Experimental analysis of seismic resistance of shear wall in traditional Haitian houses

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SUMMARY:
The seismic performance of Haitian wood structures filled with natural stones and earth mortar is estimated by using three scales of experimental tests in which cyclic and monotone loading are applied. At the connection scale, direct tension tests are performed to obtain the hysteretic behaviour depending of the nails number. At the elementary wall scale, elementary structure of a wall, shear tests are performed to obtain the hysteretic behaviour depending of the filling characteristics. By the same method, the behaviour of a whole wall without opening is obtained.
The final aim will be to use these results in a multi-scale modelling to assess the Haitian houses' behaviour under a seismic loading.

Keywords: wood structure, earth, stones, adobe, filling, seismic resistant, hysteretic behaviour ,cyclic and monotone static shear test , multi-scales

1. INTRODUCTION

During the earthquake that struck Haiti, on the 12th of January 2010, a great number of concrete block and reinforced concrete buildings were heavily damaged. The destruction or collapse of these buildings had a dramatic impact in terms of human life and huge economical loss for the country. In urban areas as well as in rural ones traditional timber frame buildings did not suffer that much, showing an enhanced structural behaviour and exposing their inhabitants to a limited risk, thanks to their lower seismic vulnerability (see [3]).

These findings raise the issue of the very limited importance given to local architectures by the scientific community and by those responsible for reconstruction, despite the fact that in Haiti as well as in other places, those structures have often shown highly relevant use of technical solutions and available resources, in relation to the constraints and the potential of the context.

Within the framework of the ReparH project, supported by the French National Research Agency (ANR), a scientific collaboration was established between researchers in the field of architecture (CRAterre-ENSAG) and engineering (3S-R - UJF) with the Haitian organization GADRU, to carry out a technical and methodological reflection to support the development of sustainable reconstruction and vulnerability reduction strategies.

This paper presents the scientific study of a building system used for housing reconstruction and based on the use of materials such as earth, stone and timber (see Fig. 1.1), aims to analyse the behaviour of the new buildings under seismic loads. Timber framed structure with masonry infill is studied at multiple scales, ranging from that of joints, the elementary component which constitutes the walls element, up to the whole shear wall. This approach makes possible to test several parameters easily and quickly such as the influence of the type of nails on the joint 'behaviour or of the characteristics of the filling on the elementary wall behaviour. Then it gives experimental data for multi-scale modelling (see [6]) (not presented herein).

Figure 1.1. Traditional Haitian house (old and new)

2. DESCRIPTION OF THE SPECIMENS AND EXPERIMENTAL SET-UP

2.1. Joint

2.1.1. Description of the specimens

The joint is presented on Fig. 2.1. It is a steel-wood nail connection made by a punched steel strip that embraces the wood parts (T shape) and is fixed by some nails, which govern the connection‘s behavior. Currently, only smooth ones are used in Haiti for wood structures but it may change thanks to Non-Governmental-Organizations (NGO), which are there for a while. Thus, ringed nails have also been used for connection in direct tension tests.

The punched steel strips have been used in Haiti for few months in the context of NGO’s project of reconstruction such as one of MISEREOR NGO. On-site, those pieces go deep in foundation (footing made by natural stones and cemented by concrete mortar) to be anchored.

Wood dimensions and classes have been chosen by architects to be as close as possible from the local wood’s characteristics.

