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Structural performance of bamboo 'bahareque' walls under cyclic load

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Abstract—In many Latin American countries, people have traditionally built and still build their houses with 'bamboo bahareque' walls (these walls have a timber frame with split bamboo in the middle, covered with cement plaster on both sides). However, this constructive technique has not been technically studied, which is necessary to validate or, if necessary, improve it as a previous step to a much needed dissemination effort. The objective of the research reported in this paper is (a) to experimentally evaluate the strength and deformation capacities of prefabricated 'bamboo bahareque' shear walls developed in Costa Rica by the Bamboo Foundation (FUNBAMBU), under horizontal cyclic loads simulating earthquake effects, and (b) to propose testing procedures and provide reliable design recommendations for 'bamboo bahareque' house design and construction. For this purpose, 7 full-scale 'bamboo bahareque' walls were built and tested at the Materials and Structural Models National Laboratory (LANAMME), School of Civil Engineering, University of Costa Rica. The dimensions of the walls are 2.4 m in height and 2.7 m in length with a thickness varying from 40 to 60 mm. The results showed that the tested 'bamboo bahareque' walls have enough capacity to withstand earthquake induced loads of considerable magnitude. They also presented some ductile behaviour under cyclic loading.

Key words: Bamboo housing; bahareque shear walls; cyclic load; seismic design.

INTRODUCTION

The housing deficit for the lower income sectors of the developing countries of the world has been in constant increase, reaching alarming figures, in spite of the significant and sustained efforts of governments, private organizations, international agencies and the needy people themselves. Additionally, the lack of adequate technologies and controls make these houses vulnerable to natural hazards. One single earthquake or strong hurricane can destroy in a moment the cumulative effort of many years, with the consequent loss of lives and socio-economic impact.

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There is a need to identify traditional bamboo housing technologies and to scientifically study them, to validate or, if necessary, improve them as a previous step to a much needed dissemination effort.

In the International Network for Bamboo and Rattan (INBAR)-sponsored 'International Workshop on Bamboo Housing for Earthquake Prone-Areas' held in Dehra Dun, India, November 23–26, 1998, this fact was recognized and specific recommendations were adopted.

One of the recommendations stated the need to test actual components and structures, in laboratories with the capability of reproduce the cyclic effect of earthquake-induced forces and displacements. This recommendation is of paramount importance because this type of tests can accurately replicate forces and displacements similar to what earthquakes produce in the shear walls of typical houses, making it possible to determine the ultimate strength and, most important, the associated modes of failure. With such information, reliable design recommendations and construction techniques can be adopted and enforced.

The general objective of this research is to experimentally evaluate the strength and deformation capacities of prefabricated 'bamboo bahareque' shear walls, under horizontal cyclic loads simulating earthquake effects, to propose testing procedures and provide reliable design recommendations for 'bamboo bahareque' house design and construction. The shear walls are built with timber as structural frame and plastered with cement mortar applied to horizontal bamboo strips or thin canes, which corresponds to the constructive technology developed in Costa Rica by the Bamboo Foundation (FUNBAMBU).

This article presents firstly the state of the art with regard to 'bahareque' construction, horizontal cyclic load testing and previous projects, secondly the methods and materials utilized during the experimental tests including the test specimens and set-up, thirdly the results with tables and figures accompanied with brief descriptions of the tests and finally a discussion about the results and several conclusions and recommendations. All the unspecified dimensions in the figures are in mm.

STATE OF THE ART

Bahareque construction

The term 'bahareque' belongs to a larger class of building technique for housing that uses timber for a structural frame capable of supporting the vertical gravitational loads. The 'skin' of the structure, meaning the separating elements that provide visual and weather protection and serve architectural purposes, can be of different materials [1]:

1. Timber boards nailed to the timber structure (timber building).
2. Cane or split and open bamboo, known as 'esterilla', plastered with mud mixed with horse dung in the past, or cement mortar in recent times.

3. Flat galvanized iron, for improved weather protection.
4. A wire mesh plastered with cement mortar.

Group number 2 is generally referred to as 'bahareque'. Solid 'bahareque' uses spaced horizontal canes or bamboo laths whose purpose is to hold an infill of mud and broken tiles that is placed in the interior infill. This type of technique has been prohibited in Costa Rica due to its poor performance against earthquakes because of the heavy weight of the interior infill and the decay of the timber due to humidity provided by the mud. In hollow 'bahareque' the plaster has traditionally a double layer, with layers applied at both sides, hiding the timber structure and creating an empty space that isolates temperature and noise [1]. The bamboo 'bahareque' tested in this research has a single layer of plaster applied to horizontal canes or bamboo laths (Fig. 1), which is the constructive technique developed by FUNBAMBU. The bamboo 'bahareque' walls have proven to be resilient to earthquakes in Colombia and Costa Rica. The improvement of this technique with respect to solid 'bahareque' is that the plaster is a layer of mortar cement with a thickness of 60 mm embedding the bamboo laths and working together as a composite material. In solid 'bahareque', the mud infill only adds to the weight and does not contribute as part of the horizontal load resisting system.

