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# Seismic Behavior of Bahareque Walls Under In-Plane Horizontal Loads

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**Abstract:** This study investigates the structural behavior of bahareque earth walls, a traditional construction system commonly used in rural areas of northern South America. Bahareque (wattle and daub) walls, consisting of guadua (a bamboo-like material) or wooden frames filled with soil mixes, have demonstrated considerable resilience in seismic zones due to their lightweight and flexible nature. Despite their widespread use in these communities, limited scientific data exist on their seismic performance under in-plane pseudo-static horizontal loading. This research addresses this gap by experimentally evaluating the seismic behavior of five wall models with different combinations of guadua, wood, and earth filling materials. The methodology included four main phases, namely field visits to document traditional construction techniques, material characterization, prototype testing under pseudo-static loads, and an analysis of mechanical behavior. Key material properties, including compressive strength and Young's modulus, were determined, alongside the mechanical and physical properties of the infill material, which incorporated natural fibers. Pseudo-static tests were conducted on five wall prototypes, featuring various configurations of guadua and wood frameworks, both with and without soil infill. The walls were subjected to horizontal in-plane loads to assess their deformation capacity, energy dissipation, and failure mechanisms. The results indicated that walls with soil mixture infill—specifically the GSHS (guadua frame with horizontal guadua strips and soil mixture infill) and TSHS (wood frame with horizontal guadua strips and soil mixture infill) configurations—demonstrated the best seismic performance, with maximum displacements reaching up to 166 mm and strengths ranging from 6.4 to 8.4 kN. The study concludes that bahareque walls, particularly those incorporating soil mixes and horizontal guadua strips, exhibit high resilience under seismic conditions and provide a sustainable construction alternative for rural regions. The scope of this study is limited by the exclusion of dynamic seismic simulations, which could offer additional insights into the behavior of bahareque walls under real earthquake conditions. The novelty of this research lies in the direct evaluation of the seismic performance of traditional bahareque configurations, specifically comparing walls constructed with guadua and wooden frameworks, while emphasizing the critical role of soil infill and guadua strips in structural performance.

**Keywords:** bahareque; earthen walls; seismic performance; guadua; bamboo; pseudo-static tests

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## 1. Introduction and Background: Traditional Timber Structures

Traditional timber structures have played a vital role in the architectural heritage of many regions worldwide, especially in areas prone to seismic activity. Examples like the Chuan-dou timber frames in China, Japanese pagodas, and European half-timbered houses demonstrate remarkable resilience to seismic forces. Understanding their seismic performance is essential not only for preserving these historical structures but also for integrating their resilient design features into modern construction practices [1,2].

Timber's flexibility, lightweightness, and energy dissipation make it ideal for seismic resistance, along with its structural configuration and connections. Some joinery techniques found in traditional timber structures further enhance their seismic resilience, as mentioned in [3]. Timber's anisotropy, damping capacity, and ability to deform without failing are key to its seismic behavior [4,5]. Additionally, timber's flexibility and energy-dissipating capacity help reduce the impact of seismic forces [4,6].

The structural configuration of timber buildings plays a critical role in their seismic performance. The arrangement of beams, columns, and infill materials enhances the structure's ability to resist seismic forces. For instance, ref. [7] demonstrated that masonry infill in traditional Chinese timber frames significantly improves load capacity and energy dissipation, highlighting its importance in seismic resilience. Similarly, studies like [8,9] on Taiwanese timber shear walls revealed that traditional design elements, such as the friction between board units and beams, along with embedment resistance, are key factors in resisting lateral forces.

Likewise, joints between timber elements are crucial to a structure's seismic resilience. Traditional joinery, such as mortise–tenon and dovetail joints, allows for flexibility and energy dissipation. However, these joints can degrade under repeated seismic loading if not properly maintained. Reinforcing joints with modern materials, like steel plates or advanced adhesives, could significantly improve seismic performance while preserving the historical integrity of the structures.

