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ORIGINAL ARTICLE

Bi-axial shaking table tests to evaluate the seismic performance of two-story rammed-earth walls retrofitted with steel plates

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Abstract

Worldwide, unreinforced earthen buildings have shown poor performance during earthquakes, causing deaths and loss of property. The Spaniards that conquest the Americas built with earthen materials for about four centuries and therefore, there are a large number of historic buildings in the northern Andean zone of South America. This territory is geographically located in intermediate and high seismic hazard zones. Over the last few years, the authors proposed a seismic reinforcement system for historic earthen buildings based on A36 steel plates (100 ×6.35 mm) installed on both sides of the walls. However, to date, the studies had been focused on tests of one-story buildings subjected to in-plane pseudo-static loads or uniaxial dynamic loads. For this reason, this research assesses the seismic performance of two-story rammed-earth walls subjected to ground motions using a bidirectional shaking table. Two 1:2 scale RE walls (one retrofitted with steel plates and another unreinforced) were tested. The specimens were two-story walls with a "C" shape, similar to that found in heritage buildings of the Historic Center of Bogota. Based on the experimental tests, the unreinforced wall presented irreparable damage at acceleration levels higher than 0.34 g. In contrast, the retrofitted wall had excellent performance with lower damage levels and residual drifts; this specimen was highly resilient, withstanding earthquakes with peak ground acceleration (*PGA*) greater than 0.76 g.

Keywords Two-story earthen buildings · Rammed-earth · Shaking table tests · Earthen walls · Steel plates reinforcement · Structural dynamic response

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1 Introduction and background

Earth is one of the oldest materials used for construction since about 8000 BC. Earth construction has thousands of years of history; there is archaeological evidence suggesting the existence of cities built entirely of earthen materials (Varum 2014). All ancient civilizations of the middle eastern used rammed-earth (RE) and mud blocks (adobes) to construct their buildings, including the Assyrians, Babylonians, Persians, and Sumerians. The Berbers introduced this construction method to Europe around 700 BC, where it was used for hundreds of years to build earthen structures. When the Spaniards began the conquest of the New World (in particular, Colombia, northern South America), they brought the knowledge of adobe and RE construction. The adobe technique consists of walls made with sun-dried mud bricks while the RE system uses moistened soil mixture compacted vigorously in a wooden formwork. In the Colombian territory, indigenous tribes used their own earth method known as "bahareque" which consisted of mud reinforced with wooden elements (Sánchez-Gama 2007). Adobe, RE, and bahareque techniques were used to construct the Kingdom of New Granada (currently the Colombian territory). As a consequence, for more than four centuries, the architectural development of the Andean zone of Colombia was based on earthen buildings. Today, due to their heritage value, several earthen buildings must be preserved. According to the literature, heritage buildings in the study area (Andean zone of Colombia) should be protected from age deterioration and damage caused by earthquakes considering their location in the seismic hazard zone of the Pacific Ring of Fire. The impact of earthquakes on earthen structures worldwide has been documented by Parisi and Augenti (2013), who statistically demonstrate their seismic vulnerability. They reported that from a total of 1996 major earthquakes analyzed, 58% of the casualties involved masonry structures. Over this percentage, 20% were brick/stone buildings and the remaining 38% were earthen and rubble constructions. Additionally, this reference highlights the effects of one of the most destructive earthquakes worldwide, the M_w 8.8 Chile earthquake, where the National Monuments Council reported massive damage to all cultural heritage buildings made of adobe. Likewise, the following earthquakes (and others not mentioned here) have also demonstrated the poor seismic performance of traditional earthen constructions: Colombian coffee-growing region (1999, $Mw = 6.2$), Cucuta-Colombia (1875, $M_w = 7.5$), Iran (2003, $M_w = 6.6$), Peru (2007, $M_w = 8.0$), Popayan-Colombia (1983, $M_w = 5.5$), Quetame-Colombia (2008, $M_w = 5.9$), and Turkey (1992, $M_w = 6.8$) (Blondet et al. 2011b; D'Ayala and Benzoni 2010; Langenbach 2003; Ruiz et al. 2023b). According to Yamín et al. 2007; Reyes et al. 2020; Ruiz et al. 2022; Tarque et al. 2022; Rincon et al. 2022, the main factors that increase the seismic vulnerability of earthen constructions are floor plan and height irregularities, inadequate distribution of the walls, loss of verticality of the earthen walls, moisture problems, deficient walls-roof and walls-floor connections, heavy floor and roof, absence of diaphragms, poor shear and tension strength of the materials (adobe and RE) and low ductility capacity of materials and structural systems. This deficient behavior has resulted in the premature collapse of earthen walls at interstory drift levels close to 0.5% (Rincón et al. 2022; Tarque et al. 2012).