Horizontal cyclic load testing

The way in which 'bahareque' shear walls should be tested under horizontal load is similar to that of other types of light walls such as timber frame walls. Many test standards such as ASTM 2126-02 [2], ASTM E 564-00 [3], ASTM E 72-98 [4] and CEN 594-95 [5] give useful recommendations on how to test a framed wall-panel under horizontal cyclic and monotonic load. ASTM E 2126-02 [2] is a recent procedure which defines a standard test for shear resistance of walls subjected to cyclic loads. This is of paramount importance for the structural behaviour of shear walls during an earthquake, especially for performance-based seismic design. ASTM E-72-98 [4] is useful when comparisons between the relative resistance of different sheathing materials on a standard timber frame are to be made. On the other hand, ASTM E-564-00 [3] is more versatile in terms of testing parameters such as size of specimens, type and location of anchorage and presence of door and window openings [6]. Reference 6 is a compilation of several studies that involve the structural behaviour of wood-framed walls under cyclic load. CEN 594-95 [5] is very similar to ASTM E-564-00 [3] with more details on the application of gravitational loads but no information on cyclic load testing. In this research, a test procedure for testing 'bahareque' walls under horizontal cyclic loading walls is proposed.

Previous projects

Even though 'bahareque' construction has been very popular in many Latin American countries, its research has been scarce. In Costa Rica, with the creation of

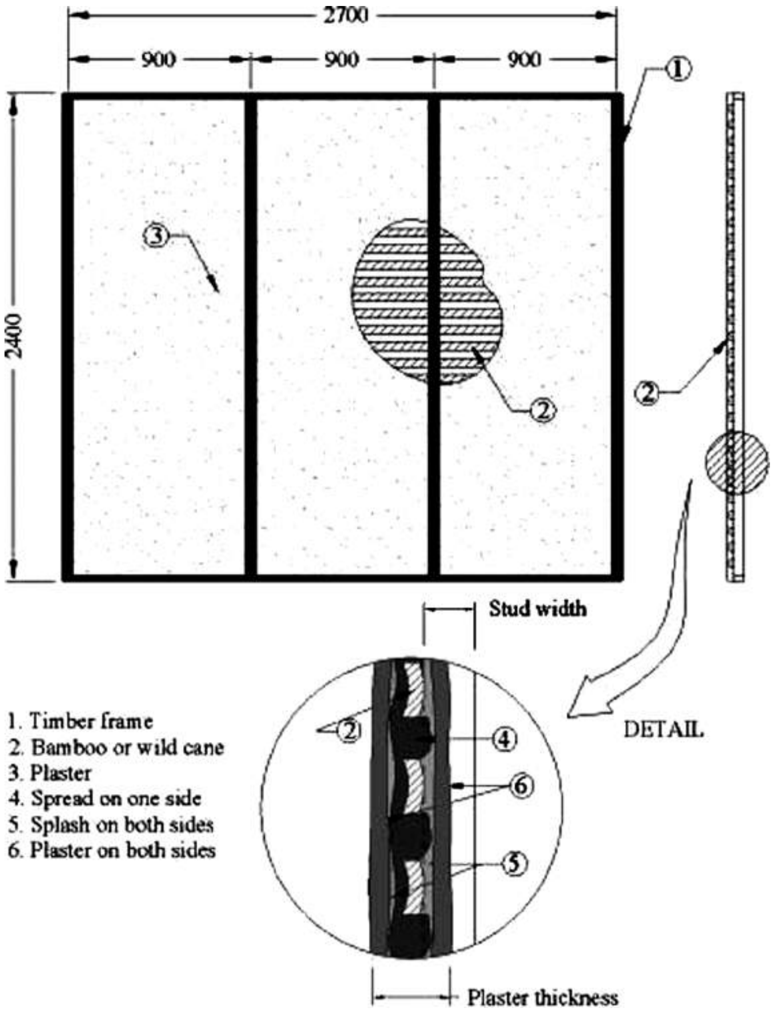


Figure 1. Test specimen (a bamboo 'bahareque' wall).

the National Bamboo Project (before becoming FUNBAMBU) there was a need in testing the 'bahareque' construction that was being used for building the houses. In a first series of tests, the strength and stiffness of 13 different walls subjected to horizontal monotonic load was investigated [7]. The major conclusions were that (i) diagonal bracings have a significant effect in the panels without mortar but no influence in the panels plastered with mortar, (ii) the mortar never fell off from the panels indicating that the use of a metal mesh is unnecessary and (iii) the capacity of the walls is as much as three times the required demand in a typical house. This demand is estimated with a typical house configuration and a seismic coefficient of 0.33. In a second series of tests, the strength and stiffness of 4 panels subjected to compressive loads (buckling) and 12 panels subjected to out-of-plane bending (flexure) were studied [8]. The main conclusions were that (i) bamboo 'bahareque' walls act as a composite material, (ii) due to the sudden failure of specimens in compression it is not recommended to build two-story houses with these panels and (iii) the capacity of the panels in flexure exceeds the demand for seismic and wind loads (the latter being the critical one for these extremely light walls). An independent research on the seismic behaviour of bamboo 'bahareque' walls has been carried out at the National University of Colombia [9]. 32 panels and two three- dimensional modules were subjected to horizontal monotonic load. For more details on the previous projects, see Ref. [10].

