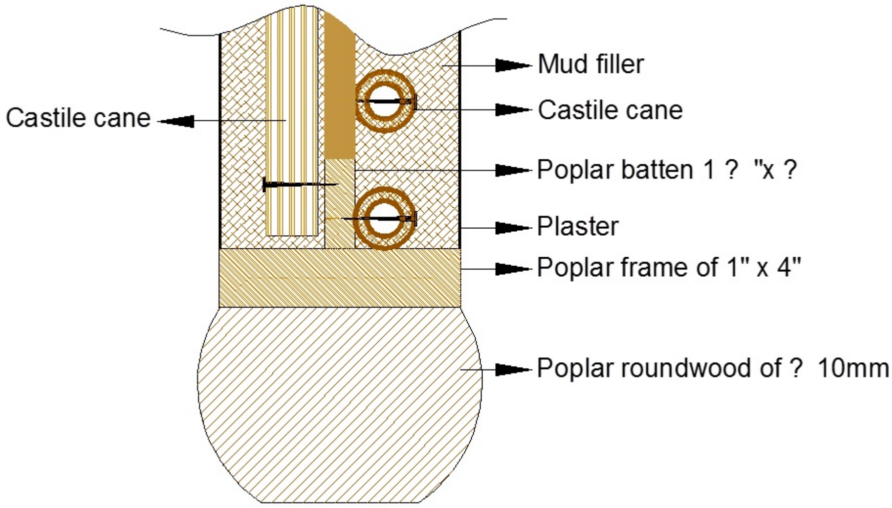


Figure 2. Detail of panel (vertical section)

thetic enamel, to observe the appearance of cracks or possible crumbling (in its real magnitude) during tests, Figure 4. In the construction of a home is not advisable to use white synthetic enamel, because it eliminates the exchange of moisture within the wall, which is important in desert environments (Minke 2005).

2.2 Compression Load Test Methodology

For purposes of the test, the panel is clamped at the base of the round wood to a rigid concrete base. Four extensometers, one in each upper corner of the panel and on both sides were placed. Two extensometers are arranged in the middle of the panel to record cross section strain (Figure 5). Extensometers characteristics are: trademark Mitutoyo; maximum reading $50mm$; accuracy $0.01mm$ and they have a direct reading. The load is applied through a hydraulic actuator (CIFIC LE-74) with dynamometer springs (AMSLER LE-01).

The load was materialized as it is specified in ASTM E 7261 Standardt (Norma IRAM 11.588 1972) through a transition metal element, which in this case was a double-T profile beam (IPN 360). It is achieved a distributed load along the panel, Figure 5. The load of profile has a weight of $892N$. It was taken into account in the total load applied to the panel at each loading and unloading cycle. In all tested cases was gave a preload of $10kN$ plus the load of profile. From this point it began take into account the extensometers readings.

The loads increments are chosen so that it can get a number of readings appropriate to allow trace the load-strain curve. In this case nine cycles of loading and unloading (Norma IRAM 11.588 1972) were made. Initially it was performed in a control panel assay, where it was loaded the panel without extensometers until the dynamometer stopped reading load, which corresponds to the fracture of the panel ($255.91kN$). From this data it is possible to know approximately the load capacity of the wattle and daub wall. With this data it was determined that the walls can be loaded up to $100kN$ without damage in the extensometer by an unexpected wattle and daub panel breakage. Completed the nine cycles, where it reached $100kN$, the extensometers have been removed. Subsequently the load is increased until the panel fracture.

