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COMPOSITE BAMBOO SHEAR WALLS – A SHEAR WALL SYSTEM FOR AFFORDABLE AND SUSTAINABLE HOUSING IN TROPICAL DEVELOPING COUNTRIES

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Abstract: *Composite bamboo shear walls (CBSW) are modern engineered vernacular-improved shear walls, that take the traditional Latin American wattle-and-daub known as bahareque, and engineer it, using modern materials and construction techniques. CBSWs consist of a frame made of timber and/or large diameter bamboo, upon which a matrix of cane, small diameter bamboo, flattened bamboo, bamboo laths or expanded steel mesh is nailed. The walls are then finished with cement or lime render to form solid shear walls. Over the past 30 years, at least 4000 one and two-storey homes utilising modern CBSWs have successfully been constructed in various countries around the world, including Costa Rica, Colombia, Nepal, Ecuador, Peru, Mexico, El Salvador and the Philippines. When properly designed and built, they have demonstrated their effectiveness as an affordable, hazard-resilient, low-carbon and durable form of housing. The system is now codified in the Colombian, Ecuadorian and Peruvian structural standards, as well as in ISO 22156. Efforts are currently underway to incorporate them into the Philippines, Mexican and Nepalese codes. This paper describes the history of the CBSW system, variations that exist across the world, the current state of knowledge with regards to codes, strength, ductility, sustainability and fire, and recommendations for areas of future research. The paper argues that the CBSW system is an effective way of creating low-carbon housing that provides excellent code-compliant strength, ductility, and durability, and has significant potential for affordable housing in lower and middle income highly seismic countries where bamboo grows.*

Introduction

There are currently three major challenges to residential housing in developing countries:

- Globally around 1.6 billion people live in inadequate housing (UN-Habitat, 2022).
- Natural disasters contribute enormously to deaths and house damage, for example:
    - On average, every year ~60,000 people die worldwide in natural disasters, the majority of which are from building collapses in earthquakes, and the majority occur in the developing world (Our World in Data, 2023; World Bank, 2009).
    - Between 2008-2020, earthquakes and storms (excluding floods) were the cause of 33.5 and 119 million displacements respectively (IDMC, 2021).
- Cement contributes towards 8% of global CO_2 emissions (Chatham House, 2018)

There is therefore an urgent need for affordable and disaster-resilient housing in lower and middle-income countries that is also low-carbon. Unfortunately, there are currently very few technologies which satisfy all these requirements. The majority of permanent and durable affordable housing is reinforced concrete (RC) with masonry infill, confined masonry or reinforced blockwork. Although these systems can be very resilient when properly designed, they tend to have a high embodied carbon, predominantly due to their high cement content.

Traditional housing systems that use natural materials may satisfy many of the homeowners' criteria, however they invariably have some downsides, for example:

- Adobe and rammed earth are generally not resilient to earthquakes.

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- Many vernacular timber or bamboo systems require significant maintenance due to rot and insect attack.
- Many traditional timber or bamboo systems do not provide the thermal mass, security, privacy or visual level of prosperity that communities need or want.
- Naturally-durable timbers were often used historically for traditional buildings. However, these have now become much more expensive and difficult to obtain, and therefore modern affordable timber construction is often unable to make use of them.

History of traditional bahareque housing

Wattle-and-daub is a vernacular/traditional construction system that has been popular in many countries across the world for thousands of years. Each country and context tend to have their own derivative of wattle-and-daub, built using local materials and designed for the local climate and hazards (Gutiérrez, 2004). This system is particularly established across Latin America, where it is variably known as *bahareque*, *bajareque*, *quincha*, *cuje*, *pao pique*, *tabiqueria*, amongst others (Carazas-Aedo & Rivero-Olmos, 2013). For the purposes of this paper, all of these derivatives will be referred to as traditional *bahareque*. Figure 1 shows some examples of traditional *bahareque* housing in Latin America.

Figure 1. Traditional urban and rural bahareque housing in Colombia: (L) Sevilla (Lopez, 2016); (R) Armenia (Kaminski, 2016).