MATERIALS AND METHODS

Test specimens

The test specimens are central panels with dimensions $b = 2.7$ m, $h = 2.4$ m (b = width, h = height). The thickness of the panels varies from 40 to 60 mm. T he manufacturing of the test specimens can be divided in the following steps: (i) making timber frame, (ii) closing frame with bamboo strips or wild cane (*Gynerium sagittatum*) and (iii) plastering. The first two steps are carried out in the factory while the panels are plastered on site.

The timber frame is assembled using four 50×50 mm studs spaced at a centre–centre distance of 900 mm and two 25×50 mm plates (top and bottom). The studs and the plates are joined with 50×3 mm helically-threaded stainless steel nails. The timber frame is then closed with bamboo strips or canes along the length of the frame. The strips or canes have the same length of the frame and are joined to each stud using staples and small nails, respectively. The width and thickness of the bamboo strips are about 20 and 5 mm, respectively, whereas the wild cane diameter is approximately 25 mm. A space of approximately 15 mm is left between each bamboo strip or wild cane. This space is essential for the mechanical bond of the plaster applied on both sides of the panel.

The plastering consists of four activities (spreading, splashing, plastering and curing) and represents the work carried out on-site once the panels have been assembled. See Fig. 1 for details of the test specimen.

Test set-up

The test set-up shown in Figs 2 and 3 was employed to subject the test specimens to horizontal cyclic load. The assemblage can be divided in foundation system, steel plates against overturning, lateral bracing, load and deformation systems.

Foundation system

The foundation system consist of a concrete footing ((10) in Fig. 2) built with the purpose to be reused in each of the experimental tests. The footing is a $350 \times 1500 \times 4500$ mm concrete block with several grooves and cavities utilized to fix it to the