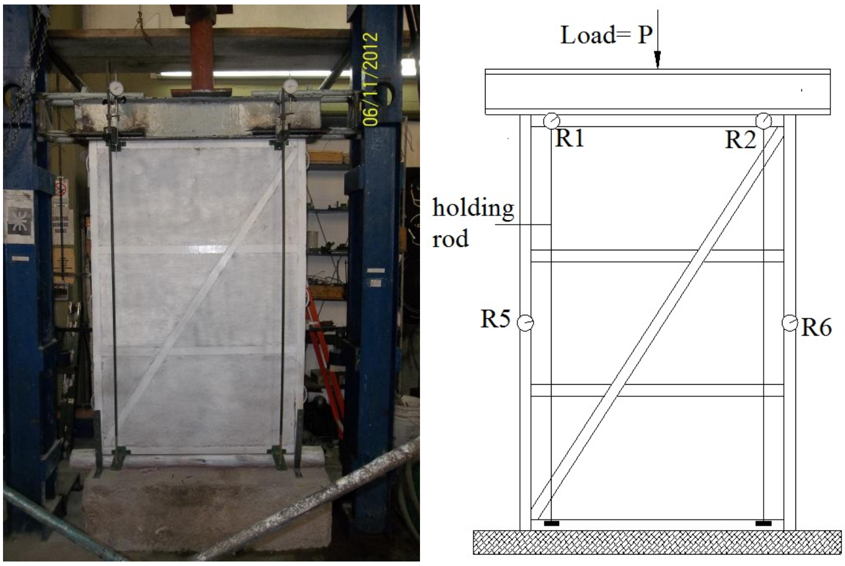
2.3 Shear Load Test Methodology

It was used the wattle and daub walls constructed with a framing of roundwood to all around, Figure 6. Static load was applied at the wall's upper end. In a first step, was loaded to the wall in the same direction of the diagonals, and in the second step was performed in

Figure 3. Nails with T shaped, manufactured with a ribbed iron of $8mm$ in diameter and $0.20m$ long)

(a) Roundwood structure perimeter (b) Filling with mud (c) Finished Panel

Figure 4. Assembly's sequence of wattle and daub



(a) (b)

Figure 5. Wall's compression load test and schema of the test

Figure 6. Wattle and daub's panel for shear loading test

the opposite direction, Figure 6. This test is called a Cantilever beam testing.

The equipment used for analyzing the behavior of the walls to shear load was: a spring dynamometer AMSLER LE-01, an hydraulic actuator CIFIC LE-35, up to 70 tons, suitable for performing static load, six extensometers direct reading Mitutoyo 50mm, with accuracy of 0.01mm.

Wattle and daub's walls were fixed at the bottom to a rigid concrete base, which simulates underrun that would be subject on the actual conditions. It is applied a horizontal load parallel to the base on the wall's upper end, as seen in Figure 7, allowing a deformation on its own plane. A control test was performed to determine the load capacity of the panel. On this instance the extensometer was not used, obtaining a fracture load of 22.55 kN. With this reference data, it was possible to determine that walls could be loaded to 60% of its capacity without damage extensometers by the wall sudden collapse. Then four walls were tested; in a first instance two walls were assayed in the same diagonal's direction reinforcement of the wall (Figure 7 left) and two in the opposite direction (Figure 7 right.). The forces applied to the wall and the corresponding displacements at each load range were recorded. The load was applied in four cycles of charging and discharging load until reach 13.73kN load.

3 COMPRESSION LOAD TEST

Wattle and daub wall's structural analysis is complex to predict, because the behavior is determined by the interaction between poplar wood frame, the framework of canes and mud fill. For this reason the walls are subjected to a continuous static load until it reaches the panel fracture.

3.1 Failure Mode of Wattle and Mud Walls

Figure 8 shows, sequentially, the response of the walls during the load test until it reaches the rupture. The behavior of the walls during the load and unload was similarly in all cases, however, the walls broke down in different ways (Figure 8).

On control panel, PQV-0 (Figure 8), for the maximum load (255.91kN), the failure occurred at the left support bracket. In this panel, the triangle located above the diagonal, moves down, leaving without cracking the area located below it. In the area where the breakage of wooden frame occurred, it can be observed that despite the breakage of the wood frame, the canes disposed inside of the panel were not damaged, being able to be reused for a new panel. Also taking into account that the set of cane-plaster maintains its original dimensions is evidence that the canes structure resists loading up the value of breakage the wall.

In the tested wall PQV-1 (Figure 8), the breakpoint was in the area located below the diagonal. In this case, the ultimate load was 216.64kN, however failure panel was affected by an existing knot in the wood frame, a common wood defect. Despite the wood defect, the strength obtained is expected for this type of wall.

On panel PQV-2 (Figure 8), the breakage occurred in the upper area of the panel framework, causing the entire area located above the diagonal had a displace, leaving without any cracks the entire area below itself. The failure was produced at 206.90kN.

On panel PQV-3 (Figure 8), in this case the charging on the panel stopped when on the wall above the diagonal had a displacement that make it impossible to continue to charge the wall. The displacement was not large enough to appreciate in Figure 8 in its full magnitude, however, the upper and middle parts, had surface cracks. In this case the failure was produced at 201.99kN.