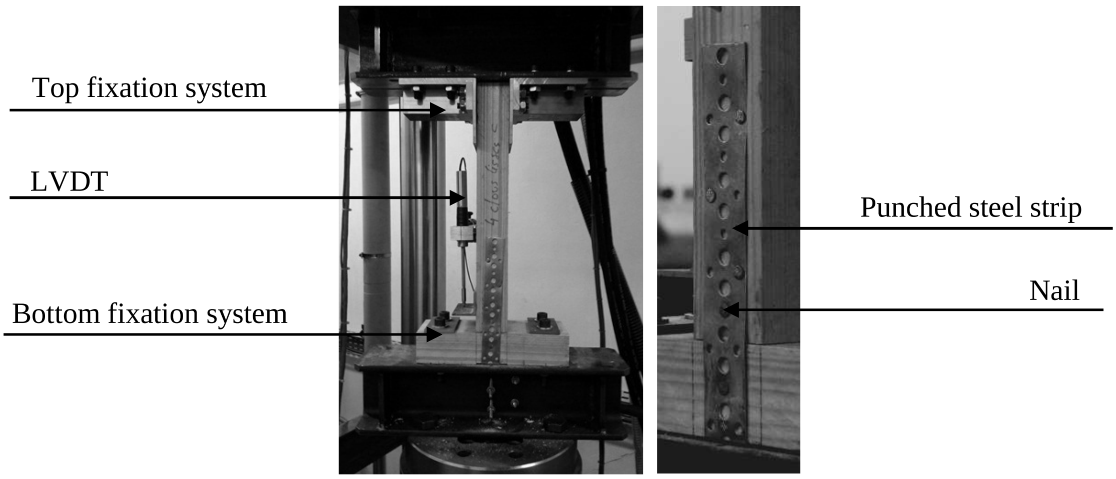


Figure 2.1. (a) Direct tension test on joint, (b) connection with four nails

2.1.2. Experimental set-up

Tab. 2.1. presents the characteristics of the direct tension tests on joint.

The loading path was adjusted taking into account the standards ISO/FDIS 21581:2010(E) (Timber structures – static and cyclic lateral load methods for shear walls). Tests are displacement controlled with displacement measured by linear variable differential transducer (LVDT) (see Fig. 2.1.) at a rate

depending of the cycle displacement (30 second between two peaks).
At this stage, just one monotonic and one cycle test have been done on each configuration of joint. More tests will be performed soon on the same connection to complete this experimental campaign.

Table 2.1. Configuration of direct tension test on joints

Type of tests	Number of nail	Nail	wood section (mm)	Wood mechanical class
1 monotonic/1 cyclic	1	2.5x70 smooth	50x100	C18
1 monotonic/1 cyclic	2	2.5x70 smooth	50x100	C18
1 monotonic/1 cyclic	4	2.5x70 smooth	50x100	C18
1 monotonic/1 cyclic	2	3.0x50 ringed	50x100	C18
1 monotonic/1 cyclic	4	3.0x50 ringed	50x100	C18

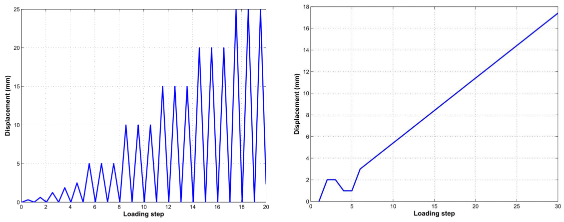


Figure 2.2. (a) Cyclic loading protocol, (b) monotonic loading protocol

2.2. Wall

2.2.1. Description of the specimens

Filled wood structures are more and more used by rural people due to its low cost (earth and stones are available on-site). There are three main kinds of structures: braced by Saint Andrew's crosses filled with natural stones linked by an earth mortar (see Fig. 1.1. and Fig. 2.3.), braced by one diagonal per elementary wall filled with adobes (handmade earth brick) and braced by cob panels. Architects chose to keep the first one because it is the easiest to build and the most used currently.