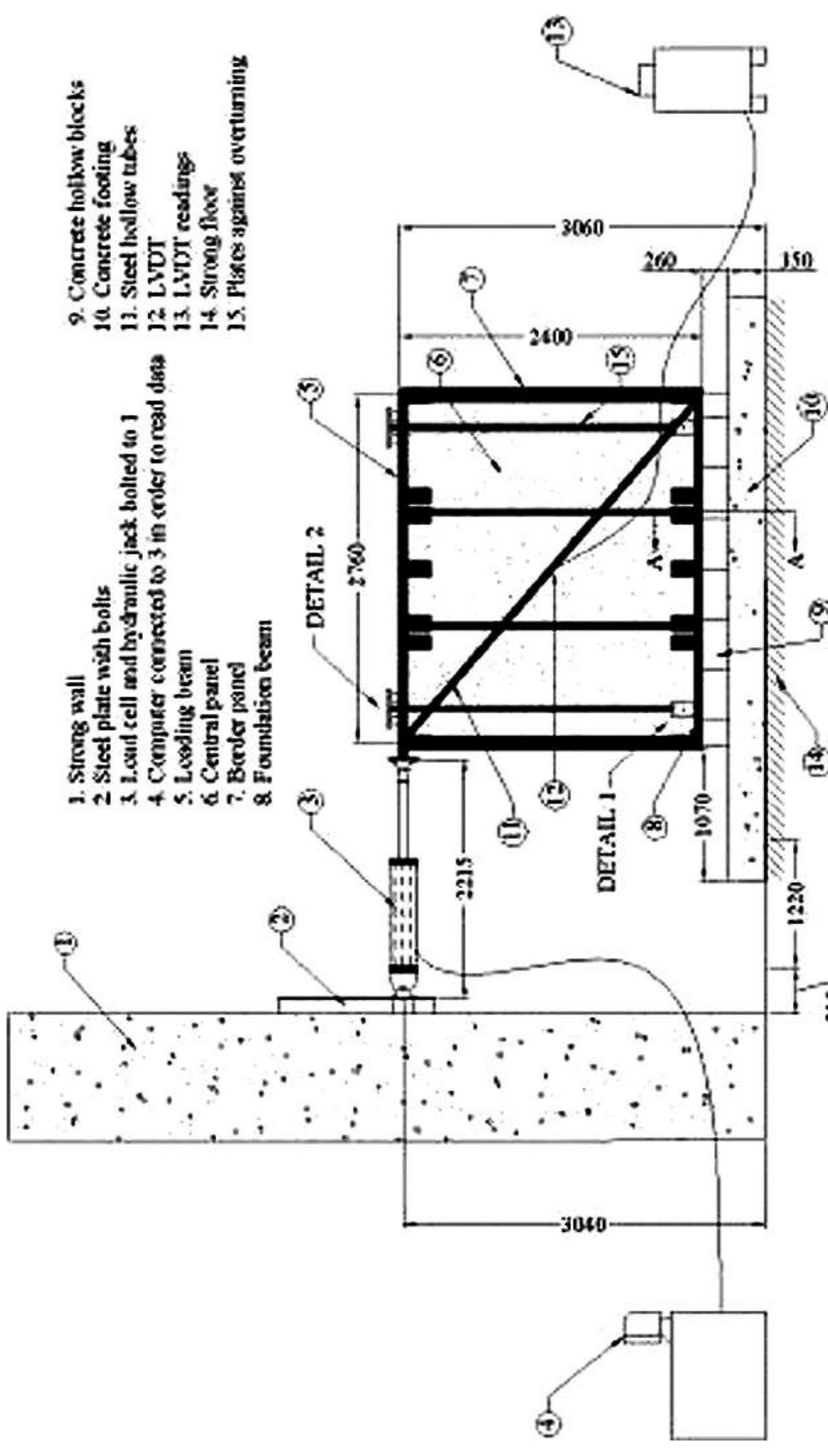


Figure 2. Test set-up.

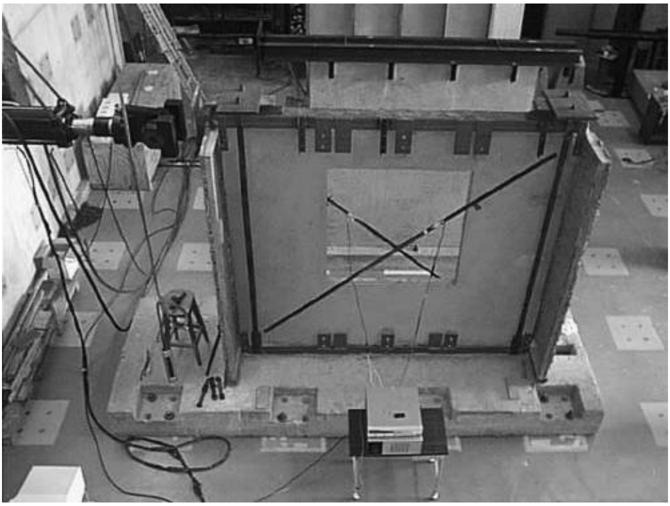


Figure 3. Photograph of set-up for BW-01 test.

strong floor (Fig. 2(14)) and to connect other elements to it. The next component of the foundation system is a row of concrete hollow blocks (Fig. 2(9)), which are employed in construction to raise the panels from the ground as a humidity and termites barrier. The concrete blocks of dimensions 120 × 200 × 400 mm are laid over the concrete footing. The third and last component of the foundation system is the foundation beam (Fig. 2(8)) which is composed of a steel U-section of 10 × 70 × 180 mm (with predrilled holes at the bottom for the anchors) and several steel plates welded to each side of the section in order to fix the test specimen. A 50 × 100 mm timber section is placed at the centre of the U-section in order to anchor the beam to the concrete footing (see Fig. 4).

Steel plates against overturning

These vertical plates placed at each end of the wall ((15) in Fig. 2) were incorporated (i) to prevent failure at the base anchors, (ii) to avoid rigid body rotation of the wall and (iii) to avoid tensile forces in the panel due to overturning moments. In real situations, the ratio b/h for the walls of a house is higher than one and consequently, the tensile forces produced in the wall are lower than for the tested specimen. Besides, in practical applications, all the walls are connected to each other by the top plate and roof structure, increasing their stability with regard to overturning. At the bottom, the steel plate is bolted to another steel plate which in turn is welded to the foundation beam (detail 1 in Fig. 2). At the top, the specimen is held by steel plates and rollers that allow its horizontal movement (detail 2 in Fig. 2). The rollers are laid directly over the loading beam. The section of the steel plates is 10 × 50 mm.