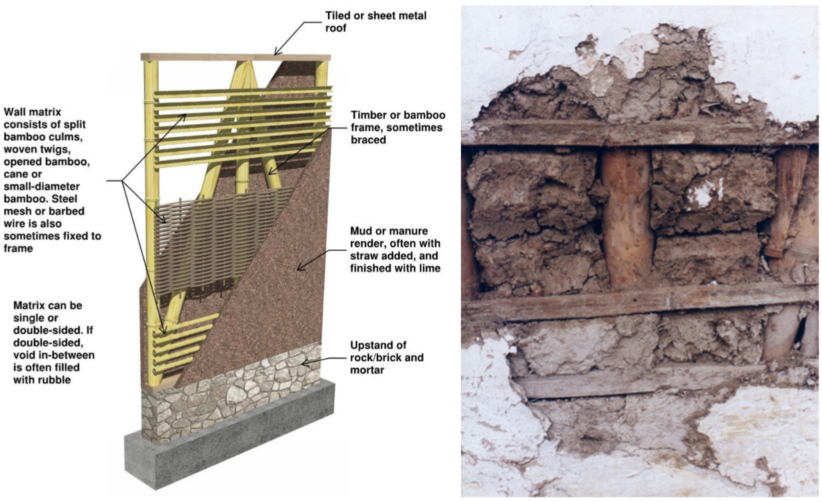

Figure 2. Traditional bahareque in Latin America: (L) structure; (R) wall detail (Lopez, 2016).

Traditional *bahareque* typically consists of a timber and/or bamboo frame, clad in a matrix of split or opened bamboo (known as *esterilla*), cane, twigs, or timber strips, and finally plastered in manure or soil, sometimes with straw added for strength (López et al., 2004). Lime may be used for the final plastered finish. The oldest houses tend to have the space in-between the matrices infilled with mud. The width of the walls can vary from 100mm up to 300mm. The walls are normally elevated on top of a stone or brick upstand to reduce the risk of dampness, have a good roof overhang, and use naturally durable timber or traditionally treated timber and bamboo

(Carazas-Aedo & Rivero-Olmos, 2013). Figure 2 illustrates some of the main structural features of traditional *bahareque* systems. Roof build-ups vary in Latin America; historically, the roof was constructed from palm fronds but switched to more durable, yet heavier, clay tiles after the Spanish colonial period (López et al., 2004). Corrugated iron sheets are now used for the roof in some areas. Wall matrix material varies according to what was most easily available locally, normally hardwood timber strips, bamboo, or cane. Figure 3 presents some of the matrix types.

Traditional *bahareque* can be constructed to differing degrees of formality, from rural informal single-storey housing that needs frequent maintenance, to urban two-storey formal housing, which may be regarded as relatively upmarket. Properly constructed and maintained traditional *bahareque* has been shown to possess good structural unity and flexibility, and therefore has a surprisingly high degree of earthquake resistance (Gutiérrez, 2004; López et al., 2004). Some forms of traditional *bahareque* can also be relatively light (20-40% of the weight of modern construction systems such as reinforced concrete with masonry infill).

Figure 3. Typical wall matrices for traditional bahareque (Kaminski, 2016): (L) esterilla/caña picada (sheets of bamboo formed by splitting bamboo along its length and then unrolling it; (R) caña brava/vara de castilla (small diameter bamboo/cane).

Traditional *bahareque* requires a reasonable standard of construction, detailing and maintenance so as not to deteriorate under fungal or insect attack. In addition, the traditional treatments used are not generally entirely effective, and damage due to termites and borer beetles is still common. Because of this, frequent maintenance is essential, which includes periodic rendering and painting, replacing damaged elements, and controlling water ingress – without this, traditional *bahareque* generally becomes very vulnerable to earthquakes after around 5-10 years. This was seen after the 1999 Quindío earthquake (EEFIT, 2000), the El Salvador 2001 earthquake (López et al., 2004) and the 2016 Muisne Ecuador earthquake (Drunen et al., 2016). Another important disadvantage of traditional *bahareque* is that it is prone to harbouring insects, notably triatomine bugs known locally as *chinche*. This small biting insect can transmit Chagas disease, a potentially life-threatening illness that is estimated to currently afflict 10 million people worldwide, mostly in Latin America (WHO, 2010). Traditional *bahareque* is also not known to be endorsed by seismic codes around the world, and therefore does not generally attract the attention of potential charities to sponsor housing projects.