3.2 Compression Load Capacity

According to IRAM Standard 11585, the failure load in wattle and daub prefabricated walls, Table 1, was determined under a compressive load, up to break them. The failure load is calculated by Eq. (1). For this analysis the information of PQV1 to PQV3 tests, has been take into account.

$$P_{kr} = P_{km} \times (1 - k \times \delta) \tag{1}$$

$$\delta = \frac{S}{P_{km}} \tag{2}$$

$$S = \sqrt{\frac{\sum (P_{PQV} - P_{km})^2}{n-1}} \tag{3}$$

where P_{kr} is the characteristic ultimate load expressed in kN, P_km is the arithmetic average of the failure load

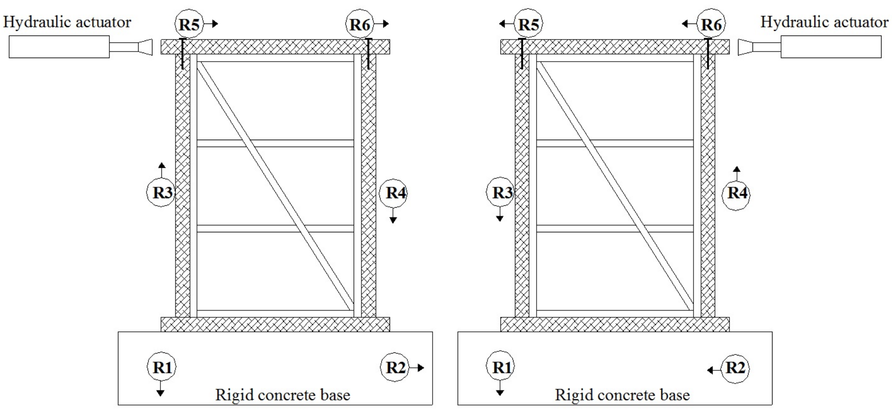


Figure 7. Wall's application diagram loaded with extensometers

(is $208.51kN$), k is the dispersion coefficient, according to IRAM 11585 - Table 2 is 2.92, δ is the normal variation coefficient, depends on the standard deviation S in kN and the arithmetic average P_{km} in kN, n is the number of wattle and daub walls tested, in this case are 3, P_{PQV} is the failure load of the walls from PQV-1 to PQV-3 in kN, f'_{cqr} is the ultimate compressive strength in MPa (see Table 1).

In conclusion, the characteristic ultimate compressive load of wattle and daub walls is $186.59kN$ and rupture compressive strength corresponding to wattle and daub wall is 1.56 MPa.