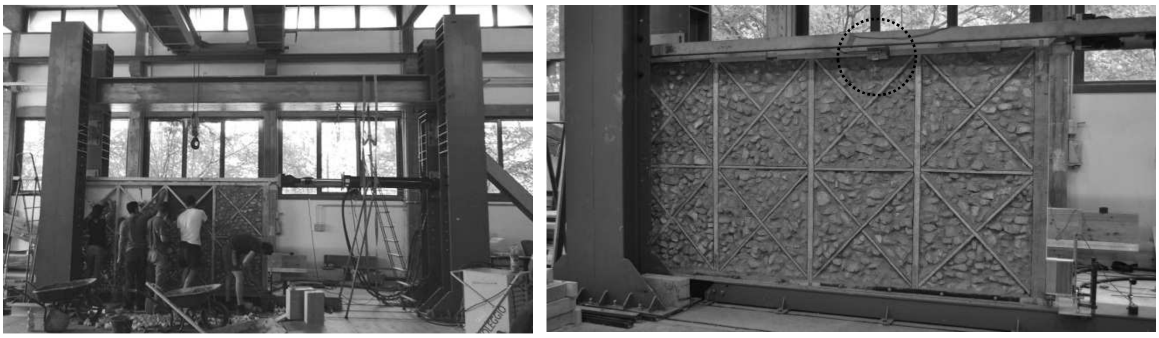


Figure 2.3. (a) Test apparatus, (b) wall cross braced filled with stones

The experimental program has been performed at CNR Ivalsa in Trento (Italy) during 1 month (august 2011) (A. Ceccotti already performed tests on the same kind of filled wood structures, see [2]). The filled walls were built directly on the testing apparatus because of the difficulty to move them (see [1]). Therefore, after wall construction, it has been covered with a plastic tarpaulin and a dehumidifier has been used to dry quickly the earth mortar (h=30%, T=20-25°C). In this way, mortar dried in three days only. To prevent from cracking, water content was limited in earth and fibres were added. The earth was composed by one measure of a clay-calcareous mix (grading < 125 μm), two measures of sand (grading < 2 mm), half-measure of water (depending of sand's water content) and one measure (very coarse measure) of sisal fibres (easy to find in Haiti). The clay-calcareous mix was chosen by architects to have a mortar as close as possible from those made with local earth.
The fibres limit cracking apparition and growth in mortar. Then, smooth nails are put inside wood triangles to improve link between the two parts.

The wood characteristics and the dimensions are identical than precedent case except for extremity posts which have 100x100 mm cross section in order to make possible the moment and load transmission by the bracings and to support the wood structure of Haitian's house.
Bracings are made by Saint Andrew's crosses with one continue beam and one diagonal in two parts. This technique makes the construction easier and does not weaken the wood in comparison with a wood connection by cutting at each diagonal's middle a piece of wood.
Joints are the same than above with four nails.

2.2.2. Experimental set-up

The loading program is made according to the ISO/FDIS 21581:2010(E) (Timber structures – static and cyclic lateral load methods for shear walls) (see Fig. 2.5.). Tests are displacement controlled considering the average displacement measured by LVDT3 (dx3, top right displacement), LVDT4 (dx4, relative displacement between the steel beams and top of specimen) and LVDT5 (dx5, top left displacement) (see Fig. 2.4.(b)). The tests were conducted at a rate of 2,2 mm/s.
The bottom of horizontal wood bar is anchored on the steel horizontal reaction beam by twelve bolts.
Vertical and horizontal displacement are also measured at each right and left extremity of wall (see Fig. 2.4.(c)) and to prevent from buckling, rollers maintain the top wood beam of the wall (see Fig 2.4.(a)).
The roof of Haitian houses is built with sheets metal so it is very light. Therefore, no vertical load is applied on the wall.
Tab. 2.2. presents the characteristics of the tested shear walls.

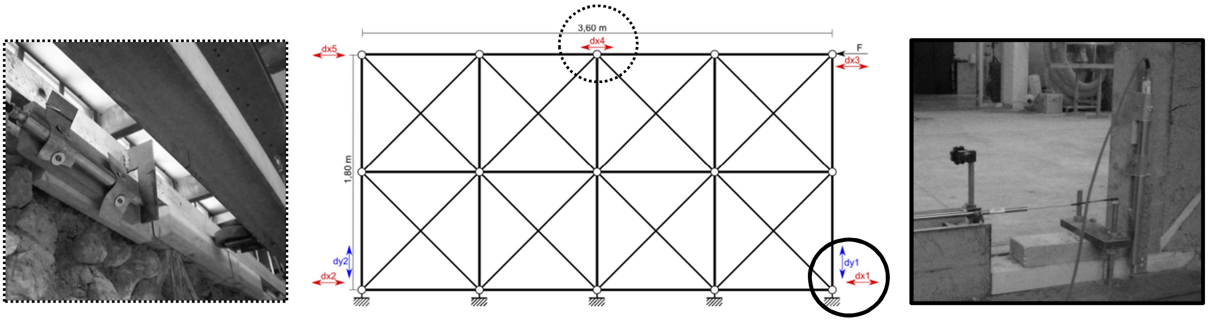


Figure 2.4. (a) anti-buckling roller, (b) LVDT position and orientation, (c) LVDT at the lower extremity of the wall

Table 2.2. Configurations of shear wall tests

Type of tests	Filling	Nail/joint
1 monotonic/2 cyclics	Stones	4 smooth 2.5*70
1 monotonic/2 cyclics	empty	4 smooth 2.5*70

