

## SEISMIC DESIGN OF LOW-COST AND SUSTAINABLE CANE, TIMBER AND MORTAR HOUSING FOR EL SALVADOR

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Arup in conjunction with an El Salvadoran NGO named REDES have developed a form of low-cost, seismically-resistant and sustainable housing that uses cane, timber and cement mortar. This paper presents an evaluation of existing low-cost housing in El Salvador, an assessment of the seismic risk within the country, and a description of the new design proposed and its seismic performance. The seismic design approach is discussed, and findings from full-scale cyclic in-plane testing of a wall panel, out-of-plane shake-table testing of a section of wall and bi-directional shake-table testing of a complete room are presented. The testing indicates that this form of technology has some ductility, exceeds the design capacity both in-plane and meets Life Safety performance for the El Salvadoran code design level, as well as the criteria based on the latest seismic hazard studies. The paper proposes that this form of housing can be used in highly seismic areas.

### Introduction

El Salvador has one of the largest divides between the rich and the poor in the world with hundreds of thousands living in poverty on only a few dollars per day. This poverty, coupled with the frequent earthquakes and other natural disasters, has left many living in sub-standard, unhygienic and unsafe housing. This problem is not isolated to El Salvador, and recent estimates of the housing deficit in Latin America as a whole are between 42-51 million dwellings (the number of new houses required to house all those in sub-standard, precariously located or overcrowded housing) (UN-Habitat, 2011).

Natural hazards including earthquakes, volcanoes, flooding and hurricanes, contribute significantly towards this housing deficit. As the worst effects of hurricanes tend to be confined to the Caribbean and the Eastern seaboard of North and Central America, Central America's greatest natural hazards are arguably earthquakes, as the Pacific Ring of Fire runs down the West coast. Many zones in this region are considered to have high seismic hazard (with a Peak Ground Acceleration greater than 0.4g for a 10% probability of exceedance in 50 years) (Benito et al., 2012). In the last 500 years, Central America has experienced numerous earthquakes that caused significant damage and loss of life, both in the subduction zone which forms part of the Pacific Ring of Fire and in the local faults along the volcanic chain.

New permanent low-cost housing in Latin America consists of a mixture of engineered and non-engineered housing. The design of non-engineered houses often rests entirely with the owners or local skilled workers, and normally consists of a vernacular design or a copy of a more modern design, often masonry (Kaminski, 2013). The design of engineered houses is normally determined by the government, donors or Non-Governmental Organisations (NGOs). The most common permanent housing options currently being constructed in Central America are: adobe, *bahareque* (a derivative of wattle-and-daub), a form of confined masonry and reinforced hollow blockwork (Table 1). Unfortunately, each of these has a number of drawbacks: adobe has very low seismic resistance, can harbour disease-carrying

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insects and is unpopular with local communities; *bahareque* is particularly susceptible to insect attack and rot; confined masonry is very workmanship dependent. The current best option for permanent low-cost housing in El Salvador is widely considered to be reinforced hollow blockwork, which is very durable and has good seismic resistance when well-constructed, however it is moderately expensive and not very sustainable.

Table 1. Selection of advantages, disadvantages and relative costs of the main permanent housing options typically constructed in El Salvador (Kaminski, 2013; López et al., 2004a; WHO, 2010)