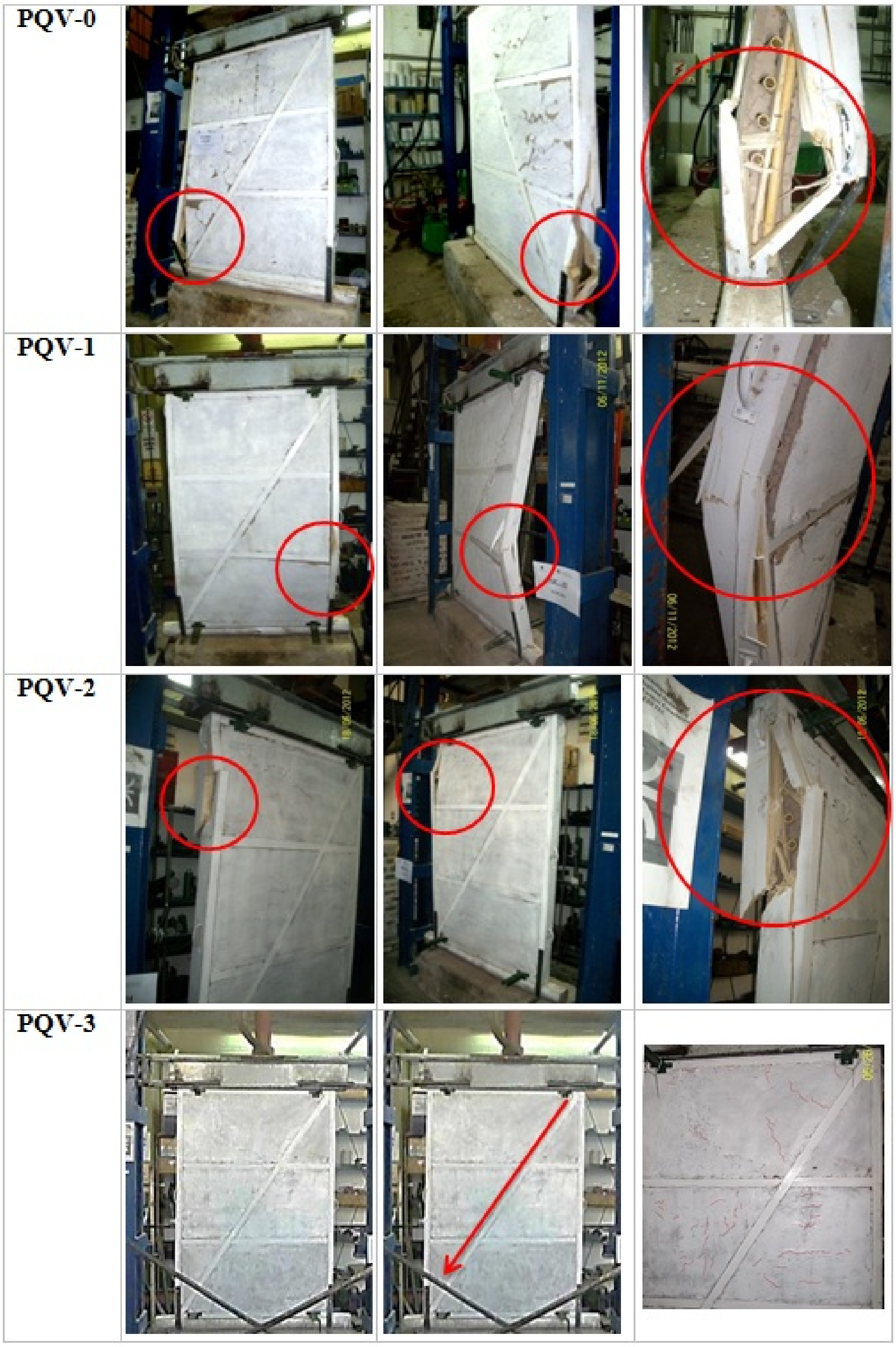


Figure 8. Sequence of wattle and daub walls to compression load tests

Table 1. Determination of characteristic fracture load

Parameter	P_{km}	S	δ	k	Characteristic fracture load	f'_{cqr}
Unit	$[kN]$	$[kN]$			$[kN]$	$[MPa]$
Value	208.510	7.452	0.036	2.920	186.590	1.560

Table 2. Elasticity modulus determination on wattle and daub walls

	1° Charging cycle		2° Charging cycle		E
	$\delta_1[mm/mm]$	$\sigma_1[MPa]$	$\delta_2[mm/mm]$	$\sigma_2[MPa]$	$[MPa]$
PQV-1	0.00024	0.1743	0.00049	0.258	336
PQV-2	0.00020	0.1743	0.00043	0.258	365
PQV-3	0.00037	0.1743	0.00064	0.258	311
Average					337

3.3 Elasticity Modulus

The elastic modulus is carried out on the elastic portion of the compression test with Eq. (4). In Figure 9, the curves correspond to compression test, and the points inside the red square are used to determine the elastic modulus. Table 2, shows the modulus of elasticity from each tested panel and the average value.

$$E = \frac{\sigma_2 - \sigma_1}{\delta_2 - \delta_1} \quad (4)$$

where E is the longitudinal elasticity modulus in MPa, δ_{1-2} is the specific deformation, is the ratio between the shortening averages of each charge cycle in mm and the panel height $1800mm$ in mm/mm, σ_{1-2} is the compressive strength corresponding to the first and second cycle of compression load in MPa.

4 SHEAR LOADING TEST

Figure 10, shows sequentially the wall's behavior during loading and unloading cycles in shear load test. The test performed in the diagonal direction and in the opposite direction to itself, has similar responses during its development, and the most important variable was the failure load obtained in each case.

4.1 Test Results: Load Cycle on Wattle and Daub Walls

In all four cases, the wall's failure was due to a displacement of the diagonal upward, causing slowly cross braces were detached, with the consequence of breaking the mud of the panels, the most affected area were located below the diagonal (the photos of the failure is negative for assessing the behavior of the panel). However, after discharge of the wall is partially recovered allowing its restoration. This is accomplished by removing the surface layer mud cracked, add water and reuse it to plaster again, as the skeleton of canes and the frame did not suffer irreparable damage. An improvement proposal for further testing on the walls, is to optimize the joints between roundwood, using lag screws, threaded rods or flat bars, providing greater resistance to pulling out. Originally armed iron nails were used with $8mm$ in diameter and $0.20m$ long, Figure 3.

4.2 Shear Load Capacity and Shearing Module (G)

Shear deformation modulus, is measured in the elastic phase of each wall, as a gradient between two points on the graph of shear stress versus the angular distortion, see Figure 11. It is considered to be the first load cycle because there was no cracking at this stage.