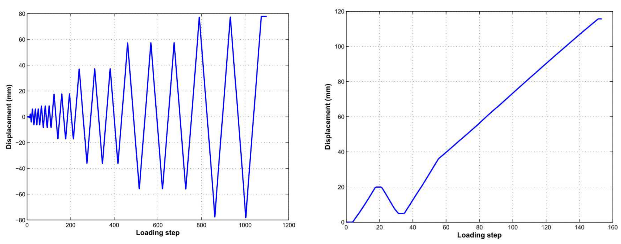


Figure 2.5. (a) Cyclic loading protocol, (b) monotonic loading protocol

2.3. Elementary wall

2.3.1. Description of the specimens

As it was already explained in §2.2., rural Haitian houses are built in different ways. Obviously, the behavior under seismic loading can be different from the measured cyclic behavior. For a good design, it is important to know and evaluate this difference. But it is quite complicated to change many

parameters on a whole wall. Thus, a new testing apparatus has been designed to test intermediate scale such as an elementary wall, which is part of the wall.
Besides, it is also relevant to get the experimental data for a simple elementary wall in order to build a new macro-element suitable for simulating the behavior of an elementary wall and then the whole wall (not presented in this paper).
On the contrary of conventional wood structures in which all the non-linearities of their behaviors under seismic loading are in steel connections, in Haitian houses, non-linearities are also due to the friction between earth and wood, damage of the filling and the flexibility of the structure.
Design and improvement of the testing apparatus took a long time. This is the reason why, for the first experimental program, only one kind of cross has been tested with stone or adobe.
All the characteristics of the elementary wall are identical of whole wall (wood structure and earth) except that only three nails were put in steel joint (see Fig 2.7.).

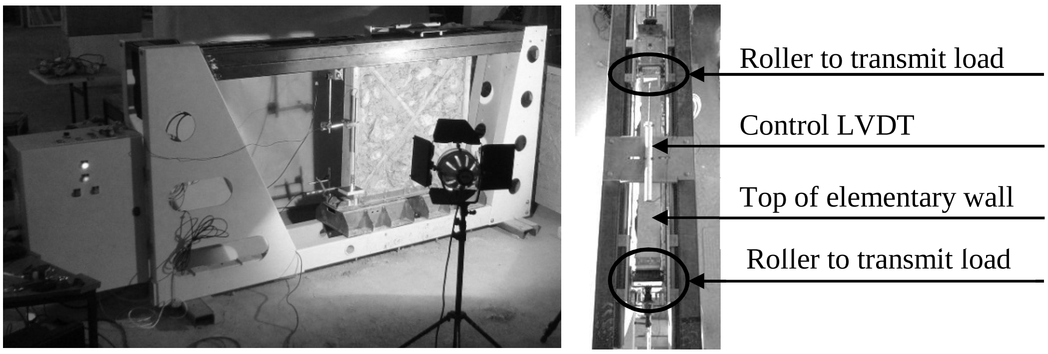


Figure 2.6. (a) Shear test on elementary wall, (b) top view

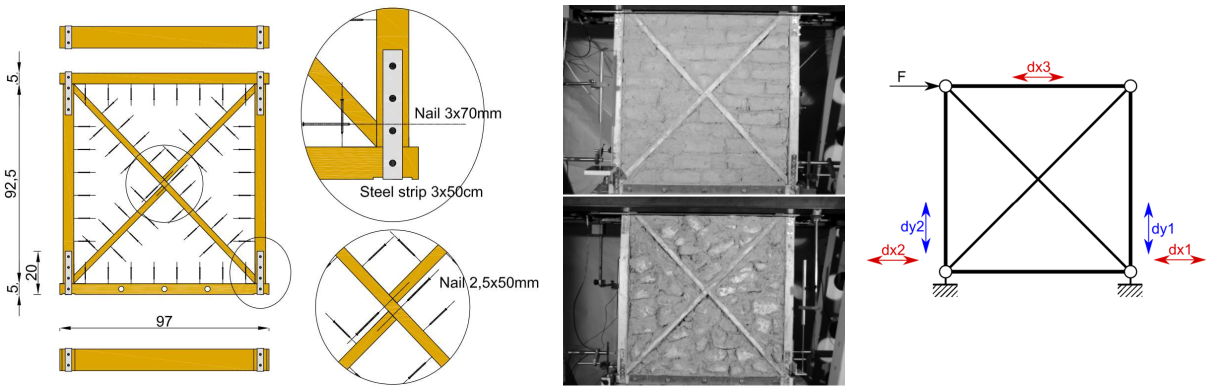


Figure 2.7. (a) Empty elementary wall dimensions, (b) elementary wall filled with adobes (top) and stones (bottom), (c) LVDT position and orientation

2.3.2. Experimental set-up
On both top sides of the elementary wall, rollers applies the loading through a steel plate fixed on wood. The rollers prevent from parasite moment transmission and steel plate distributes load in both horizontal and vertical beam preventing from large shear stress.
The elementary wall is embedded by the same method than the whole wall.
The loading path is the same than for the whole wall or for the connections (see Fig. 2.5) and tests are also displacement controlled using linear variable differential transducer (LVDT 3 (dx3), see Fig. 2.7.).

