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Seismic retrofitting of rural rammed earth buildings using externally bonded fibers

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HIGHLIGHTS

- A retrofitting technique for existing rammed earth walls is proposed.
- The most suitable retrofitting materials and adhesives are selected by bonding tests.
- The technique can greatly increase the seismic behavior of the rammed earth wall.
- The proposed technique is simple and economical for implementation.

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ABSTRACT

The 2014 Mw 6.5 Ludian earthquake, in rural Yunnan Province, China, claimed 615 lives. This disaster reminds us of the importance of developing practical, inexpensive and effective retrofitting techniques to strengthen the seismic capacity of rammed earth residential dwellings in underdeveloped rural regions. This study proposes a retrofitting technique for such buildings involving externally bonded fibers. The most suitable and practical retrofitting material and adhesive were chosen based on a series of tests of candidate materials and combinations. The rammed earth wall specimens were strengthened with the proposed retrofitting technique and loaded to failure condition under in-plane shear loading. It was observed that the lateral-load capacity and ductility of the reinforced walls were greatly increased using the proposed technique.

1. Introduction

Rammed earth buildings (Fig. 1) are common in some of the world's most earthquake-prone regions, including Latin America, Africa, the Indian subcontinent and some parts of Asia, the Middle East and Southern Europe [1]. Such structures usually have thick walls made of local soil and they are often susceptible to earthquake damage because of their heavy weight, low strength and brittle behavior. In the Ludian earthquake, which struck Yunnan Province, China on 3 August 2014, more than 66,400 houses experienced severe damage or collapse. This Mw 6.5 earthquake claimed the lives of 615 people, which is extremely high for an earthquake of this magnitude. The main reason was that over 90% of the local residential houses in the earthquake-affected area were rammed earth structures, which lack basic engineering design against earthquakes. Similarly, in the 6.6 earthquake of 22 July 2013 in Gansu, China, most collapsed constructions are rammed earth or adobe buildings which caused 89 death. In the 6.6 earthquake of 26 December 2003 in Bam, Iran [2], 7.8 earthquake of 8 October 2005 in northern Pakistan [3], etc., most of earth buildings collapsed. Because the local economy remains underdeveloped, rammed earth buildings will continue to be used for a long time. Therefore, seismic retrofitting of these buildings is urgent and necessary to improve their seismic performance, particularly their ductility. This will significantly reduce casualties during earthquakes.

Much research has been undertaken to improve the seismic performance of new rammed earth buildings using various reinforcement technologies and materials (e.g., bamboo, cane, straw, fiber) [4–7]. The principle of these techniques is to improve the mechanical behavior of soils by embedding relatively high tensile strength materials in the soil. The fibers resist tensile resistance in the soil and this imparts greater strength to the soil [7].

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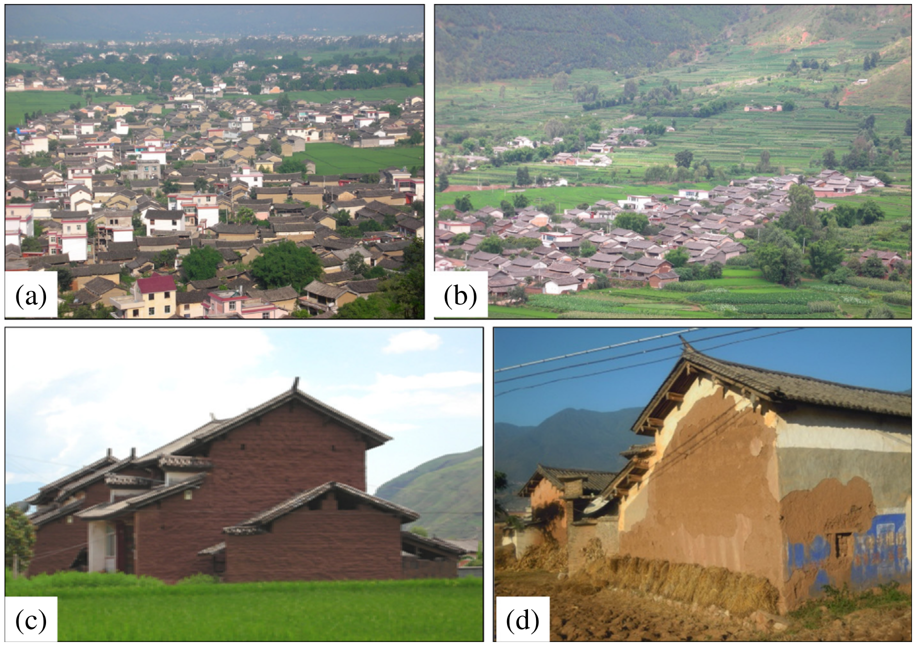