The shear stress was calculated as the ratio between the difference of lateral load and the shearing area, corresponding to the full width of the wall ($1.40m$), including roundwood, by the thickness of the wall ($0.10m$). Table 3, shows the values of G obtained for each wall, calculated by Eq. (5) and Eq. (6).

$$G = \frac{P_1 - P_2}{A \times \gamma} \quad (5)$$

$$\frac{\Delta_1 - \Delta_2}{H} \quad (6)$$

where G is the wall shear modulus in MPa, $P_1 - P_2$ are

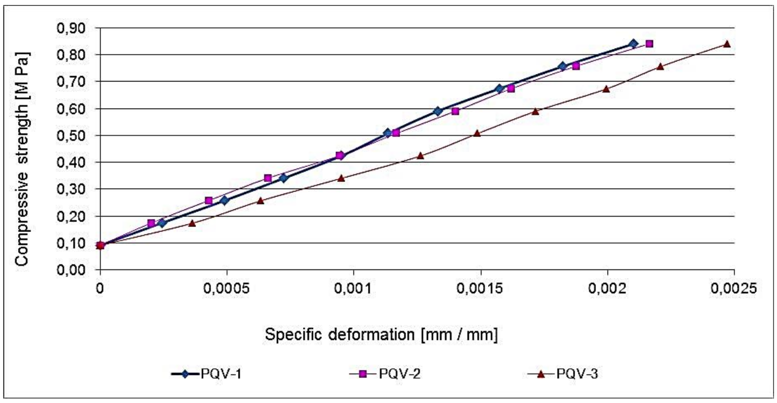


Figure 9. Compression test's curve of wattle and daub walls

the load applied to the top of the wall at the instant 1 and 2 in N, A is the application load area equivalent to 1400mm wide and 100mm thick, express in mm^2, γ