During the last 40 years, researchers proposed different seismic strengthening techniques for this type of building, aiming to preserve as much as possible the original architecture. Some of these seismic rehabilitation techniques are: steel cables, reinforced concrete dowels and wedges, polyester fabric strips, concrete beams, wooden floor beams anchored to RE blocks, tensors, straps, textile-reinforced mortar, externally bonded fibers, confining wooden elements, confining steel plates and mesh reinforcement (Zavala and Igarashi 2005; Bossio

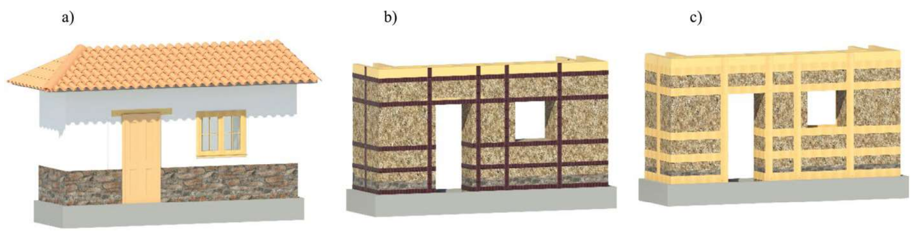

Fig. 1 Retrofitting strategies for RE and Adobe buildings: **a** original house, **b** confinement steel strips, **c** confinement wooden elements

et al. 2013; Reyes et al. 2019a, b, c, 2020; Ruiz et al. 2022, 2023b; Yamín et al. 2007; López et al. 2007, 2020; Zegarra et al. 1997; Varum et al. 2011, 2014, 2021; Blondet et al. 2005, 2006, 2011a, b; Charleson and Blondet 2012; Tarque et al. 2022; Liu et al. 2015; Miccoli et al. 2017; Shrestha et al. 2019, 2020; Figueiredo et al. 2013; Hamilton et al. 2006, Cassese et al. 2021). The most studied reinforcement techniques are those based on meshes (steel or plastic mesh). However, according to Yamín et al. (2007); Reyes et al. (2019a, b, 2020); López et al. (2020); Gómez et al. (2016); Ruiz et al. (2014, 2017, 2022, 2023a, b); and Uribe et al. (2014), the reinforcement based on confinement elements (wood strips or steel plates) has shown superior seismic performance. Nevertheless, despite the good structural behavior, seismic reinforcement with confining wooden elements has durability problems caused by moisture or insects; and that is why the authors have focused the research on steel plates protected with anti-corrosion paints (Ruiz et al. 2023b).

The steel-plate retrofitting alternative consists of the installation of horizontal and vertical elements on the faces of the earthen walls conforming rings. The distance between vertical and horizontal rings must be less than 1200 mm but an exception applies to the horizontal steel rings close to the base (these rings have a spacing of about 500 mm). One of the most important advantages of this alternative is to improve the flexural strength of the walls and preserve the unity of the structure. The steel elements must be placed on both the external and internal faces of the walls and the horizontal elements form rings that prevent the disarticulation of the different walls. A36 steel is used for all plates and the typical dimensions for vertical and horizontal steel elements are 100×6.35 mm. The aim of this new retrofitting technique is not only to stiffen the walls but to reinforce them so that each wall works as a section composed of earth and steel. Compatibility between these two materials is ensured by passing-through ties (9.5 mm in diameter) placed every 500 mm. In addition, the retrofitting system takes into account openings of the walls by placing steel elements next to zones of stress concentrations (doors and windows). The seismic rehabilitation technique based on steel plates has been widely studied in Colombia and was included in the country's earthquake-resistant design standard through the document AIS-610-EP-2017 (AIS, 2017). This document establishes the design process and construction details for the seismic rehabilitation of historic earthen constructions (adobe and RE). Figure 1 shows an example of the seismic retrofitting applied to a one-story house (steel plates and wooden elements).

Despite the large amount of research carried out by the authors in the last 20 years on the reinforcement system with confining elements, most full-scale experimental research have focused on the behavior of one-story buildings. Furthermore, no bi-axial shaking table tests of two-story buildings typical of the architecture of the Andean zone of South America have been reported to date. However, a significant fraction of the historic earthen constructions are two-story buildings. For instance, according to the results of field research carried out by the

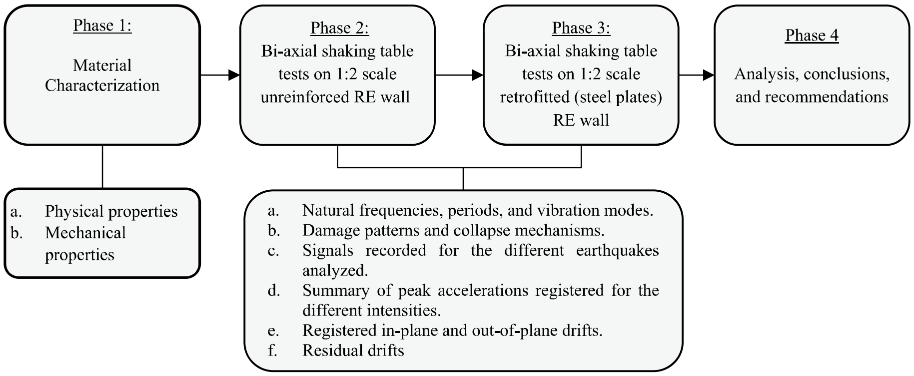

Fig. 2 Proposed methodology to assess the seismic behavior of a two-story RE wall (1:2 scale) retrofitted with steel plates