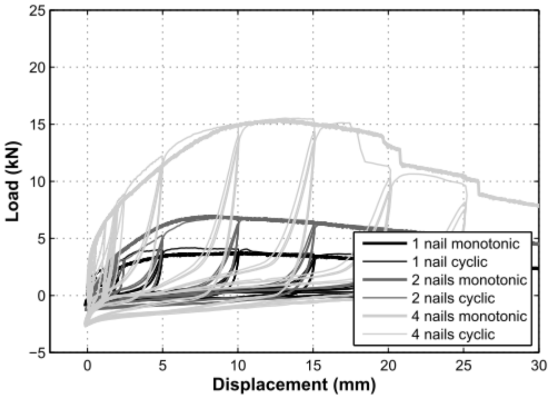
Table 2.3. Configurations of shear elementary wall tests

Type of tests	Filling	Nail/joint
1 monotonic/2 cyclics	stones	3 smooth 2.5*70
1 monotonic/2 cyclics	adobes	3 smooth 2.5*70

3. RESULTS

3.1. Connections

Results of direct tension tests on joints can be seen on Fig. 3.1. and are summarized in the Tab. 3.1..



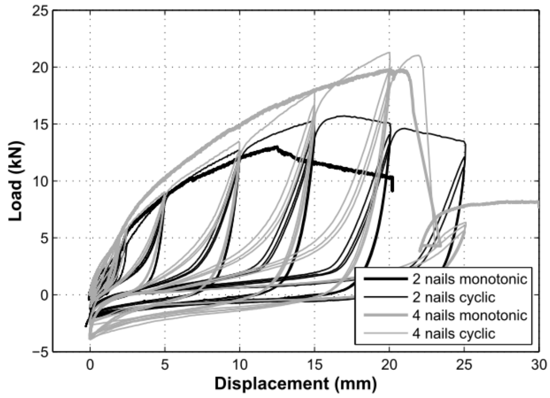


Figure 3.1. Load-displacement diagram for: (a) Smooth nails, (b) ringed nails

Table 3.1. Direct tension tests results on smooth nails

Number of nail (n)	Type of nail	Loading	F_{max} (kN)	$F_{max}(n)/F_{max}(n/2)$	d_{max} (mm)	Location of failure
1	Smooth	Monotonic	3,7	-	10,3	Nails
1	Smooth	Cyclic	4,2	-	7,1	Nails
2	Smooth	Monotonic	6,9	1,9	8,5	Nails
2	Smooth	Cyclic	6,8	1,6	10,0	Nails
4	Smooth	Monotonic	15,4	2,2	12,7	Nails
4	Smooth	Cyclic	15,5	2,3	13,2	Nails

Table 3.2. Direct tension tests results on ringed nails

Number of nail (n)	Type of nail	Loading	F_{max} (kN)	d_{max} (mm)	Location of failure
2	Ringed	Monotonic	13,0	12,5	Nails
2	Ringed	Cyclic	15,7	17,0	Nails
4	Ringed	Monotonic	19,8	20,1	Steel strip
4	Ringed	Cyclic	21,3	20,0	Steel strip

3.1.1. Connection with smooth nails

Fig. 3.1. (a) shows that monotonic tests are close to cyclic tests. It means that unlike the nailing connection with wood-wood contact, there are only few damages between two cycles mainly due to the little deformation of the steel strip during the test. It shows also that the joint is very ductile.

The brutal loss of resistance after the peak that appears in the cycle test in the case of the four nails connection can be explained by a failure of one nail's head. The same phenomenon on the monotonic test is due to the fact that deformed nail crossed the edge of wood as it can be seen on Fig. 3.2. (b). Consequently the contact between nail and wood vanished quicker.

Based on Tab. 3.1., it can be noted that the maximal resisting force of the connection is almost proportional to the number of nails. Due to the large ductility, d_{max} has less meaning for connection with few nails (one or two). For all these tests, the connections always failed due to a large deformation of the nails.

Complementary tests will be important to improve the accuracy of the data.