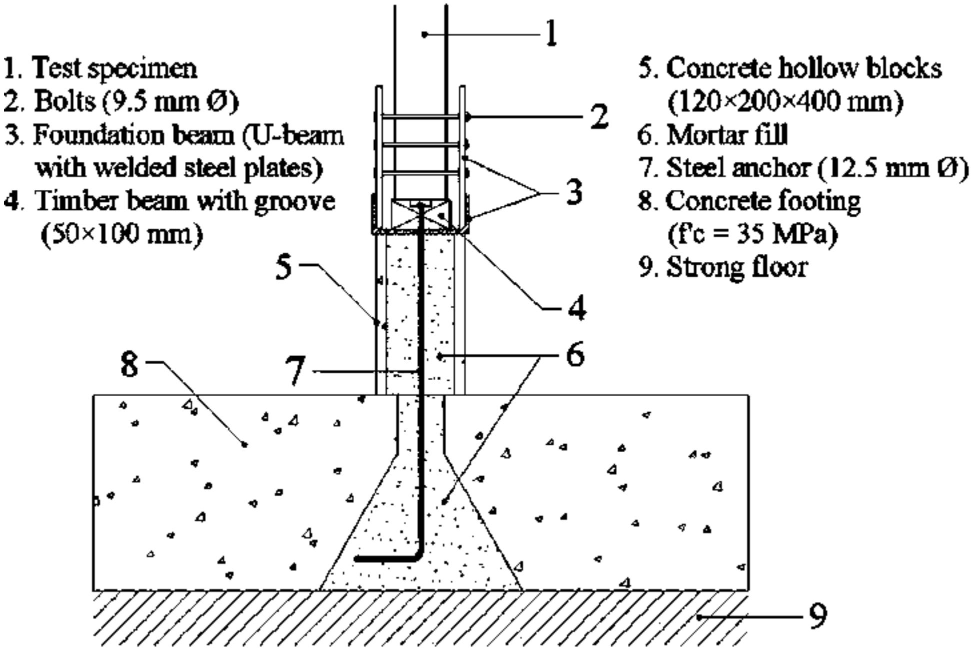


Figure 4. Foundation system (section A–A).

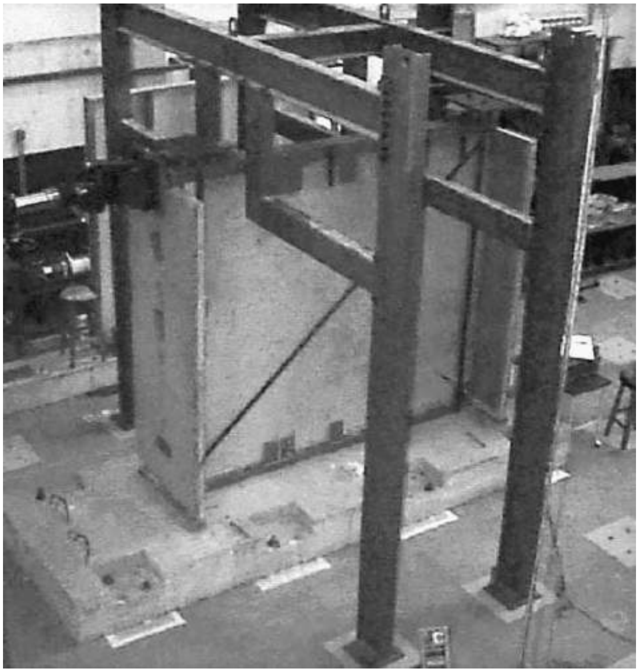
Lateral bracing

The lateral bracing was used to avoid undesirable out-of-plane displacements of the specimen. In real situations, this will be achieved by the roof structure and the top plate which connect all the panels of the house together. This lateral bracing consisted of two steel frames placed over the test specimen. The steel frames were equipped with adjustable steel plates that are located directly on the loading beam in order to avoid out-of-plane movement. Oil was applied to the steel plates in order to allow free horizontal displacements, minimizing the friction forces. The steel frames were fixed to the strong floor using bolts (see Fig. 5).

Loading system

The load application was carried out with a hydraulic jack ((3) in Fig. 2) capable of transmitting a total force of 50 tons. The jack is fixed to a strong wall (Fig. 2(1)) through a steel plate (Fig. 2(2)) and is controlled by a computer (Fig. 2(4)) programmed with the type of load and the range of displacements required. Load and displacement data are recorded and saved during the tests.

The load is transmitted from the hydraulic jack to the test specimen by the loading beam (Fig. 2(5)) which is composed of a steel hollow tube (150 × 150 mm) formed by two cold formed steel C-sections with several steel plates welded at each side of the tube. The central panel is bolted to these plates. The jack is connected to the



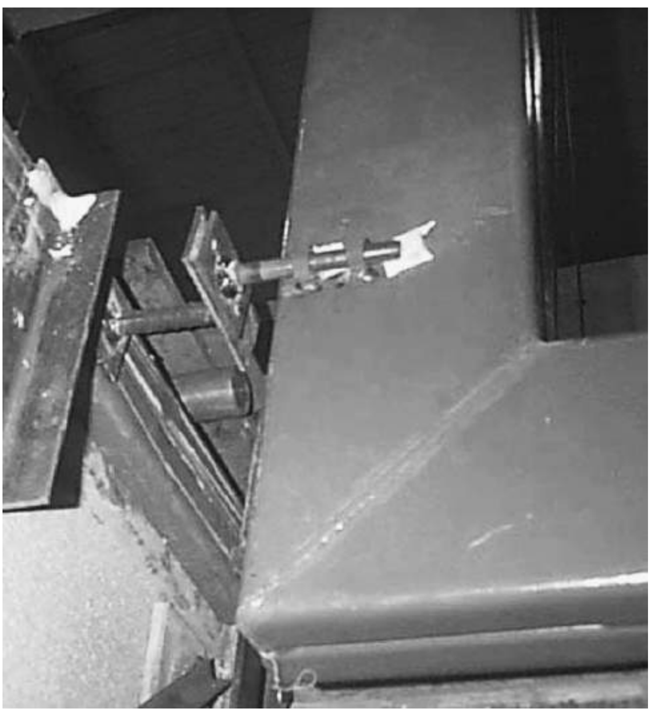


Figure 5. (Top) Photograph of test set-up showing steel frames for lateral support. (Bottom) Photograph of detail of the connection between the loading beam and the lateral support.