Historical records and experiments show timber structures' resilience, as seen in the Great Kanto (Japan) and Sichuan (China) earthquakes, due to their flexible frameworks and energy-dissipating joints. Studies [1,2,7,10] highlight how these buildings have withstood significant seismic forces due to the effective combination of the inherent properties of wood and traditional construction techniques; for example, these traditional wood structures have shown outstanding earthquake performance due to their excellent deformation capacity and energy dissipation properties.

Experimental research has provided further evidence of the seismic resilience of traditional timber structures. For instance, ref. [11] demonstrated through shake table tests that proper structural configuration is critical, with column-and-tie timber frames showing excellent resistance to collapse under maximum earthquake scenarios. Similarly, ref. [12] performed pseudo-static cyclic tests on Chuan-dou timber frames with varying infill configurations, analyzing key parameters such as force deformation behavior, failure mechanisms, stiffness, and energy dissipation capacity using 1:2 scale models. More recently, ref. [13], inspired by traditional Romanian architecture, conducted pseudo-static tests on the TRAROM lightweight timber frame system, further validating the seismic performance of timber-based designs.

Detailed case studies provide further insight into the seismic performance of specific traditional wood structures around the world. For example, ref. [8] studied Taiwanese timber shear walls, while [14] analyzed European timber frames (a timber frame structure called "gaiola pombalina" used in downtown Lisbon after the 1755 earthquake), emphasizing how design details—such as the use of bamboo nails in Taiwanese structures and the integration of masonry infill in European designs—affect seismic performance. Ref. [15]

further investigated the seismic behavior (strength, stiffness, ductility, and energy dissipation) of traditional Mediterranean infilled timber frame walls subjected to pseudo-static tests. The infill consists of masonry lath and plaster. The authors also tested a timber frame without infill for comparison. The tests showed how the infill was able to guarantee greater stiffness, ductility, and the ultimate capacity of the wall. Ref. [16] performed static cyclic tests on timber frame specimens, which were constructed based on findings from field investigations of traditional Romanian buildings. Some of the specimens tested exhibited excellent deformation capacity, with drifts greater than 5%. Similarly, ref. [17] tested double-span traditional timber structure models, highlighting that the experimental pseudo-static tests had stable hysteretic loops and that the P–Δ effect could affect the response of timber frames.

Shaking table tests and cyclic loading experiments confirm timber-framed walls with infill materials like adobe or fired bricks can withstand lateral displacements and ground accelerations without collapsing [18]. The results indicated that walls with bamboo or timber frameworks provided superior seismic performance, particularly in terms of energy dissipation and the reduced likelihood of catastrophic failure.

Computational modeling has become an essential tool for predicting the seismic response of traditional timber structures. For example, ref. [19] developed a hysteretic model for "frontal" walls in Pombalino buildings, providing valuable insights into their seismic behavior. Finite element analysis (FEA) has also been widely applied to simulate the performance of timber frames with various infill materials, demonstrating how different configurations influence structural response. Similarly, ref. [20] created numerical models calibrated with the experimental results of timber frames, both with and without masonry infill, incorporating key effects such as flexural behavior, pinching, and strength degradation. Advancements in modeling techniques include shear spring models proposed in [21], which accurately replicate initial stiffness and peak strength, effectively capturing the complex interactions between structural elements during seismic events. Various software tools have facilitated these analyses, with OpenSees employed in [19] and ABAQUS utilized in [22] to assess the dynamic properties of timber frame masonry systems.

While the technical literature and several reports from Colombia (northern South America) have studied the behavior of cemented bahareque (a type of timber-framed structure) with bolted connections (actually included in the Colombian earthquake-resistant code) or contemporary systems such as prefabricated wattle and daub [23], there are few studies in the scientific literature focused on the structural behavior of traditional timber-framed bahareque modules used in the rural areas of northern South America.