Housing Type	Advantages	Disadvantages	Relative cost
Adobe (unfired clay bricks)	<ul style="list-style-type: none"> <li>• Very cheap when the correct soil type is available locally.</li> <li>• Widely-known technology.</li> <li>• Negligible environmental impact.</li> <li>• Good thermal mass hence very cool inside.</li> </ul>	<ul style="list-style-type: none"> <li>• Typically performs very poorly seismically.</li> <li>• Requires considerable maintenance.</li> <li>• Can harbour disease-carrying insects.</li> <li>• Very unpopular with locals.</li> <li>• Traditionally combined with a heavy tiled roof, increasing the seismic loads and the risk of injury if it falls.</li> </ul>	Low
<i>Bahareque</i> (a local derivative of wattle-and-daub)	<ul style="list-style-type: none"> <li>• Relatively low-cost.</li> <li>• Can have good seismic resistance when in good condition.</li> <li>• Low environmental impact.</li> <li>• Good thermal mass hence very cool inside.</li> </ul>	<ul style="list-style-type: none"> <li>• Can harbour disease-carrying insects.</li> <li>• Requires considerable maintenance.</li> <li>• Susceptible to insect attack and rot.</li> <li>• Relatively unpopular with locals.</li> <li>• Traditionally combined with a heavy tiled roof, increasing the seismic loads and the risk of injury if it falls.</li> </ul>	Low
Confined masonry (generally poorly detailed)	<ul style="list-style-type: none"> <li>• Good seismic resistance when well-constructed.</li> <li>• Very durable.</li> <li>• Challenging to construct properly (difficult to place rebar and concrete in small confining elements).</li> <li>• Good thermal mass hence very cool inside.</li> <li>• Popular with locals.</li> </ul>	<ul style="list-style-type: none"> <li>• Higher cost.</li> <li>• Generally poorly detailed.</li> <li>• High environmental impact (fired clay bricks and concrete).</li> <li>• Seismic design rules generally mean houses often have smaller and/or fewer windows.</li> <li>• Typically combined with a heavy tiled roof, increasing the seismic loads and the risk of injury if it falls.</li> </ul>	Medium-high
Reinforced hollow blockwork	<ul style="list-style-type: none"> <li>• Good seismic resistance when well-constructed.</li> <li>• Very durable.</li> <li>• Relatively simple to construct.</li> <li>• Good thermal mass hence very cool inside.</li> <li>• Very popular with locals.</li> <li>• Normally combined with lightweight zinc-aluminium roof sheeting, reducing the seismic loads and risk of injury if it falls.</li> </ul>	<ul style="list-style-type: none"> <li>• Higher cost.</li> <li>• High environmental impact (concrete).</li> <li>• In most cases not all code ductile detailing requirements are met.</li> </ul>	Medium-high

Arup (a UK-based design consultancy), Engage for Development (a UK-based charity) and the Imperial College El Salvador Project (a UK-based charitable organisation) have been working with REDES (a small El Salvadoran NGO) for the past five years, with the aim of developing an alternative, low-cost, sustainable, seismically-resistant and appropriate low-cost house design suitable for El Salvador. The design should also be easy to construct and maintain by the local communities themselves, and ideally use local materials such that more money goes back into the local economy.

### Overview of the Design

After conducting research into existing low-cost housing in the Latin American region, in particular using bamboo structurally (Kaminski, 2013), the team developed a solution which takes the vernacular *bahareque* design and “engineers” it by essentially: treating the timber and wall matrix against insect attack, replacing the mud render with a more durable and stronger cement mortar and engineering the connection details (Figures 1-4).



Figure 1. Prototype cane and mortar house under construction (El Salvador Project, 2012)



Figure 2 (L). Blockwork to timber connection detail (El Salvador Project, 2014); Figure 3 (R). Cane, mesh and wire wall detail before application of cement mortar (Kaminski, 2014)

The design that has been developed is a single-storey four roomed building, approximately 6m x 6m, with two bedrooms, one living room and one kitchen. The foundations of the house are a thin reinforced concrete slab sitting on reinforced concrete ground beams under the walls. The walls sit on two courses of hollow reinforced blockwork, protecting the frame above from water and insect attack. The wall and roof structural frame sits on the blockwork and consists of a simple 2”x4” structurally graded and pressure-treated pine frame, nailed together with capacity-designed steel straps at key locations to resist wind and seismic loads. The walls are wrapped in a thin galvanised chicken mesh on both sides, and *vara de castilla* (also known as *caña brava* – a local type of cane approximately 25mm in diameter and up to 6m long (Chan, 2014)) is nailed to the frame. The *vara de castilla* is sourced from local farmers and is treated on site against insects with boron. Cement mortar is then

plastered on both sides of the walls to form the 60mm thick shear walls. The lower halves of the walls are painted with waterproof paint to protect against driving rain. The roof consists of lightweight cement fibreboard sheeting screwed down onto the timber purlins and rafters. The design life of the house is 30 years with minimal maintenance (painting and keeping the walls dry). In comparison with reinforced blockwork, which is widely seen and used as the current low-cost housing of choice by the government, NGOs and communities themselves, this new form of housing uses up to 40% less cement and steel. It is also overall lighter and hence easier to transport to more rural areas.



Figure 4. Prototype cane and mortar house, completed in 2012 (El Salvador Project, 2012)

### **Prototype houses**

Two prototype houses were successfully constructed in El Salvador in 2012 and another one in 2014, and have allowed the house design and construction method to be optimised (El Salvador Project 2012, 2012; El Salvador Project 2014, 2014). They were evaluated again in 2013 and the families living there were very happy with them, with no reported structural problems.

### **Seismic Design Approach**

The lateral stability system of the structure relies upon perpendicular shear walls in both directions, roughly evenly spaced. With a light roof, most of the seismic load is generated by the self-weight of the walls themselves.