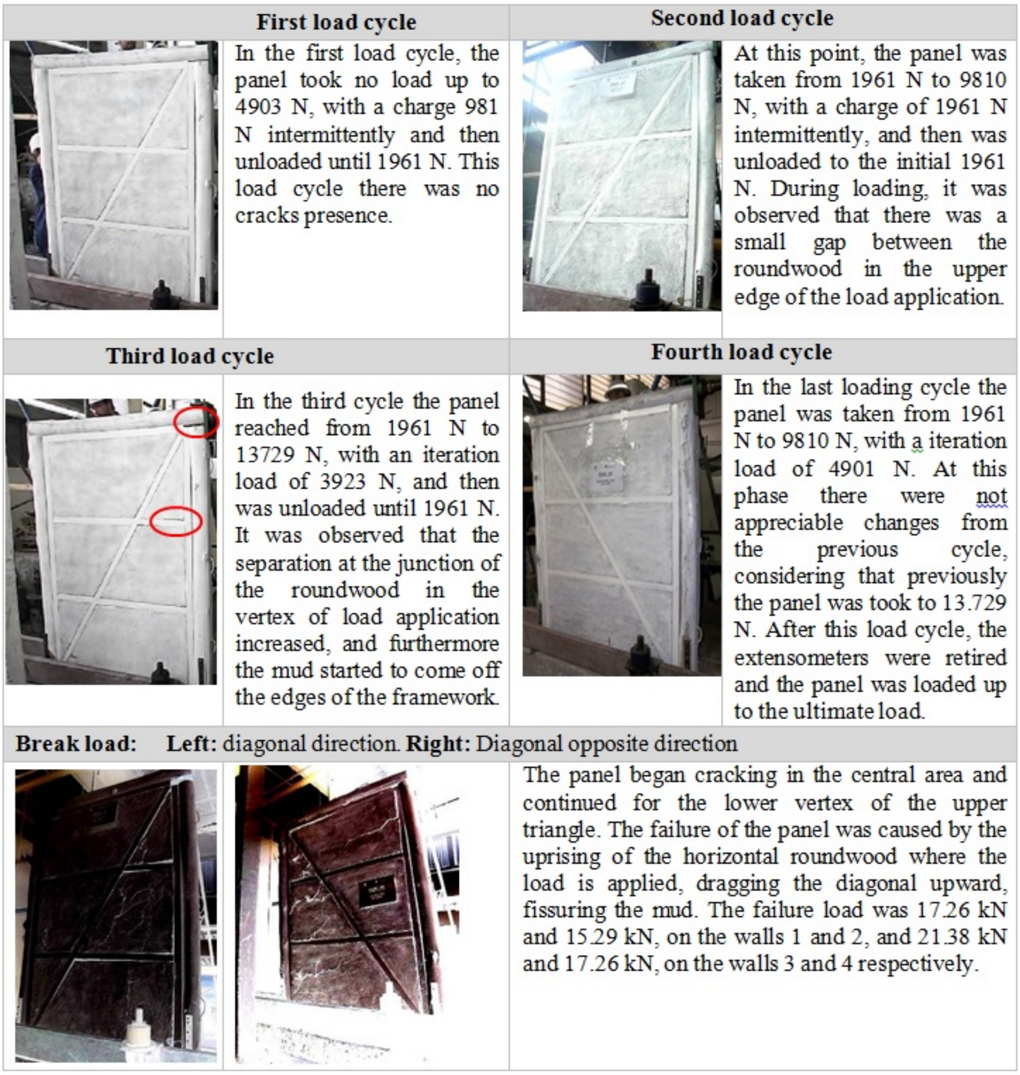


Figure 10. Wall's sequence behavior to shear loading

Table 3. Summary of walls resistant parameters

Wall	L	b	H	1^{st} load		2^{nd} load		γ	τ	G	τ_m
				P_1	Δ_1	P_2	Δ_2				
	[mm]	[mm]	[mm]	[kN]	[mm]	[kN]	[mm]	[mm/mm]	[MPa]	[MPa]	[MPa]
PQC-1	1400	100	1800	0.000	0.000	1.960	0.590	0.00033	0.014	42.42	0.123
PQC-2	1400	100	1800	0.000	0.000	1.960	0.840	0.00047	0.014	29.78	0.109
PQC-3	1400	100	1800	0.000	0.000	1.960	0.800	0.00044	0.014	31.81	0.153
PQC-4	1400	100	1800	1.960	0.025	2.940	0.525	0.00028	0.0071	25.35	0.123
Average										32.34	0.13
Standard deviation										7.24	

Note: L - the wall's length.
b - the wall's width.
H - the wall's height.
P_1 - the first load.
Δ_1 - the horizontal displacement for load 1.
P_2 - the second load.
Δ_2 - the horizontal displacement for load 2.
γ - the wall angular distortion.
τ - the wall's shear stress.
G - the shear module.
τ_m - the shear strength.

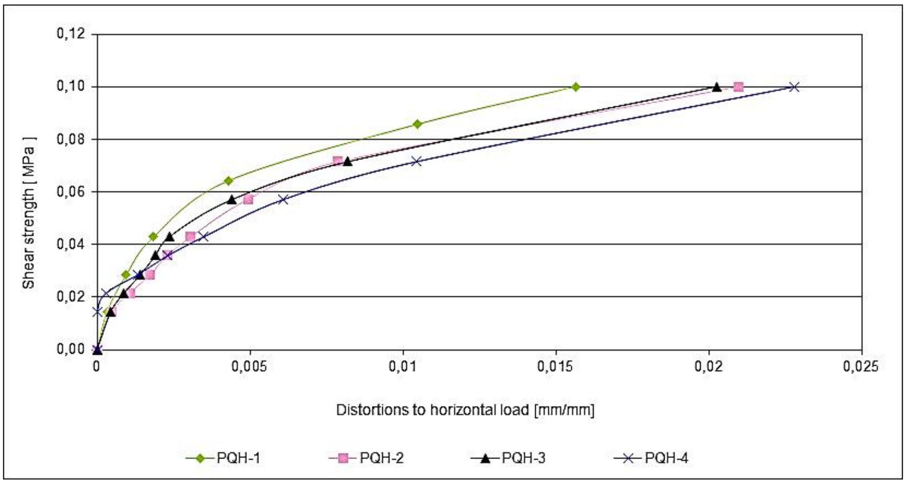


Figure 11. Shear strength vs. distortions to horizontal load

is wall's angular deformation in mm/mm, $\Delta_1 - \Delta_2$ are the displacement measured at lateral load application level at the moment 1 and 2 in mm, and H is load height application in mm.

The results obtained shows that the average shear modulus is $32.34MPa \pm 7.24MPa$ and the average shear strength is $0.13MPa$.

5 MATHEMATICAL MODELING OF WATTLE AND DAUB WALL

Once the experimental assays on wattle and daub prefabricated walls were completed, it proceeded to the wall's simulation using the Abaqus / CAE v6.11 Software.

The wall had been simulated with the Finite Element Method, in addition, was used an analytical rigid shell type elements to simulate the load devices. The element's size and the mesh density were defined in a manner that allow the study on the panel's thickness, that shows the response of the diagonal and the mud and cane behavior to different load states (González del Solar et al. 2013), Figure 12.

In the case with the compressive load, was observed that the characteristic ultimate load in experimental essay reached a value of $187kN$ and the mathematical model had a ultimate load of $195kN$.