3.1.2. Connection with ringed nails

Fig. 3.1. (b) shows a rapid decreasing of resistance during the monotonic test with two nails. It is due

to a bad orientation of nailing (in the direction of the loading).
For four nails specimens, the steel strip failed and leads to a fragile behavior of the connection. This kind of rupture must be avoid.
Tab. 3.2. shows that the ratio of resistance between the ringed nails connections and smooth nails connections is more than two. But the price ratio between them is almost twenty (non-galvanized smooth nails versus galvanized ringed nails). Therefore, in relation with the constraints and the potential of the Haitian context, it is not relevant to use this ringed nail.

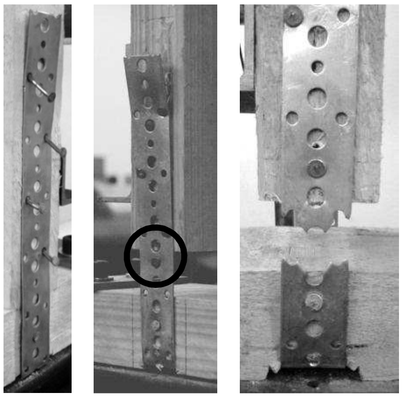


Figure 3.2. (a) Failure of joint due to nail deformation, (b) failure of joint due to nail deformation, (c) failure of joint due to steel strip failure

3.2. Wall

Fig. 3.3.(a) shows a good correlation between the two cyclic tests and the monotonic one. Main values are summarized in Tab. 3.3.. The sudden loss of resistance during the monotonic test and the cyclic 1 test is due of the failure of nail's head as described above. This phenomenon seems to be important because it makes the global behavior of the wall more fragile whereas it is important to keep a ductile behavior in case of seismic loading.
This figure also shows the significant pinching effect of these shear walls which is very important for timber structures under seismic loading.

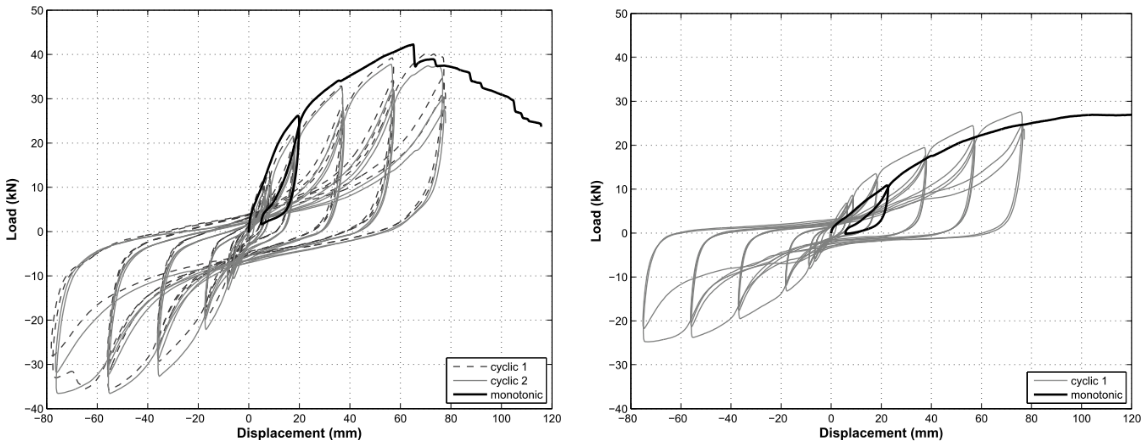


Figure 3.3. Load-displacement diagram for: (a) Wall filled, (b) empty wall

As shown in Fig. 3.4.(a), despite the large displacement applied to the wall, between wood beams, filling undergoes only few damages. The filling limits the wood structure deformation and therefore concentrates the energy dissipation in steel connections. On the contrary, without filling, the wood structure is free to move and does not use the steel connection resistance capacity. (see Fig. 3.5.(a)).
This last remark is illustrated by Fig. 3.3. that show the higher resistance obtained for the filled wall in comparison with the empty wall under shear loading. But the resistance of the filled walls decreases

after the peak whereas in the case of the empty walls the resistance is quasi-constant and no hardening appears.

