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Article

Finite Element Modeling of the Structural Response of Bahareque Walls Under Cyclic Loads

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Abstract

Some communities in Valle del Cauca department (Colombia) live in houses made of bahareque walls. It is important to study the seismic performance of these structures as they are in an earthquake-prone region. This study develops a finite element modeling strategy to assess the cyclic behavior of bahareque walls in Colombia. Two types of walls are analyzed, including wood and guadua for the bare frame. The Puck failure criterion is used. The model is calibrated from results of pseudo-static tests on three walls without infill and two with infill. Results show that the model correctly predicts the first load cycles, but it presents convergence difficulties for higher cycles. It is necessary to further simulate some phenomena, such as the separation of nails in the joints.

Keywords: bahareque walls; pseudo-static tests; finite element-modeling; non-linear behavior

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1. Introduction

Earth construction plays a vital role as a sustainable housing solution worldwide, offering remarkable versatility through a wide range of techniques and creative approaches developed across different regions. The economic feasibility of this construction method depends on several factors, including the construction process, structural durability, maintenance requirements, material stabilization, and labor availability [1]. Among the various earth-based construction systems, commonly employed techniques include adobe brick masonry, rammed earth, cob, wattle and daub, and poured earth [2]. In the southwestern region of Colombia, bahareque construction is widely used by local communities for diverse purposes, including residential buildings and schools. Bahareque is a traditional building system characterized by a structural framework of wood and/or guadua (a bamboo-like material), filled with an earthen mixture and finished with a coating, which often includes a blend of soil and cagajón (a locally sourced organic additive) [3]. It is worth noting that cagajon can be substituted with finer soil or other materials.

Previous studies have highlighted the economic advantages of bahareque construction. Palacios and Angumba [4] estimated the cost of a 130 m^2 bahareque house in Cuenca, Ecuador, at USD 36,387, demonstrating a significant cost advantage compared to conventional housing in the region. Similarly, Tello-Ayala et al. [5] conducted a life-cycle cost analysis comparing a two-story social housing unit built with bahareque to one constructed with reinforced concrete. Their results indicated a 40% reduction in total cost and a 50% reduction in construction time for the bahareque alternative. From an environmental performance, bahareque construction was shown to generate only 27% of the embodied carbon emissions associated with reinforced concrete housing. Despite these benefits, further research is needed to deepen the understanding of bahareque construction methods and structural performance to promote its broad adoption as a sustainable and resilient building technology, particularly in seismic-prone areas.

Understanding the seismic performance of earth construction in earthquake-prone regions is a critical global concern. Risk assessment and structural reinforcement have emerged as major research trends in this field, as noted by Sánchez-Calvillo et al. [6]. To evaluate the seismic behavior of earthen structures, several pseudo-static tests have been carried out on different wall systems. Vieux-Champagne et al. [7] tested one- and two-story timber-framed walls with stone and earth infill, reporting that failure typically occurred at the connections when a 3% drift level was reached. Zhou et al. [8] compared the seismic performance of one-story adobe walls built with different types of bricks, concluding that the inclusion of core columns is essential for maintaining structural stability. Ruiz et al. [9] performed full-scale testing on a two-story rammed earth wall, demonstrating the effectiveness of a steel plate retrofitting system that meets architectural requirements while ensuring long-term durability due to its non-biodegradable nature. In Colombia, two notable studies have addressed the seismic performance of bahareque wall systems. Herrera and Takeuchi [10] conducted full-scale pseudo-static tests on two-story Guadua angustifolia frames with precast bahareque panels, underscoring the critical importance of connection detailing in ensuring structural integrity. Cristancho et al. [11] performed in-plane pseudo-static tests on one-story bahareque walls and found that employing a wooden frame increased lateral strength by 23% compared to a guadua-based structural frame. Collectively, these experimental investigations highlight the need for continued research aimed at enhancing the seismic resilience of earth construction systems and developing innovative reinforcement strategies that are both effective and compatible with local construction practices and materials.