For the case of shear load, in the experimental essays, the average breaking load in the direction of the diagonal was $16.20kN$ and the numerical model designed reached a breaking load of $10.00kN$. In the last case, the experimental average breaking load in diagonal opposite direction was $19.4kN$, regarding the numerical model, which showed a breaking load of $10.4kN$.

6 RESULTS ANALYSIS

6.1 Compressive Load Results Analysis

The experimental results obtained on wattle and daub walls are contrasted with the values recommended by the regulations. In this case brick and mud walls, have been take into account as representative materials of higher and lower resistance than wattle and daub wall, respectively. The elasticity modulus values and compression resistance for each case are presented in Table 4, for brick wall, values are obtained from CIRSOC

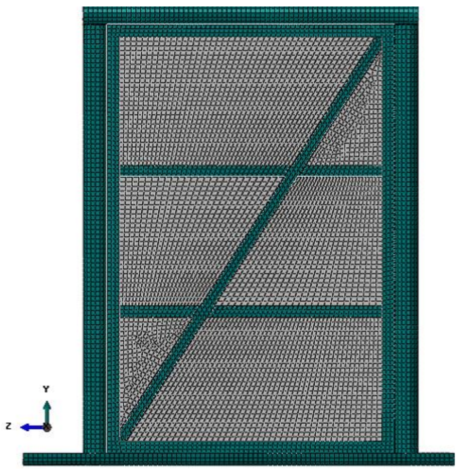


Figure 12. Wattle and daub wall mesh

Table 4. Summary of mechanical properties of mud walls, wattle and daub and brick

	Mud walls			
	E-080	NZS-4297	Wattle and daub	Brick
Compressive strength $[MPa]$	$f_c = 0.20$	$f_c = 0.50$ (3)	$f'_{cqr} = 1.56$	$f'_m = 2.50$ (1) $f'_m = 1.75$ (2)
Elasticity modulus $[MPa]$	$E_m = 174$ (4)	$E_m = 300 f_c$ (5) $E_m = 60$	$E_m = 337$	$E_m = 850 f'_m$ (1) $E_m = 1488$

Note: (1)−(2) - High and normal resistance of strength of bricks masonry, respectively (Norma CIRSOC 501 2007).
(3) - Morris (2006).
(4) - Tarque (2008).
(5) - $f_c = 2.04 kg/cm^2$. Standard E-080: Mud wall compression resistance.

501 Regulation (Norma CIRSOC 501 2007). For mud walls is used the Standard Building Technical (Norma 'ecnica de edificación E.080 2000) used in adobe constructions in Peru and also the Standard New Zealand (Standars New Zealand 4297 1998).

The behavior of wattle and daub walls under to compression load presents intermediate values between the walls of brick and mud walls. However, wattle and daub has the advantage that with a smaller thickness in its structure, provides better resistance to compression, respect mud walls. If analyzed the elastic response, is observed that wattle and daub walls has higher strain capacity than mud walls, this is an advantage because this means that can absorb greater load before reach a plastic behavior than mud wall.

In the mathematical modeling of the walls, is observed the stresses distributions on wattle and daub walls subjected to compression load, Figure 13. Is possible to see that simulated response is similar to the experimentally behavior, allowing to use the mathematical model as a guide to design wattle and daub buildings. Also, as an alternative material, with a few antecedents in the field of structural numerical simulation, this first approximation to the real behavior, is accurate and interesting to further investigation.

6.2 Shear Load Results Analysis

Table 5 compares the data obtained experimentally for wattle and daub walls, with the values indicated in Standard CIRSOC 103 part III (2007) for brick, and with mud walls. In the case of brick, it is considered the behavior of a brick wall of $0.18m$ without confinement.

Wattle and daub walls presents, a better resistance than mud walls unconfined, although not respect to bricks walls. However, because in low economic resources areas tend to build their houses with earth material, the use of cane framework on the walls for a greater structural strength is highly recommended. Respect to shear modulus, the wattle and daub walls has a similar value to mud wall, being in evidence that the wattle and daub walls and mud walls mostly, do not have the same capacity to resist shear stresses that compressive stresses. Therefore must be made constructive improvements to increase the resistant capacity to this effort. The stress state on wattle and daub walls, Figure 14, obtained numerically, shows the areas that are subject to bigger stress state, where can be confirm the similarity with the affected areas during the experimental essay. The damage zones are those for wall joints, and where is emphasized to make improvements. In future essays prefabricated wattle and