Development of modern "cemented" *bahareque* in Colombia

In the early 19th century in the area of Caldas (Mogollon Sebá, 2001) in Colombia's coffee-growing region, buildings that contained timber were observed to perform better than simple adobe or *tapial* (solid earth) systems (Saleme, 2001). As a result, communities began to incorporate timber into their homes (Trujillo, 2021). The system was considered so much more resilient that it received the name *temblorero* – 'tremor-proof style'. The *temblorero* style of *bahareque* architecture had a ground floor made of adobe or rammed earth, while the second floor was constructed using early versions of *bahareque*. The frames of the second floor were typically made of bamboo and/or wood and were completely infilled with mud.

Gradually, timber-framed housing became the norm. Bamboo would also be incorporated as an inexpensive and abundant alternative, though, as deemed of lesser value, its use was reserved for poorer communities or less visible locations within a building. With the arrival of cement to the region in the 1930s, the old plaster made of soil, manure, and lime was gradually replaced by a new plaster made from cement and sand. This technological upgrade helped to extend the lifespan of many of the traditional *bahareque* houses in the region, allowing them to survive to the present day – some are now more than 100 years old. The decline of traditional *bahareque* technology began in the 1920s, when a devastating fire consumed 26 blocks in the city of Manizales. This disaster marked a turning point, with modern materials like reinforced concrete and steel coming into prominence, while traditional *bahareque* construction was subsequently relegated to informal settlements and poor rural areas.

Modern "composite bamboo shear walls"

Over the past 45 years, there have been several initiatives that use the "cemented" *bahareque* system, but "engineer" it to reduce or remove its natural deficiencies, and improve it with modern materials, knowledge and construction techniques. The international umbrella name for this new system is "composite bamboo shear walls" (CBSW), since:

- The walls nearly always contain bamboo in the frame or the matrix.
- The walls work as shear walls.
- The walls work through the frame, matrix, wire mesh and render all acting compositely as shear walls.

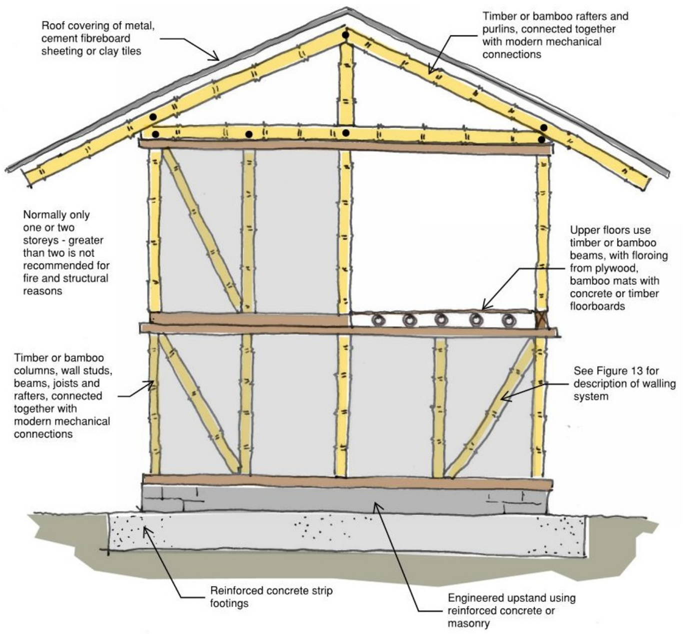

Figure 4. Characteristics of modern CBSW housing.

Modern CBSW systems typically have the following characteristics (Figure 4 and Figure 5):

- Foundations: reinforced concrete strip footings.
- Upstand elevating base of wall: reinforced concrete or reinforced masonry upstand.
- Primary wall structure: timber or bamboo columns, wall studs, beams, floor joists and rafters, joined together by modern mechanical connections such as bolts, nails or screws. In some systems, bracing is used, especially in two-storey buildings. Damp-proof membrane separates the frame from the upstand.
- Walling system: a matrix consisting of either cane, small diameter bamboo, bamboo laths, or bamboo mats is nailed to the timber or bamboo wall structure, and galvanised steel chicken mesh nailed to the matrix acts as reinforcement. The mesh is then plastered with cement mortar render, sometimes with lime. In some systems an expanded steel mesh acts as both the matrix and the reinforcement. The most common system is large diameter bamboo studs with a timber sole plate and head plate, with bamboo *esterilla* forming the matrix. The walling system is both structural and forms the internal partitions and external façade. The matrix and cement mortar render can be fixed to just one or both sides of the studs.