As El Salvador is in a region of high seismic hazard, the seismic demands govern the design of the lateral system; hurricane winds do not tend to affect El Salvador as it is on the West coast of Central America. The relatively basic El Salvadoran seismic code (MOP, 1994) is based on the Mexico City code and loosely in turn on pre-1997 versions of the Uniform Building Code (UBC). In addition, the other El Salvadoran material design codes are also limited in their scope or refer back to US or Mexican codes (López et al., 2004b). Therefore, in order to be able to use an up-to-date, comprehensive and consistent set of design codes, the most recent US design code has been selected as the design basis (IBC).

A comparative study of different seismic hazard assessments for El Salvador was conducted in order to determine the most appropriate design parameters. Table 2 presents the

maximum seismic hazard determined for any area within El Salvador from a number of different published sources.

Table 2. Maximum seismic hazard for any area within El Salvador

Code and date	Maximum equivalent PGA at 475 year return period (g) for El Salvador	Comments
El Salvadoran Seismic Code (MOP, 1994)	0.40	
GSHAP Database 1999 (USGS, 2011)	0.38	
A New Evaluation of Seismic Hazard for the Central America Region paper (Benito et al., 2012)	0.50	Value appropriate for the capital, San Salvador.
An Earthquake Catalogue for El Salvador and Neighboring Central American Countries (1528-2009) and Its Implication in the Seismic Hazard Assessment (Salazar et al., 2013)	0.50	

A maximum design PGA of 0.5g (10% probability of exceedance in 50 years) has been selected for the design because Benito et al. (2012) and Salazar et al. (2013) are considered to best reflect the most up-to-date seismic hazard studies of the region, and which involved a collaborative effort between different specialists in the region. It also reflects the design criteria that the houses will be built anywhere within the country.

Two performance levels have been considered for the design:

1. Small frequent event (e.g. 43y return period): limited cracking to walls, no primary structural damage.
2. Large infrequent event (e.g. 475y return period): cracking and limited crushing to wall render, rotation of connections, structure remains life-safe. Frame remains largely intact and in many cases structure can be fully repaired.

### Design Methodology

The wall structure both in-plane and out-of-plane does not comply with any codified lateral system and its behaviour and strength is difficult to quantify by calculation. Accordingly, whenever possible simple calculations have been used to design elements and connections, complemented by full-scale testing where appropriate to validate some of the results.

#### In-plane

In-plane testing of a bamboo/cane matrix wall and with cement mortar has been conducted in both Costa Rica (González & Gutiérrez, 2003) and Colombia (Farbiarz, 2001) as part of research to develop low-cost bamboo housing. These studies provided useful preliminary evidence that such walls could resist considerable in-plane seismic loads, however because the design for El Salvador was slightly different from the tested walls and the variables and number of tests previously conducted were limited, further testing was conducted in 2013 at Imperial College London supported by an ICE Research and Development Grant (Elghazouli et al., 2013; Málaga-Chuquitaype et al., 2014).

Because the global in-plane flexural capacity of the panel could be relatively easily determined by hand (governed by inspection by tension on the rear end), the aim of the test was to determine the shear capacity and behaviour, and therefore vertical pre-stressed ties were introduced on the return walls in order to force the panel to fail in shear.

The 2013 study tested at full scale six different wall panels each with different geometrical and material characteristics. The wall panels tested were 3m long, 1.85m high, and with 1m return walls at each end, with most tests incorporating a 1m x 1m window (Figure 5). The panel dimensions matched the typical wall size to be used in the final design. The panel was

bolted down to the lab floor along its length and on the wall returns, replicating the fixings in the final design. Steel chicken mesh was fixed to only one side of the panel. The load was applied via a loading beam situated with multiple bolts along its length (in order to distribute the load and avoid local crushing) and situated at  $\frac{1}{4}$  of the way down the height of the panel, in order to better replicate the actual centre of application of net horizontal load (and reduce the risk of a flexural failure occurring).