authors in the Historic Center of Bogota (HCB), 48% of the historic earthen buildings are two-story (Ruiz et al. 2023c). The novelty of this research is: (1) performing for the first time, a biaxial shaking table test of a colonial two-story wall with floor and roof elements; (2) using LIDAR technology to measure the residual displacement of the earthen wall tested; (3) performing for the first time tests of a 1:2 scale two-story RE wall retrofitted with steel strips.

2 Methodology

The methodology phases implemented to assess the seismic behavior of a two-story historic RE wall (1:2 scale model) retrofitted with steel plates are presented in Fig. 2. The phases of the research are:

Phase 1: Material characterization: Laboratory tests to evaluate the main physical and mechanical properties of the RE material were based on standardized tests (ASTM standards). The physical properties determined are Atterberg limits, granulometric parameters, moisture content, and unit weight. Mechanical properties included uniaxial compressive strength and Young's modulus. These physical and mechanical parameters were compared with the results of previous research. For the steel elements used in the retrofit technique, tensile tests were performed to determine parameters such as Young's modulus, yield stress, and ultimate strength.

Phase 2: Bi-axial shaking table tests on 1:2 scale unreinforced RE wall: To evaluate the seismic performance of an existing unreinforced RE wall, shaking table tests were performed on a 1:2 scale wall model in the structures laboratory. A biaxial shaker device was used to evaluate the in-plane and out-of-plane behavior of the wall. In these dynamic tests, parameters such as natural periods, vibration modes, and damage patterns (for different return period motions) were obtained. In addition, the instrumentation included accelerometers and laser displacement sensors to obtain acceleration records and to calculate in-plane and out-of-plane drifts for the two levels of the wall.

Phase 3: Bi-axial shaking table tests on 1:2 scale retrofitted (steel plates) RE wall: After the first RE model was tested on the biaxial shaker, another identical wall was built. This second wall was retrofitted with steel plates and tested using the same test procedure followed for the unreinforced RE wall. The results of both tests were compared to determine the improvement in the behavior of the retrofitted wall. The main parameters compared included natural periods, damage patterns, accelerations, and displacement (drifts) records.

Phase 4: Conclusions and recommendations: Based on the experimental results obtained with the dynamic shaking table tests, conclusions were drawn about the seismic performance of the retrofit system for earthen walls with confinement steel plates.

3 Mechanical and physical properties of RE material

The wall models were constructed with RE material from a demolished 120 years old house (historic building) located next to HCB RE blocks were demolished, packed and transported to the structures laboratory. In this way, the earthen material used to build the shaking table models had the same physical properties (granulometry, optimum water content, maximum dry density) as the studied historic buildings. The RE material was compacted again to build the two-story 1:2 scale models. Using this material and with the experience of construction workers from the municipality of Barichara, the models to be tested in the laboratory were built. In Barichara town, they still build houses with earth and use the construction processes and traditions available at the time of the colony of the New kingdom of Granada (currently Colombia). A mechanical and physical characterization of the material was carried out and the following properties were determined: Atterberg's limits according to ASTM D4318 standard (ASTM 2017a), granulometry using standard ASTM D422 (ASTM 2007), maximum dry density and optimum moisture content based on standard ASTM D698 (ASTM 2021). The summary of the physical characteristics determined in the laboratory is shown in Table 1. Also, compressive strength and Young modulus are presented in Table 2.

Also, Tables 1, 2 include the results obtained in past published research. In general, it is observed that while the physical properties are similar, the compressive strength and modulus of elasticity show different average values and high variability. The latter is due to the fact that these two parameters depend on the compaction process and on the workers because the process is carried out manually, as was done during the colonial and conquest periods (years 1500–1900). Current and past experimental research performed on RE materials used to construct historic buildings of the Andean zone, report lower values for compressive strength and Young modulus when compared with parameters of international

Table 1 Physical characteristics of rammed-earth

References	Atterberg's limits, %			Passing sieve, %			Maximum dry density γ_{dmax}, kN/m^3	Optimum water content w, %
	LL	*PL*	*PI*	# 200	# 50	# 4		
Yamín et al. (2007)	32	21	11	65	76	86	17	19
Reyes et al. (2020)	31	18	13	69	82	93	18	15
Ruiz et al. (2022)	33	17	16	77	91	100	16	17
Ruiz et al. (2023b)	33	17	16	78	91	100	16	17
Average present study	35	19	16	78	85	94	18	15

LL = liquid limit, *PL* = plastic limit, *PI* = plastic index