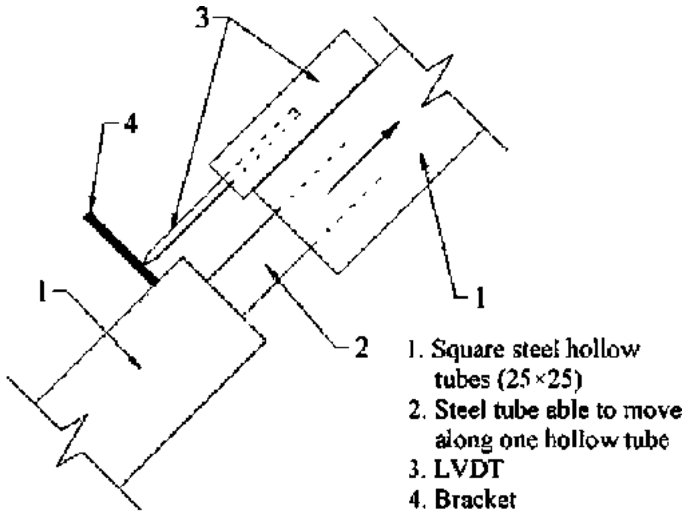


Figure 6. Measurement of diagonal deformations.

loading beam through a steel plate, which is welded to the loading beam and bolted to the jack.

Measurement of deformation

To measure the deformation of the diagonals of the test specimen, two steel hollow tubes (1650 × 25 × 25 mm) are placed along the diagonals on each side of the central panel with an LVDT (Linear Variable Differential Transformer) in each one. The two tubes are connected at the centre as shown in Fig. 6. Whenever there is a deformation of the diagonal of the panel, the LVDT will register it.

For the experimental phase, five load cycles were applied to each level of displacement. The maximum horizontal wall drift permitted by the Costa Rican Seismic Code [11] is 0.008 times the height of the wall and, hence, values lower and higher than this limit were established as displacement levels. The values were 0.004, 0.008, 0.01, 0.015 and 0.02, which for a wall of 2400 mm correspond to a lateral displacement of the tested specimens of 10, 20, 24, 36 and 48 mm, respectively. Five load cycles were applied to each displacement level. For the last four specimens, 8 levels of displacement were taken: 5, 10, 15, 20, 30, 40, 60 and 100 mm. However, only three load cycles were applied to each displacement level because the load capacity in the second and third cycle is almost the same.

RESULTS

Seven tests were carried out. The first three tests were part of an experimental phase to evaluate the test set-up [12]. The results are given in Table 1. The load–

Table 1.
Table 1. Results of the experimental phase (k_1 = initial stiffness, k_2 = wall stiffness)

	Level of displacement				
	1	2	3	4	5
Displacement (mm)	±10	±20	±24	±36	±48
Load (kN)					
C-01 test	15.0	29.4	31.8	—	—
CW-01 test	9.4	13.7	14.5	—	—
B-01 test	15.1	31.5	24.3	43.9	45.6
Stiffness (kN/mm)					
k_1 (B-01 test)	0.42	0.37	0.37	0.26	0.18
k_2 (B-01 test)	4.4	4.4	3.9	3.5	2.9

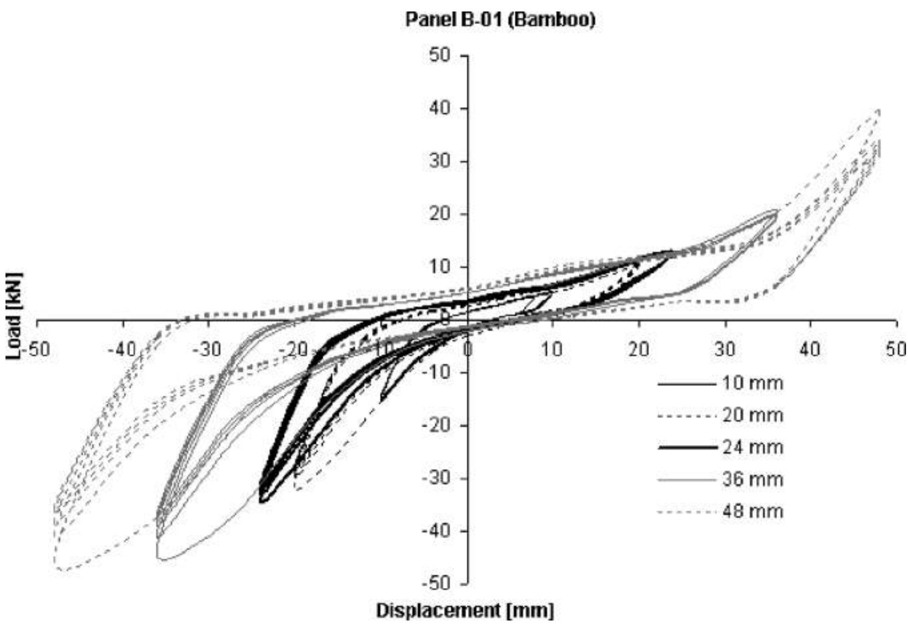


Figure 7. Load–displacement curve for B-01 test.

displacement curve of one of the test specimens (B-01) is shown in Fig. 7. For more details see Ref. [10].