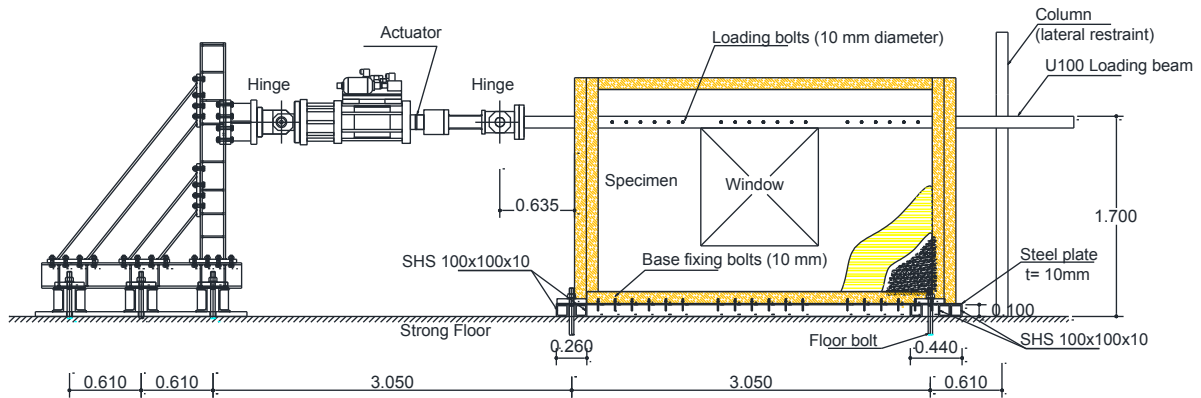
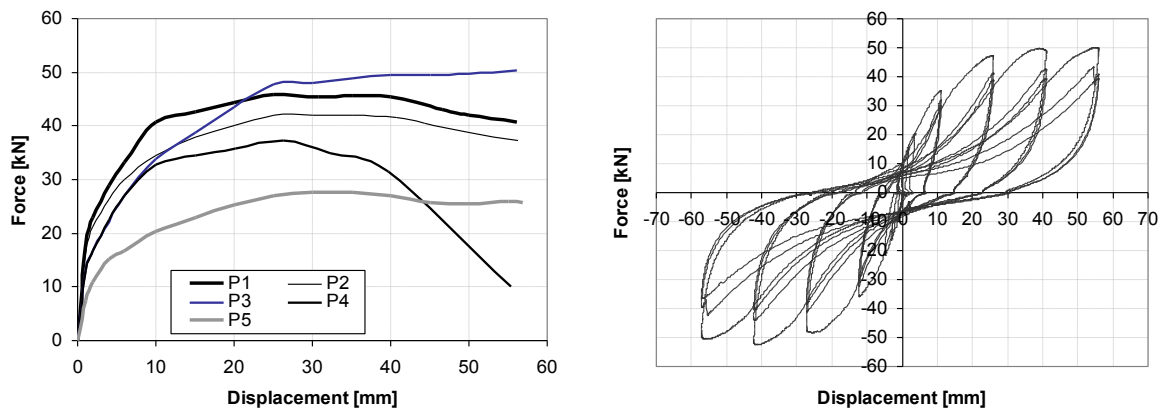


Figure 5. Elevation of in-plane test specimen (Málaga-Chuquitaype et al., 2014)

The panels were each tested under cyclic displacement control based on the EN12512 protocol (CEN, 2005). The results of the tests demonstrated that for drifts under 1% the panels showed relatively stable hysteresis, with reasonably good levels of energy dissipation (Figures 6 and 7), and the level of damage seen was considered acceptable. Initial cracking occurred at 15-20kN (drifts of  $\sim 0.1\%$ ), with the ultimate load achieving 37-50kN (drifts of  $\sim 1.5\%$ ). Initial failure manifested itself by a combination of diagonal shear cracking and spalling of the side of the panel without mortar (Figure 8). The steel mesh was found to stabilise the diagonal compression strut in the remaining mortar, and the ultimate failure mode was local buckling and crushing of this mortar.



Figures 6 (L). Envelopes of the force-displacement hysteresis for different panel types (Málaga-Chuquitaype et al., 2014); Figure 7 (R). The force-displacement hysteresis for one of the panels (Málaga-Chuquitaype et al., 2014)

The test panels achieved the design horizontal load before the initial cracking load was reached. The design for the strength of the panels assumed no ductility reduction factor (i.e. to Eurocode 8 ductility factor  $\mu = 1$ , or to IBC response modification factor  $R = 1$ ). In addition, the relatively stable hysteresis demonstrates that these forms of panels have some ductility, in the region of an R value of 2 to 3 for drifts under 1% and assuming the elastic capacity is approximately 15-20kN. Lastly, the variables used in the tests, such as the mortar strength,

were all lower bounds suggesting that the system will have some additional overstrength, and that high levels of quality control of the mortar are not essential. The testing suggests that the panels more than meet the design capacity assumed, and that in future a response modification factor greater than 1 could be used.