From a structural design standpoint, numerical modeling techniques are essential for the analysis and design of earth buildings, particularly through finite element method (FEM)-based software. Several studies have examined the seismic performance of bahareque-like wall systems using numerical simulations. Quinn et al. [12] developed a numerical model of historic Quincha walls that incorporated vertical uplift effects, semi-rigid rotational connections, and shell elements for the infill. Their results showed discrepancies of up to 20% when compared with experimental cyclic test data. Parisse et al. [13] proposed an OpenSees-based FEM model for Romanian timber-framed masonry walls, employing an equivalent timber frame representation, a lumped plasticity approach, and spring-based elements to simulate the joint behavior. Jiménez and Pelá [14] applied a macro-mechanical FEM approach combined with lumped plasticity to evaluate the seismic performance of infilled Quincha frames, implementing the equivalent strut method to capture the nonlinear behavior of the infill. Mite-Anastacio [15] investigated the structural response of cement-stabilized bahareque houses in Guayaquil (Ecuador) using a simplified FEM model that incorporated frame elements for guadua, idealized connection behavior, and shell elements for the floor slabs. The study highlighted the challenge of accurately replicating real-world construction details and material variability in numerical simulations. The above works demonstrate that each earth construction technique possesses unique structural characteristics, requiring tailored finite element modeling strategies to achieve accurate and reliable structural performance assessments under seismic loading.

This study proposes a finite element-based methodology for modeling the structural response of Bahareque walls built in Colombia under cyclic loading. Calibration data were obtained from pseudo-static seismic tests on Bahareque walls reported in reference [11], considering both wood and guadua frames. The modeling process began with unfilled conditions to isolate the frame behavior, after which two additional tests were incorporated to account for the influence of the soil infill. Accordingly, Section 2 describes the in-plane pseudo-static tests conducted on five specimens. The numerical model incorporates key construction characteristics, including the potential loss of structural element connections. Ansys 2022 R1 was selected for FEM modeling, as it has been successfully used in previous earth construction studies [16–18].

2. General Description of Pseudo-Static Test of Bahareque Walls

The Valle del Cauca department, located in southern Colombia, is highly susceptible to seismic activity due to its proximity to the Nazca Plate subduction zone and the presence of active crustal faults [19]. In this region, bahareque is commonly used for housing, particularly in rural communities, because of the abundance and accessibility of local construction materials. Figure 1 illustrates a bahareque house located in the Estrella Community, Jamundí, which incorporates a lighthouse-type structural configuration. Despite its widespread application, research on the seismic performance of bahareque buildings in Colombia remains limited. Advancing research in this area could foster significant improvements in self-construction practices and support the development of more earthquake-resistant rural housing. Notably, several institutions have already developed preliminary guidelines for supporting the seismic-resistant design and construction of bahareque structures [3,20,21].

Figure 1. Example of bahareque wall in a typical house of the Estrella Community in the Jamundí District (Valle del Cauca, Colombia).

Cristancho et al. [11] conducted in-plane pseudo-static tests on bahareque walls at the Pontificia Universidad Javeriana's Structural Engineering Laboratory, with researchers from both Cali and Bogotá campuses collaborating on the project. This study reflects the university's commitment to advancing knowledge on the seismic performance of informal structures, in a country where more than 80% of the population lives in earthquake-prone regions. Five bahareque wall specimens were tested, as shown in Figure 2, each with a height of 2.2 m and a width of 2.2 m. The first specimen corresponded to a bare guadua frame, while the second and third included horizontal strips and were built with wood and guadua, respectively. The fourth and fifth specimens incorporated soil infill within the wood and guadua frames. The infill, applied in accordance with standard construction practices in Colombia, consisted of silt mixed with sand and a native natural fiber (*Andropogon glomeratus*, Poaceae family), with an average thickness of 5 cm. For the connections, 3-inch steel nails were used to join the wall elements, a factor that may play a critical role in ensuring adequate seismic performance.