Figure 3.4. (a) Filled wall deformation at the end of the monotonic test, (b) steel strips view at the same moment

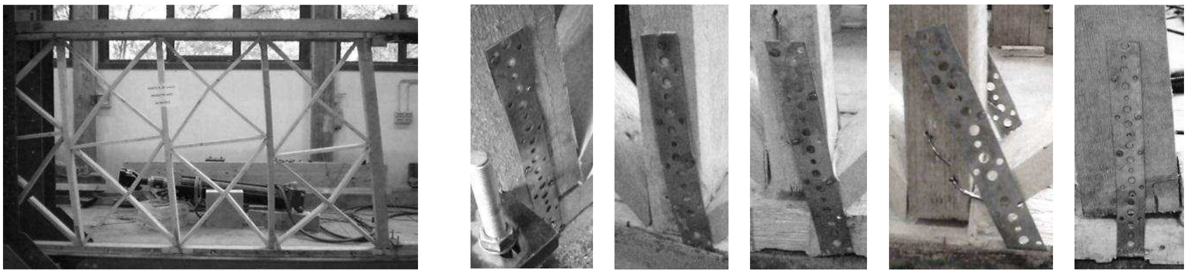


Figure 3.5. (a) Empty wall deformation at the end of the monotonic test, (b) steel strips view at the same moment

Fig. 3.4.(a) et 3.5.(a) show the difference of the connection behavior between filled and empty walls during the monotonic test. In Fig. 3.4.(b), steel strips are in traction whereas in Fig. 3.5.(b) they are also solicited by shear stress which can explain the difference of resistance.

Table 3.3. Shear wall tests results

Type of wall	Loading	F_{max} (kN)	d_{max} (mm)
Filled	Cyclic 1	40,7	70,4
Filled	Cyclic 2	37,8	56,0
Filled	Monotonic	42,3	65,1
Empty	Cyclic	27,6	75,6
Empty	Monotonic	25,9	104,1

It is also important to note the similarities of the present work with the one of H.A. Mereiles and *al.*(see [4]) and S. Pompeus Santos (see [5]) on “frontal” walls in *Pombalino* buildings submitted to cyclic loading and the work of Q. Ali and *al.* (see [1]) on Dhajji-Dewari structural system.

3.3. Elementary wall

Results are presented in Tab. 3.4. and in Fig. 3.6..
First, the cyclic tests are not symmetrical. It depends of how work the steel strips when positive or negative displacement is applied. There are two cases: elementary wall rotates around the lower extremity of a vertical post. The steel strip of the other vertical post is under tensile stress (see Fig. 3.7.(b) and Fig. 3.8.(a)). Or elementary wall displays a lateral displacement with limited rotation. So, the steel strips are under shear stress (see Fig. 3.7.(a) and Fig. 3.8.(b)). In the first case, global resistance of the elementary wall is higher because steel strip connection is more resistant in tension. This elementary wall behavior during the test was not controlled.
Secondly, a problem appeared during the monotonic test on the elementary wall filled with stone. For this reason, its force-displacement curve is in the wrong way and begins by a linear behavior (see Fig. 3.6.(a).

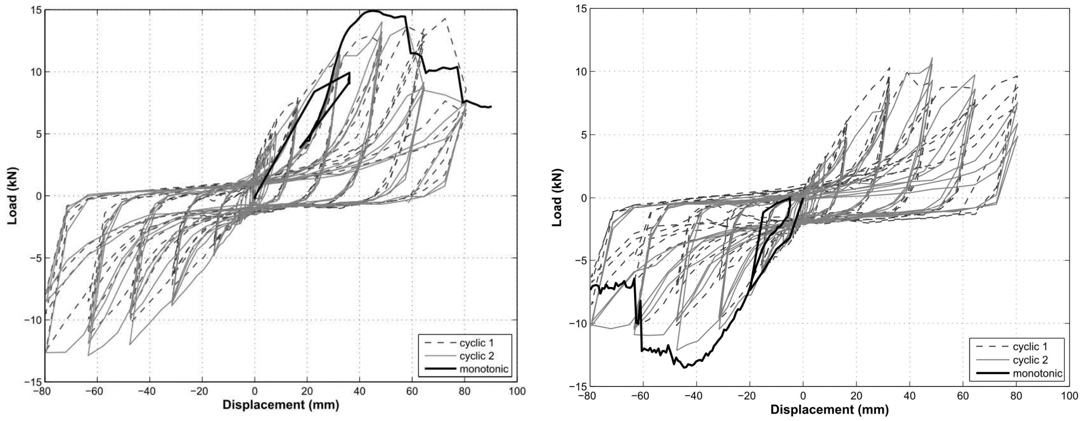


Figure 3.6. Load-displacement diagram for: (a) Elementary wall filled with stones, (b) elementary wall filled with adobes