Figure 8. In-plane testing of wall panel at Imperial College London, 2013. Image shows typical damage state at failure, using singly-sided chicken mesh on reverse side only (Kaminski, 2015)

### **Out-of-plane**

Out-of-plane, because the cane is placed horizontally, the only reliable load-path is using the cane flexurally. Testing of the cane flexurally at Coventry University indicated that it had a considerable strength, similar to bamboo, considerably exceeding the maximum out-of-plane loads assuming no composite action (Chan, 2014). Subsequent testing at Cambridge University on their small uni-directional shake-table was conducted in order to determine the panel failure mechanism and extent of spalling out-of-plane (Figure 9) (Davies, 2014). This is important as spalling can be dangerous to people and also reduces the capacity of the panel to resist in-plane loads.

Testing was conducted on panels with chicken mesh on one side and with chicken mesh on both sides. Static 3-point bending tests indicated that the mortar tensile capacity is more reliable than anticipated, and once the mortar has failed in tension the cane and the mortar on the compression side attempt to work compositely, until the bond between them breaks down and the cane resists the load flexurally by itself. The dynamic tests also indicated that the bond between the cane and the mortar was more reliable than expected, however that once the bond has failed the mortar may spall off quickly. This risk was shown to be reliably mitigated by introducing chicken mesh on both sides of the panel with steel wire through-ties connecting each face. This detail has now been adopted for the structural system.

### **Full-scale shake-table testing**

A full-scale room of the house using the structural system was tested on a shake-table at the Universidad Mariano Gálvez in Guatemala City (Figure 10). The specimen consisted of four walls forming a 3m x 3m box on plan, 3m high and included one door and one window. Chicken mesh was placed on both sides of each wall panel. The house was tested bi-directionally by exposing it to two simultaneous time-histories of the 13th January 2001 El

Salvador earthquake (taken from the two orthogonal strong-motion components records from a single station with hypocentral distance 80km) (Centre for Engineering Strong Motion Data, 2015). The stronger of the two strong-motion records had a PGA of 0.86g, and the second 0.70g. Both time-histories were then scaled down to 10% of the original history and the house tested bi-directionally simultaneously. This test was then repeated but with the directions of the stronger and weaker records now swapped, hence allowing both axis of the house to be tested using the stronger of the strong-motion components. A thorough visual damage assessment was then conducted, and the testing repeated for the same time-histories but now each scaled to 15% of their original history. This testing cycle continued in 5% increasing increments, until 85% of the original history was reached.



Figure 9. Out-of-plane testing of wall panels on a uni-directional shake-table at Cambridge University (Kaminski, 2015)

The results were positive. Minor flexural cracking (<1mm) propagating from the corners of the lintels and doors occurred around and after the design event (0.5g). Bed joint sliding to one wall also occurred, however this joint is intended to slide and the ductile steel ties took the full load with little displacement. After this event, considering the load path and capacities of this particular structure, and assuming this damage level occurred throughout a whole real building (arguably conservative since a building would have a larger width-to-height aspect ratio), this damage could be considered “insignificant” to FEMA 306 (Applied Technology Council, 1998), with the building able to remain “Operational” to FEMA 356 (American Society of Civil Engineers, 2000).

Testing continued up to 85% of the original time-histories, with recorded PGAs >1.0g. The final three tests involved running three full cycles of the bi-directional time-history. At this point, the extent of flexural cracking had increased slightly (however all cracks were <1mm), and some minor spalling was visible from the corners of the doors and lintels. Bed joint sliding and some minor spalling of the mortar at the base also occurred. Upon inspection, it was found that on one wall 9 out of 12 of the steel straps had sheared under metal fatigue – this was considered to occur because these straps were inadvertently installed a little loose, so the wall had the ability to move and fatigue the straps. Despite this, the damage could be considered “moderate” to FEMA 306 because the vertical load carrying capacity remained

unaffected and the structure still had some horizontal capacity. Had this damage level occurred throughout a whole real building, it could be considered “Life Safe” to FEMA 356.



Figure 10. Damage state at end of bi-directional shake-table testing for a full-scale model of a room of a house at the Universidad Mariano Gálvez in Guatemala City (Kaminski, 2015)

### Conclusion

The testing conducted provides significant evidence that such a structure constructed using cane, timber and mortar, even with lower bound material properties, has some ductility, exceeds the required design capacity both in-plane and out-of-plane and meets Life Safety performance for high seismicity areas. The technology is also of comparable cost to the alternative blockwork housing yet is considerably more sustainable, is easier to transport to more rural areas, is popular amongst the community, is simple to construct and can be easily repaired even after a major seismic event. With the correct treatment measures, detailing and basic maintenance, it is also a durable form of construction with a lifespan exceeding 30 years. Overall, it is a viable and high-performing alternative to reinforced blockwork.

The current design and testing has focused on single-storey structures. There may be potential to use it in two storey houses, however further testing would be required to determine this, and higher mortar strengths may be necessary in order to achieve the minimum shear capacity.

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