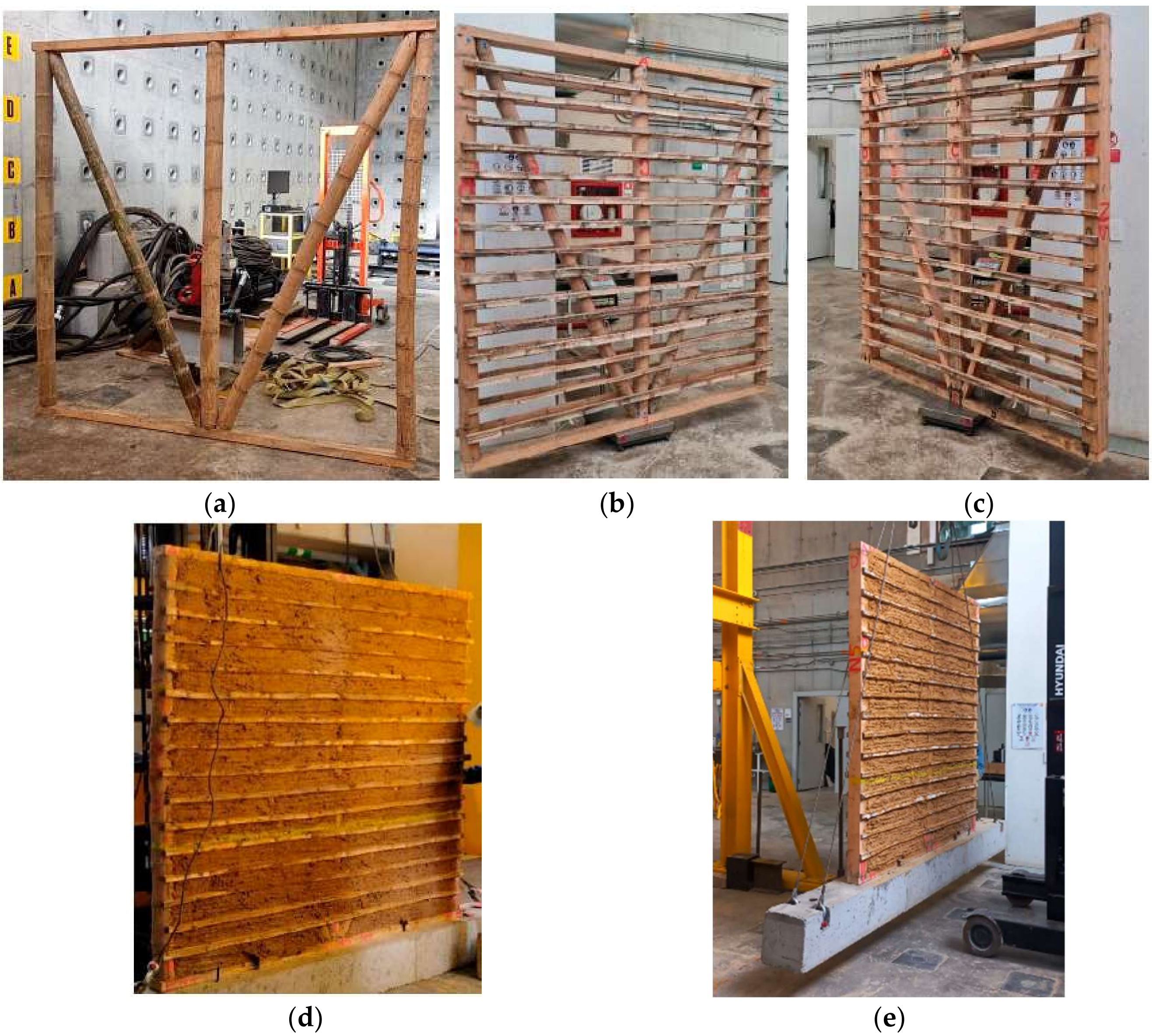

Figure 2. Tested bahareque walls: (**a**) guadua skeleton (GS); (**b**) guadua skeleton with horizontal guadua strips (GSH); (**c**) timber skeleton with horizontal guadua strips (THS); (**d**) guadua skeleton with horizontal guadua strips and soil mixture infill (GSHS); (**e**) timber skeleton with horizontal guadua strips and soil mixture infill (TSHS).