- Upper floors: timber or bamboo beams, with flooring made from plywood, bamboo mats with concrete poured on top, or timber floorboards.
- Roof: timber or bamboo rafters and purlins form the frame, joined together by modern mechanical connections such as bolts, nails or screws, with a roof covering of metal or cement fibreboard sheeting, or clay tiles.
- Number of storeys: currently limited to two or three for fire and structural reasons.

The timber used is either naturally durable or treated timber, and the bamboo is always treated.

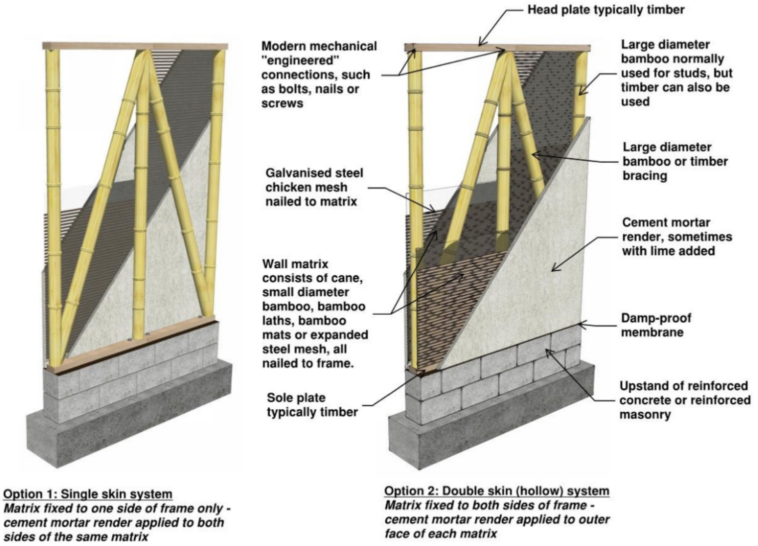

Figure 5. Shear wall details of modern CBSW housing.

With the changes outlined above, coupled with good construction and maintenance, CBSW systems are a significant improvement over traditional *bahareque* in terms of:

- Durability: the system can have a design life exceeding 50 years.
- Structural performance in earthquakes and winds: the system can meet earthquake and typhoon design requirements, even in high hazard zones.
- Hygiene: the use of cement mortar render provides a finish that is easier to clean and durable, hence providing a more hygienic internal environment.
- Status: the system is perceived as a modern-looking home, important for communities in lower socio-economic brackets who aspire to have what they perceive to be a better and more durable house, and one which reflects a higher level of prosperity in comparison to their neighbours (Gutiérrez, 2004; López et al., 2004; Kaminski, 2013).

In comparison with other modern forms of low-cost housing currently constructed around the world in both post-disaster and development contexts, CBSW housing has been shown to be of equal or lower cost, greater seismic resistance, superior sustainability credentials, and can use more local materials, which brings more direct benefit to local communities.

Case Studies

Over the past 35 years, over 4000 one and two-storey homes utilising modern CBSW have successfully been constructed in various countries around the world, including Costa Rica, Colombia, Nepal, Ecuador, El Salvador, Peru, Mexico and the Philippines. Several case studies of specific projects are presented below.

National Bamboo Project, Costa Rica, 1988-1995

In 1988 the Costa Rican National Bamboo Project (Proyecto Nacional de Bambú – PNB) (Gutiérrez, 2004) developed and implemented CBSW housing. Because there was no significant tradition of building with bamboo, the project involved a technology transfer of designing and growing with cane and bamboo from Colombia, based on the traditional "cemented" *bahareque*. The designs used a naturally durable hardwood or treated *guadua* for the frame, with a wall matrix of *esterilla* or *caña brava* (a small-diameter cane), covered in cement mortar render, with a lightweight corrugated iron sheeting roof (Figure 6). The *guadua*, *caña brava* and *esterilla* were all treated with boron. In total, u4 until 1995 around 2000 of these single storey low-cost houses were built for low-income communities across the country.

Figure 6. National bamboo project housing in Milano, Costa Rica – photos taken at 20+ years since construction (Kaminski, 2012).