The novelty of this research lies in providing the first scientific report on the structural behavior of traditional bahareque walls subjected to in-plane horizontal loads, as constructed in the Valle del Cauca and Cauca regions of Colombia. This study highlights the potential of bahareque as a safe and resilient construction system, particularly for seismically vulnerable areas. Furthermore, it offers a unique experimental comparison, under controlled and identical loading conditions, of the seismic performance of bahareque walls constructed with guadua (a bamboo-like material) versus wooden frameworks, incorporating insights into their distinct mechanical behaviors, emphasizing the role of soil infill and guadua strips in structural performance.

The primary objective of this study is to experimentally evaluate the seismic performance of traditional bahareque walls, focusing on the influence of material configurations (guadua, wood, and soil infill) on their ductility, stiffness, and failure mechanisms. Addressing a critical gap in the literature, this research provides much needed empirical data on the seismic behavior of bahareque systems, which have received limited attention despite their widespread use in rural South America. By grounding its findings in robust experimental analysis, this study not only preserves traditional construction knowledge but also lays the foundation for enhancing the seismic resilience of bahareque walls, aligning them with modern performance standards and sustainable building practices.

## 2. Methodology

The methodology implemented in the current study is presented in Figure 1, consisting of the four following phases:

- Phase 1: Field Visits: During field and technical visits, the materials and structural characteristics of bahareque constructions in rural areas of southern Colombia (northern South America) were documented. Material specimens, including wood, guadua, and soil, were collected for laboratory analysis. Existing houses were studied to determine the main dimensional characteristics of bahareque modules.
- Phase 2: Material Characterization: Given that earthen bahareque is composed of sawn timber frames combined with guadua and soil mixtures, with or without natural fibers, this phase involved the evaluation of the physical and mechanical properties of these materials. The characterization included testing for compressive strength and the modulus of elasticity for both wood and guadua. For the soil, Atterberg limits, maximum dry density, optimum water content, percentage passing through sieves, compressive strength, and indirect tensile strength were determined.
- Phase 3: Pseudo-Static Tests on Five Models: To evaluate the in-plane behavior of bahareque walls and components, pseudo-static tests were conducted. The wall specimens included vertical and diagonal elements made of wood and guadua. The dimensions of the test modules were based on observations from the field visits and on typifications of heritage construction systems, as described in [24] in the Colombian Coffee Cultural Landscape and as reported [25]. All prototypes were constructed with a base width of 2.2 m and a height of 2.2 m.
- Phase 4: Conclusions and Recommendations: Based on the experimental results from the material characterization and pseudo-static tests, conclusions were drawn regarding the performance of the bahareque system, along with recommendations for future research and applications.