Table 3.4. Shear elementary wall tests results

Type of filling	Loading	$F_{max,+}$ (kN)	$d_{max,+}$ (mm)	$F_{max,-}$ (kN)	$d_{max,-}$ (mm)
Stones	Cyclic 1	14,3	72,6	12,5	79,5
Stones	Cyclic 2	14,0	48,5	12,9	63,5
Stones	Monotonic	14,9	44,8	-	-
Adobes	Cyclic 1	11,0	32,5	9,3	63,5
Adobes	Cyclic 2	11,8	48,5	12,1	47,5
Adobes	Monotonic	-	-	13,5	44,7

Tab. 3.4. shows finally a good correlation between the maximal load obtained for the same way of loading. Elementary wall filled with stones are more resistant and are stiffer than the ones filled with adobes. They are stiffer because stones are rigid blocks (all in contact) whereas adobes have a low resistance capacity. Elementary wall filled with stones are also more resistant due to the stiffness of the stone filling that makes possible to transmit a part of the loading to the ground and so reduces the load in the steel strip.

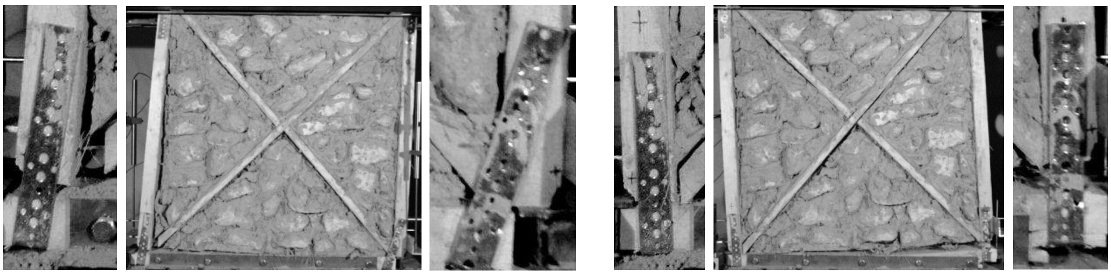


Figure 3.7. Deformed shape of elementary wall filled with stones and the steel strip connection for: (a) negative displacement (b) positive displacement

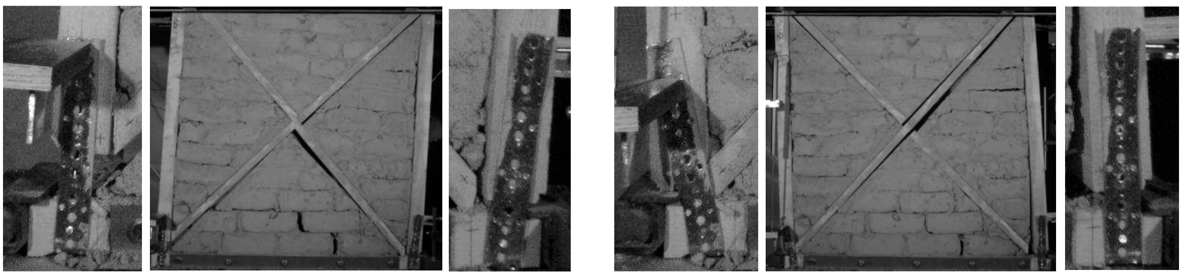


Figure 3.8. Deformed shape of elementary wall filled with adobes and steel strip connection when: (a) negative displacement (b) positive displacement

4. CONCLUSION

This paper presents a multi-scale experimental program in which connection, elementary wall (part of the wall) and a whole wall has been tested.

Direct tension tests on connection have shown that using smooth nails in rural places of Haiti for the wood construction is relevant giving the local context. They show also that the resistance of these connections is almost proportional to the number of nails.

Shear wall tests showed the interest of the filling in the wall and the high ductility of theses filled wood structures. Besides, they show the significant pinching effect, then it can be considered that the specimens would have a good performance under seismic actions.

Shear elementary wall tests confirmed these observations. They also showed that stones filling bring more resistance to elementary wall than the adobes filling.

This experimental program gave relevant results to perform the multi-scale modelling in order to assess the vulnerability of Haitian structures under seismic loading.

In order to reinforce those observations and to valid the multi-scale approach, another experimental program would be performed next year on a whole wall and a Haitian house on a shaking table.

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