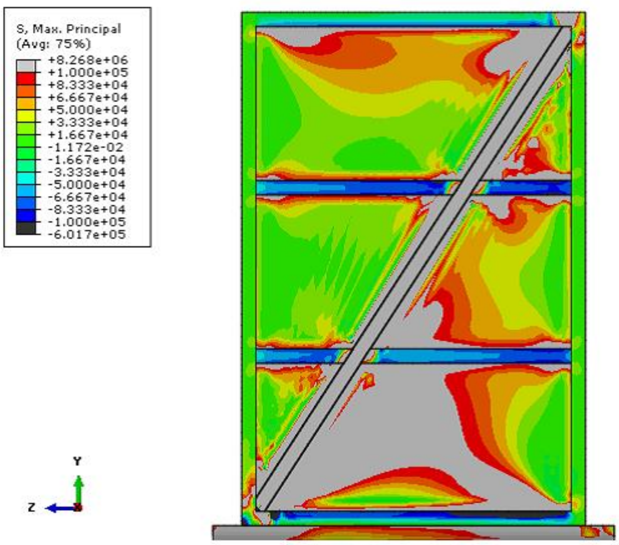
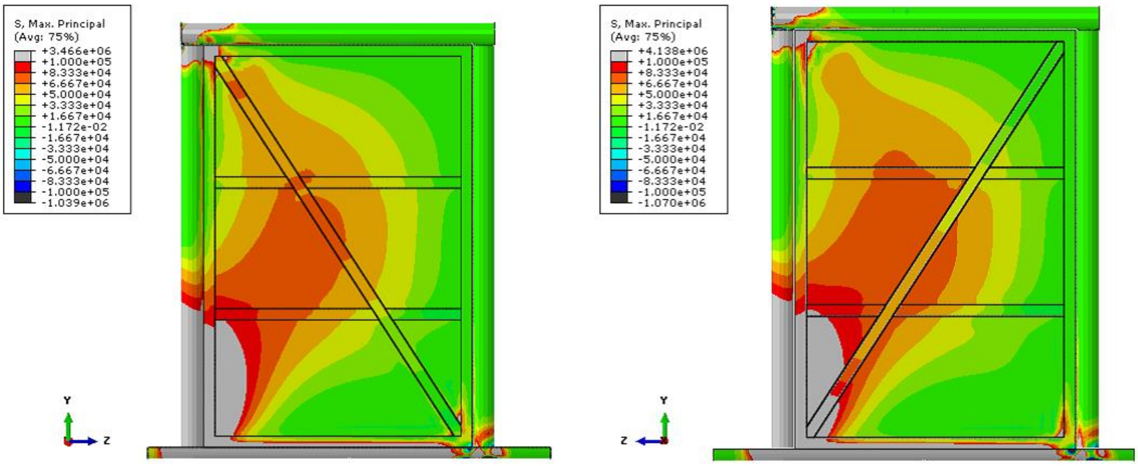


Figure 13. Compression maximum stresses distribution

Table 5. Summary mechanical shear properties on mud, wattle and daub and brick walls

	Mud wall	Wattle and daub	Brick
Shear Strength $[MPa]$	$\tau_m = 0.03$ (1)	$\tau_m = 0.13$	$\tau_m = 0.40$ (2) $\tau_m = 0.30$ (3)
Shear modulus $[MPa]$	$G_m = 30$ (1)	$G_m = 32.34$	$G_m = 0.3E_m$ $G_m = 446$

Note: (1) - (Yamin et al. 2003).
(2) - High shear strength of masonry with solid bricks Norma CIRSOC 501 (2007).
(3) - Normal shear strength of masonry with solid bricks Norma CIRSOC 501 (2007).



(a) In the diagonal direction (b) In the opposite diagonal direction

Figure 14. Maximum stresses distribution: Shear load application

daub walls, is intended to use coach screws, threaded rods or flat bars, to improve resistance to rip out. In the worst case, can happen a cracking or detachment of mud plaster from walls, in these cases, is also allows a faster repair of the walls after this type of disaster.

7 CONCLUSIONS

The wattle and daub wall, if is constructed with the specification that describes in this work, can have a compressive strength of $1.56MPa$ and a elasticity modulus of $337MPa$, a shear strength of $0.13MPa$ and a shear modulus of $32.34MPa$, which is so many better than mud walls, because the canes inside the walls, gives an elasticity that allows a higher deformation before starts to cracking the clay surface. Is interesting to continue this investigation, changing wattle and daub wall's characteristics, such as the width and observe if the shear strength improves. In agrarian areas, there are so many people that have a wattle and daub house, and that continue building their homes with this technic, that is important to create a regulation with data to help during the design, this essay can give some information about this issue. The mathematical response is similar to the experimental behavior, so it can be used to predict the response to different loads. To complete this investigation, is pretended to study de thermal response to be able to use in the different climates areas.

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