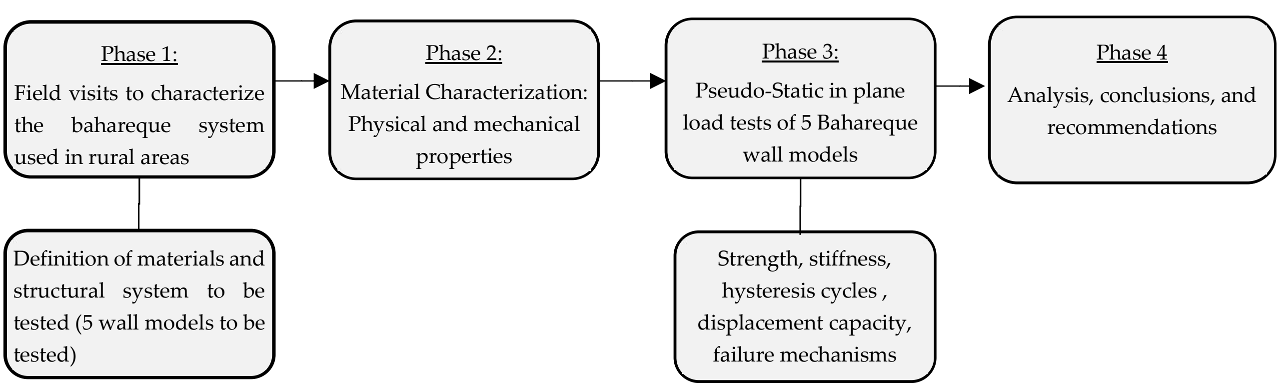


**Figure 1.** The proposed methodology to assess the mechanical characteristics of Bahareque walls.

## 3. Characteristics of Bahareque-Framed Earthen Walls and Field Visits

A typology of traditional wooden structures, used for centuries in South America, Central America, and Asia [26–29]), is known as bahareque in Colombia and Ecuador (quincha in Peru, taipa de mão in Brazil). This system is renowned for its use of natural materials such as bamboo, wood, and earth, making it not only sustainable but also highly resilient in seismic zones [30]. In recent years, these construction techniques have seen renewed interest due to their low environmental impact and inherent seismic resistance. The basic characteristic of the bahareque system (native from the Andean region of South America) is the reliance on a bamboo or wooden framework (braced and with sill beams), infilled with a mixture of soil and fibers (organic). According to [31], this framework is usually plastered or coated with mortar to protect it from the weather.

In reference [32], the authors mention that bamboo is a natural construction material found in tropical, sub-tropical, and mild temperate regions of at least four continents (America, Oceania, Asia, Africa). This natural material is particularly widespread in Colombia (Northern Andean region of South America), where it serves as the primary structural element of some rural and urban dwellings due to its abundance and favorable mechanical properties [33]. As indicated in [34], modern adaptations often use engineered bamboo products, such as laminated bamboo, which provide enhanced strength and uniformity by bonding layers of bamboo strips, making them stronger and more durable than traditional bamboo. Bamboo's rapid growth also makes it a highly renewable resource [35].

Bahareque is a traditional construction technique that weaves bamboo or wooden strips with mud or clay, creating walls that are both thermally efficient and highly durable. As reported in [36], these walls can endure harsh environmental conditions and remain functional for decades with minimal maintenance. A key advantage of bahareque systems lies in their capacity to absorb and dissipate seismic energy, a result of the materials' flexibility and lightweight nature. Bamboo-framed structures, in particular, demonstrate exceptional seismic performance due to their ability to undergo large deformations without failure. Research in [37] highlights the critical role of joint design, such as bolted steel-to-bamboo connections, in ensuring structural strength. Similarly, ref. [38] showed that adding diagonal bamboo strips to the walls significantly enhances seismic performance, improving both lateral load capacity and stiffness.

Field studies conducted after the 1999 Armenia earthquake in Colombia revealed that bahareque structures performed remarkably well compared to modern construction technologies. Ref. [33] reported that houses constructed with well-maintained bahareque walls suffered minimal damage, whereas those with poorly maintained walls experienced significant failures. This underscores the importance of maintenance and the use of high-quality materials to ensure the longevity and seismic resilience of these structures.

Additionally, several studies have highlighted the potential of combining traditional materials with modern construction techniques. For instance, ref. [23,39] explored bahareque in contemporary construction, demonstrating its viability as an alternative to conventional materials, especially for low-income housing projects in seismic regions. Combining traditional bahareque techniques with modern materials, such as reinforced concrete for foundations, can further enhance the seismic performance of these structures.

Hybrid wood–soil systems (HWSs), particularly those integrating bamboo, wood, and soil, have gained attention for their potential to meet global housing demands sustainably. Traditional systems like bahareque, prevalent in Latin America, utilize natural materials such as bamboo, soil, and mortar, providing low-cost and environmentally friendly solutions [31]. Modern iterations of HWSs have adapted these techniques to incorporate engineered materials, improving performance under seismic and environmental conditions [34]. Studies demonstrate that combining traditional materials with engineered