Figure 3 illustrates the pseudo-static test setup for bahareque walls. A servo-controlled MTS hydraulic actuator (MTS Systems, 14000 Technology Dr, Eden Prairie, MN, USA), mounted on a reaction wall, applied cyclic horizontal displacement at the top of specimens. A rolling mechanism, supported by a reaction steel frame, ensured in-plane motion. The actuator was connected to the bahareque walls through two steel plates linked by four rods, allowing reversible displacement. A steel beam placed on top simulated roof loads, applying a total vertical load of 1.9 kN. The foundation consisted of a concrete beam designed to replicate stone or cyclopean concrete foundations commonly found in the field. This foundation beam was anchored to the strong floor of the structure's laboratory. For additional details on test procedures, material characterization, construction considerations, experimental results, and failure mechanisms, refer to [11]. Future research will focus on full-scale house models that incorporate out-of-plane behavior and the dynamic effects of earthquakes.

Figure 3. General Scheme of the test.

The cyclic displacement protocol was designed with incremental displacements applied at the top of the walls, using three cycles per increment, up to a maximum displacement corresponding to a 6.0% drift relative to the height of the bahareque wall. Figure 4 presents the final protocol for all specimens, which was terminated once failure occurred. Similar protocols can be found in references such as [22].

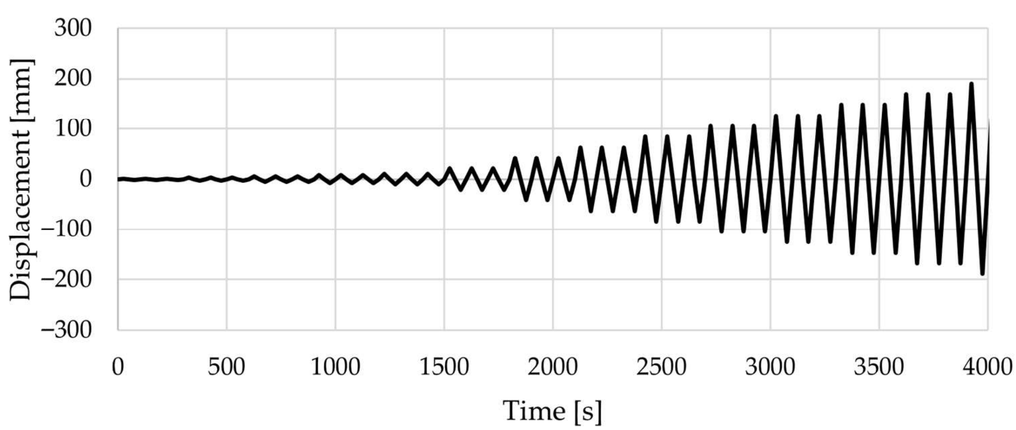

Figure 4. Cyclic displacement protocol for all the tested bahareque walls.

Instrumentation consisted of a total of seven LVDT sensors (OMEGA Engineering, Stamford, CT, USA) to measure horizontal and vertical displacements at strategic points on the walls, as shown in Figure 5. Three horizontal sensors were placed at the base, mid-height, and top of the central vertical axis of the wall to record lateral displacements, while four sensors were used to measure vertical uplift between the base element and the vertical side elements. The horizontal sensor at the base was installed to verify any relative movement between the wall and the foundation. During testing, it was necessary to remove some sensors once the allowable displacement was nearly reached. In addition, the hydraulic actuator was instrumented with a 250 mm-range LVDT sensor to verify that the displacement protocol was applied correctly, and it was also equipped with a load cell to measure the horizontal load applied to the wall specimens.