Full scale in-plane wall tests were conducted at the University of Costa Rica in order to determine the shear capacity of the walls to resist wind and earthquakes (Mendoza & Villalobos, 1990). Further confirmation of the strength of these walls was seen when a number of newly constructed houses survived a Magnitude M_w 7.8 earthquake in Limón in 1991, with local MMI intensities up to IX (Gonzalez & Gutierrez, 2003). An independent review of 26 of these houses in 2012, i.e. 12-24 years since construction, concluded that they were sufficiently well-liked by the beneficiaries to have changed many of their preconceptions regarding building with bamboo (Kaminski, 2013). The majority of the houses appeared to be in excellent condition.

Figure 7. Post-earthquake CBSW housing in Barcelona (L) and Montenegro (R), near Armenia, Colombia (Kaminski, 2012).

1999 Quindío earthquake, Colombia, 2000-2010

In 1999 a Magnitude M_w 6.4 earthquake struck the coffee-growing region of Colombia, resulting in 300,000 people made homeless. Due to the generally positive behaviour of traditional bahareque (Trujillo, 2007), a number of NGOs and international development agencies implemented reconstruction projects that principally used bamboo for the building structure following the *bahareque* style, but with engineering input and modern details (Figure 7). This interest spurred the Colombian Earthquake Engineering Association (AIS) to conduct research into CBSWs, which included a series of shear tests on wall panels. Following this, the Construction Manual for Seismically-Resistant Housing using Mortared Bahareque (*Manual de construcción sismo resistente de viviendas en bahareque encementado*) was published (Prieto et al., 2002), alongside a new chapter in the Colombian design and building code – NSR-98 (AIS, 2002). The houses were a mixture of one and two storeys, and varied from detached to terraced.

Wall systems varied and included braced and unbraced *guadua* and/or timber frames, and used either *esterilla* or expanded steel mesh for the matrix. Most of the bamboo was treated using boron. An independent review of 29 of these houses in 2012 (around 10-12 years after construction) concluded that for the house designs that had no issues, the homeowners opinions were very positive (Kaminski, 2013). Opinions were less positive where housing experienced water ingress, which appeared to be a function of design issues.

REDES housing, El Salvador, 2012+

Since 2012, Arup, in conjunction with the El Salvadoran NGO REDES (*Fundación Salvadoreña para la Reconstrucción y el Desarrollo*), have been exploring CBSW housing for low-income communities across the country (Kaminski et al., 2016a). The CBSW system selected for this context uses a frame made from timber, connected together with nails and steel straps. Timber was used because significant quantities of large diameter bamboo are not available in El Salvador, and therefore the traditional *bahareque* system there also uses timber frames. The walls are wrapped in a thin galvanised chicken mesh on both sides, and *caña brava* was nailed to the frame. All timber and cane was treated. Cement mortar render was then plastered on both sides of the walls to form the 60mm thick shear walls. No bracing was added. The roof consisted of lightweight cement fibreboard sheeting screwed down onto the timber purlins and rafters, and had a large overhang on all sides (Figure 8).

Figure 8. CBSW housing, El Salvador (Kaminski, 2016).

A series of cyclic shear tests of the walls were conducted at Imperial College London using different geometrical and material characteristics (Málaga-Chuquitaype et al., 2014). A full-scale 3m x 3m model of one room of the house was also constructed on a shake-table at the University Mariano Gálvez, Guatemala City. The specimen was subjected to earthquake design loads up to 1.5 times greater than the code requirements, and experienced insignificant damage. On completion of two prototypes of the house in 2012, a structural and sociological evaluation of the design was carried out showing very positive results (Kaminski et al., 2016a) – all the beneficiaries liked the design, and some now prefer it to reinforced masonry.

BiBa System by Bambuterra, Mexico, 2014+

Bambuterra have been working in Mexico since 2014 on CBSW housing. The project tested 16 different panels of CBSW under monotonic loads, with and without diagonals, with different sheeting/renders, and with different aspect ratios (Correa et al., 2014). In addition, two full scale houses prototypes were subjected to three types of testing: ambient vibration testing, free vibration testing and a deformation controlled quasi-static cycling testing (Correa et al., 2021). These tests provided design and ultimate strengths, global ductility, stiffnesses and damping.