The final test series consisted of 4 tested specimens [13]. The results are given in Tables 2 and 3. The load–displacement curve of one of the test specimens (WC-02) is shown in Fig. 8. For more details see Ref. [10]. Table 4 summarizes in a chronological way, all the tests carried out during this research with details on changes in the test set-up, modes of failure and improvements. All the results and load–displacement curves presented in this paper were obtained from the data acquisition system of the hydraulic jack. The displacements represent the horizontal

Table 2.
Experimental results for the final test series concerning failure load

Test	Fill	F_u (kN)	Δ at F_u (mm)	Reason for failure
B-02	Bamboo	63.1	20	Anchors are withdrawn
BW-01	Bamboo with window opening	82.1	50	Timber beam at the bottom is crushed through the washers
C-02	Wild cane	157	60	Bending of foundation beam
C-03	Wild cane	161	60	Bending of foundation beam

Table 3.
Stiffness values (k_2) derived from the load–displacement curves for different displacement levels in kN/mm

Displacement	Test			
level (mm)	B-02	BW-01	C-02	C-03
+5	8.8	8.9	17.7	14.1
−5	8.4	7.1	11.2	10.7
+10	9.3	6.9	14.2	11.1
−10	7.6	5.9	9.3	8.5
+15	7.3	4.8	11.6	8.6
−15	7.5	4.9	8.4	7.8
+20	5.5	2.5	10.4	7.4
−20		4.3	7.6	6.3
+30			8.3	7.1
−30			6.8	5.2
+40			6.9	6.9
−40			5.0	4.2
+60			5.5	
−60			4.2	

displacement of the jack at the top of the wall. The deformation data obtained from the LVDTs (elongation and contraction of the diagonals) were not reliable. Hence, these data were discarded for the analysis. The paper by Gutierrez [14] contributed to the development of this article.

DISCUSSION

The structural response of all the tested panels can be summarized as follows:

1. With the load applied in one direction, three different phases are evident:

    (a) Initial stiffness (k_1), which is quite low due to the accommodation of the testing apparatus and the elements within the structure (pinching effect). This effect was reduced by making improvements to the test setup, resulting in higher initial stiffness.

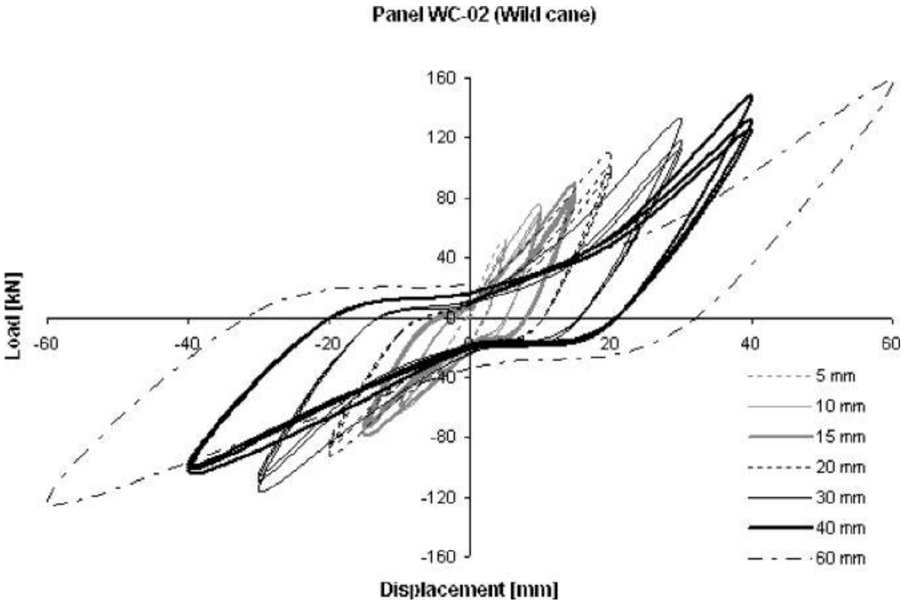


Figure 8. Load–displacement curve for WC-02 est.

Table 4.
Chronological summary of experimental tests with relevant observations

Phase	Experimental phase			Test series			
Test	C-01	CW-01	B-01	B-02	BW-01	C-02	C-03
Plates for overturning	No	No	No	*Yes*	*Yes*	*Yes*	*Yes*
Row of concrete blocks	Yes	Yes	Yes	Yes	*No*	*No*	*No*
Timber in foundation beam	Yes	Yes	Yes	Yes	Yes	Yes	*No*
Lateral bracing	*Yes*	*Yes*	*Yes*	No	No	*Yes*	*Yes*
Strong anchors	No	No	No	No	*Yes*	*Yes*	*Yes*
Loading system	A	B	C	C	C	C	C
Failure	1	2	3	4	5	6	6
Improvement	—	a	a	b	c	d	—

Italics indicates the changes made to the test set-up.