Fig. 1. Rural rammed earth dwellings in Yunnan Province, China: (a) and (b) widely distributed rammed earth structures; (c) and (d) typical rammed earth dwellings.

However, investigations and applications of seismic strengthening techniques for existing rammed earth buildings are very limited. Available techniques include reinforcement with grouting or externally welded mesh [8,9]. Applications of these techniques may be restricted because they may be expensive and involve relatively complicated processes. Recent research has shown that fiber reinforced polymers (FRPs) provide an effective and cost-efficient technique for the seismic retrofitting of masonry buildings [10–14]. In these studies, experimental program and theoretical analysis were carried out to investigate the strengthening effect of FRPs on the shear capacity of the masonry wall. By externally bonding fiber reinforced polymer on the masonry walls it was found that the shear capacity of the wall was considerably improved. The technique has several advantages over other techniques, including its low cost, ease of implementation, and low intervention with existing structures.

The aim of this study was to investigate the use of externally bonded fiber materials to enhance the seismic behaviors of existing rammed earth buildings. A series of laboratory tests have been conducted to evaluate and select appropriate fiber and bonding materials that can provide sufficient strength and compatibility with rammed earth walls. A series of wall monotonic lateral load tests (with and without reinforcement) have been conducted to validate the effectiveness of the proposed technology and materials.

2. Selection of retrofitting material and adhesive

2.1. Materials and adhesives

Fiber materials were selected based on the following six principles: (1) strength, (2) workability, (3) ductility, (4) availability and (5) cost. Several candidate fiber materials were considered and tested: canvas, bamboo shavings, and tarpaulin. The commercially available canvas and tarpaulin have a mass density of 480 g/m^2 and 680 g/m^2, respectively. The physical properties of these four fiber materials were tested and the results are shown in Table 1.

The adhesives (bonding materials) that bond the substrate and the fiber materials should have the following characteristics: (1) good permeability, (2) good shrinkage resistance, (3) sufficient strength, (4) good environmental compatibility, and (5) economic affordability. Based on these guidelines, three candidate adhesives, including epoxy adhesive, sodium silicate and NF compound[1] were selected. The mean values of mechanical properties of epoxy adhesive and sodium silicate are provided by manufactures as given in Table 2.

Table 1
Physical properties of fiber materials.

Retrofitting material	Thickness [mm]	Young's modulus [MPa]	Tensile strength [MPa]	Equivalent tensile strength [kN]
Canvas	1.195	39.20	17.64	2.108
Bamboo	0.021	10,000	59.46	0.125
Tarpaulin	0.83	128.88	49.03	4.070

The compressive strength of NF compound was tested according to ASTM c109 [15], specimens were prepared using 51 × 51 × 51 mm cubical specimens. While the splitting tensile tests were performed on cubical specimens (70.7 × 70.7 × 70.7 mm) according to BS 1881-117 [16].

2.2. Test specimens

Bond tests were carried out to characterize the mechanical and bonding performance of the selected fiber and bonding materials [17–19]. Specimens used for tests were obtained from a typical local rammed earth dwelling from a village near Kunming, Yunnan Province. The specimens had dimensions of 160 × 160 × 90 mm (Fig. 2a).

During the tests, strips of the fiber materials were bonded on the two side surfaces of the rammed earth blocks as shown in Fig. 2b. The size of the bonded zone in all specimens was 100 × 120 mm. The bonding surfaces of each specimen were roughened by grinding before the adhesive was applied. Strips of

[1] The NF compound is composed of sand, sodium silicate and hardener with a specific ratio. The application for a patent is currently in progress.