Base Bahay Foundation, The Philippines, 2014+

In 2012, the Hilti foundation selected CBSWs inspired by the Colombian *bahareque encementado* system for social housing in the Philippines. The system is known locally as “Cement Bamboo Frame Technology”, and prefabricates all components of the houses, including walls, trusses and purlins. The local design had to consider both earthquakes and powerful typhoons, and is fully compliant to the Philippines code. The Base Bahay Foundation has so far built more than 1500 houses, mainly in the Philippines and Nepal, using this technology (Figure 9). Although most are single storey, over 20 are two-storey. Large-scale construction is now being implemented together with partner organisations.

Figure 9. CBSW housing in in Ilo ilo city, the Philippines (Lopez, 2014).

Current state-of-the-art

Codes and guidelines

The CBSW system is codified in the Colombian, Ecuadorian and Peruvian standards, as well as ISO 22156 (ISO, 2021). Efforts are currently underway to incorporate it into the Philippines, Mexican and Nepalese codes. Several design and construction guides also exist providing additional guidance to engineers, architects and builders (Kaminski, 2016b; INBAR, 2015).

Strength, ductility and seismic performance

CBSW housing can resist earthquakes and strong winds in even the most hazardous regions of the world. The frame, matrix and cement mortar render has been shown to behave compositely, acting as a shear wall in-plane. The walls are also significantly lighter than traditional *bahareque*. The system has been tested in-plane under monotonic and cyclic loading to destruction, and several full-scale shake-table tests have also been conducted, suggest that the system may demonstrate a displacement ductility capacity of at least 2-3 (Kaminski et al., 2015; Correa et al., 2022). Out-of-plane, the studs and matrix can comfortably resist the required demands, and the render does not spall.

Durability

CBSW housing can achieve a 50-year design life through good design (Kaminski et al., 2022). Bamboo and timber are vulnerable to insect and rot attack and therefore need to be protected. To protect against insects, the bamboo should be treated with boron and the timber should either be treated or naturally durable. To protect against rot, the bamboo and timber must be kept dry through good design details such as: elevating the frame on an upstand, including a damp-proof membrane, large overhangs to protect the walls from driving rain, an impermeable wall (e.g. painted cement mortar render), good drip details, and ventilated cavities. Steel connections should be painted, galvanised or stainless steel.

Sustainability

CBSW housing has been shown to be superior to many other forms of modern permanent housing in terms of sustainability and environmental impact, especially housing using materials such as masonry and concrete (Zea Escamilla et al., 2019). The two main reasons are: the bio-based and mineral materials used have significantly lower carbon footprints and emissions from transportation (Celentano et al., 2018); the use of bamboo and timber serves as a carbon sink (Zea Escamilla et al., 2016). Bundi (2022) assessed the environmental impact of CBSWs and compared them to houses built to the same standard using conventional masonry. The results showed that CBSWs have 45% of the embodied carbon of a conventional house, with the major contributors to the environmental impact being the concrete foundation and cement render.

Behaviour in fire

The CBSW system provides a convenient way to protect the naturally susceptible timber and bamboo from fire. Using 15mm of cement mortar render can provide a nominal level of protection, while increasing this to 25mm on one side can provide a 30 minute fire resistance rating (Kaminski et al., 2016b). Preliminary tests have also suggested that 20-25mm mortar both sides could potentially achieve 60 minutes (Tambunan et al., 2022).

What have been the barriers in wider global adoption of this technology?

Some of the following barriers have limited the wider global adoption of this technology:

- Limited approval by National Codes.
- Limited technical guidance for designers and builders.
- Limited numbers built to date, which limits confidence.
- Poor perception of bamboo and timber amongst donors, construction professionals and potential beneficiaries.
- Pressure from traditional construction industry against the use of timber and bamboo.
- Quality of designs and builds varies worldwide, in particular regarding durability, which erodes stakeholders' confidence.
- Absence of proper bamboo treatment facilities and poor bamboo value chains.

Various initiatives and projects are underway to break down these barriers.

Conclusion

Composite bamboo shear walls (CBSW) are an affordable, low-tech, low-carbon and durable technology that has been demonstrated to have a good seismic performance when correctly designed, detailed, built and the timber and bamboo elements are preservative treated. Thousands of houses have been built using this technology, but adoption is slower than the technology warrants – there are some barriers to adoption that need to be investigated in detail, and the technology needs to be further developed and improved. However, the authors believe that this is a technology that has great opportunity for tackling the simultaneous crises of climate change and hazard vulnerability that millions of people face worldwide.

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