A, bolts in single-shear; B, steel plates (direct contact with the specimen); C, bolts in double-shear; 1, loading beam-to-panel connection; 2, gap between loading plates and specimen; 3, leading studs-to-foundation beam connection; 4, foundation anchors are withdrawn; 5, bottom timber beam is crushed through the washers; 6, bending of foundation beam; a, loading system is modified; b, plates against overturning; c, row of concrete blocks is eliminated and washers are substituted for larger ones; d, bottom timber beam is eliminated.

(b) Shear stiffness (k_2), which is the stiffness of the test specimen under horizontal cyclic load once the panel starts to resist loads.

(c) Unloading, which gives a representative elastic stiffness (values in Table 3) until the pinching effect begins again in the opposite loading direction.

2. The previous phases are repeated in the opposite loading direction until the first cycle is completed. In theory, the behaviour in both directions should be the same, but in reality the panel may have different behaviour in the opposite direction, as was the case in some of the tested specimens.
3. As the number of cycle increases, the panel starts to degrade, meaning that some of the internal connections lose their stiffness due to the cyclic loading effect. Usually, the second cycle gave lower stiffness and strength values than the first one but the difference between the second and third cycles was very small. As the number of cycles increases, the panel tends to reach a stabilizing load.
4. As the level of displacement increases, the stiffness degradation is quite evident, especially after some connections start to yield and the first cracks occur. Under this condition, the load increases.
5. After reaching a maximum load, the capacity of the panel decreases as the level of displacement is increased. This final stage could not be reached in the actual tests due to premature failures of the anchorage system. However, there are reasons to believe that the maximum loads for the last two tests are very close the ultimate capacity of the panels under horizontal cyclic loading: stiffness degradation, lower load at the negative displacement (also due to bending of foundation beam) and cracks.

CONCLUSIONS AND RECOMMENDATIONS

1. It is important to establish a displacement application program that simulates the real conditions of a shear wall subjected to an earthquake. For ‘bamboo bahareque’ walls with dimensions similar to the specimens tested in this research, the following displacement levels are recommended: 5, 10, 15, 20, 30, 40, 60 and 100 mm. This will give crucial information for performance-based seismic design of ‘bamboo bahareque’ walls.
2. The load transference system from the test apparatus to the specimen should be adequate, which means that its internal deformations must be minimized. This could be achieved by estimating the maximum expected load in order to calculate how many connectors and types of elements are needed (e.g., bolts, anchors, steel plates, steel beams, etc.).
3. Besides measuring the diagonal deformations of the panel, it is recommended to use dial gages in different positions of the test specimen. This will help to corroborate the diagonal deformations and check the deformations due to the loading system.
4. The real shear stiffness and strength of the panel under horizontal cyclic load should be obtained avoiding the overturning of the panel as well as its out-of-plane movement. In the first case, steel plates similar to the ones used in this research could be used. Another option is to use steel bars fixed to the base (e.g.,

strong floor) and bolted to a steel plate at the top. In the second case, steel frames similar to the ones utilized in this research might be employed providing that the test specimen can move freely in the horizontal direction. This could be attained with adjustable steel rollers fixed to the supporting frames and placed directly on the loading beam.

5. The test specimen must be well anchored to a fixed base. One solution is to employ a foundation beam similar to the one used in this research, checking that the anchorage capacity is enough. It could be that in practical applications the shear strength is not achieved due to premature failure of connections. That is why these connections must be designed to resist the shear strength of the panel with some safety factor.
6. With the performed cyclic load tests it has been corroborated that the 'bamboo bahareque' walls consisting of a timber frame plastered with cement mortar, applied to horizontal bamboo strips or canes have enough strength and stiffness to withstand earthquakes of considerable ground shaking intensity.
7. Tests on shear strength (both monotonic and cyclic loading), out-of-plane strength and axial compression strength have been carried out. Future research should concentrate on the following topics:

   (a) Testing specimens representing a part of the house under horizontal cyclic load. This would give information about the structural response of the real building including wall-to-wall, foundation-to-wall and roof-to-wall connections. This will be the more ambitious research.

   (b) Testing different types of 'bamboo bahareque' walls, besides the one tested in this research, under horizontal cyclic load and compare their behaviour.

   (c) Developing a draft for a possible ISO (International Standardization Organization) standard for testing bamboo 'bahareque' walls under horizontal cyclic load based on the reported setup.

Acknowledgements

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The prototypes tested and reported here are representative of the walls developed by the National Bamboo Project (PNB) and the National Bamboo Foundation (FUNBAMBU) of Costa Rica that were used in the construction of several thousand dwellings during the past decade. The cyclic load tests were carried out by F. Gonzalez and J. L. Troyo as part of their graduation projects at the School of Civil Engineering, University of Costa Rica, under the academic direction of the second author.

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