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Shake Table Test on Rammed Earth Wall Panels

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Abstract: Traditional Rammed earth houses, which possess people traditional cultures, are still widespread in rural areas of western China. However, the earth houses damage is usually serious due to its poor seismic resistance. A simple and low-cost method to reinforce the rammed earth wall is put forward in the paper. In order to test the reinforcement effectiveness, shake table testing for both the wall panels with and without structural reinforcements have been carried out. The performances of the wall panels during dynamic testing are presented and discussed briefly. The result of the test demonstrated the effectiveness of the reinforcement method on improving the seismic capacity of the rammed earth wall. The reinforcement can restrain the crack development and increase the structural integrity of the wall panels. The method can be applied to both existing and new building rammed earth houses.

Keywords: Rammed earth wall, seismic reinforcement, shake table test

Introduction

Rammed earth construction has a long and continued history in many regions of the world. Many old traditional rammed earth dwellings possess high culture and historic values, such as Hakka earth building in Fujian province listed in world culture heritage. In the rural area of western China, which is an earthquake prone area, traditional rammed earth house are still widely used, contributing to the local culture and old villages fabric. In addition to its culture values and low cost, traditional rammed earth house has other advantages, such as excellent thermal and acoustic properties. As earth is an ultimate recyclable and renewable raw material, earth house has appealing eco-friendliness characteristic, helping with sustainable management of the natural resources.

As is commonly known, however, houses built of earth are highly vulnerable to earthquake and most of the rural houses are non-engineered with poor construction quality. Gernot (2001) and Marcial et al. (2003) introduced and summarized various reinforcing methods for earth houses. In most published reinforcing measures which have been tested through dynamic tests were about masonry structure, whereas little research has been conducted on dynamic tests of rammed earth structure.

In order to investigate the seismic behaviour of rammed earth structure and study the effectiveness of reinforcing method, two scaled U-shaped rammed earth wall panels with and without reinforcement have been built and subjected to dynamic excitation using shake table. The earthquake resistance capacity of rammed earth structure can be enhanced by the application of the simple reinforcing measure, as described in the following sections.

Description of Specimens

Material and Dimensions The tested specimens were U-shaped in 1:3 scale rammed earth wall unit. They represent a wall section of an average traditional rammed earth house in Qinling mountain area in Shan'xi province. The earth material used to build the specimens was from a rammed earth construction site in a village in Qingling mountain area. To reduce material and specimen variation, both specimens were made using consistent raw materials, curing conditions and local construction practices.

The two specimens have same dimensions and configuration, while specimen A was unreinforced and specimen B was reinforced with horizontal and vertical wire mesh strips. The dimensions and configuration of the units are illustrated in Fig. 1.

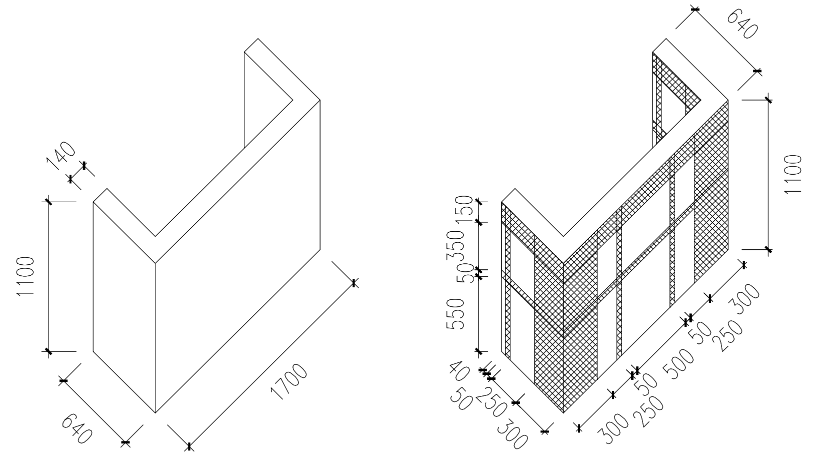

Figure1: Dimensions (mm) and configuration of specimen A (left), B (right)

Model Similitude The laws of similitude for linear elastic behavior (LinGao et al. 2000) were used for model similitude in the test. A listing of similitude ratios (the ratio of the parameters of the model to prototype) are given in table 1.

Table 1 Model scaling

Scaling parameters	*length*	*time*	*frequency*	*modulus of elasticity*	*acceleration*	*displacement*
ratio	1/3	1/3	3	1	3	1/3

Reinforcing Method The seismically reinforcing measures for the rural houses in poor area should be low cost, readily operable and easy to be transported from outside if necessary. To use of wire mesh as reinforcing method has been proved to be effective for adobe structure in Peru (Marcial Blondet etal. 2003). Limited quantity of wire mesh is light weight to be transported and low cost. The reinforcement used in specimen B was wire mesh strips covered by cement-sand mortar. According to the typical earthquake damage of rammed earth buildings only critical parts of the wall panel were chosen to be applied with wire mesh strips in order to reduce the cost. The reinforcement consist a wire mesh nailed with metallic bottle caps against the wall. The mesh strips were placed horizontally and vertically and covered with cement and sand mortar. Figure 1 shows the dimensions of the mesh strips. All the mesh strips were located on both sides of each wall. Horizontal mesh strips were fixed on both the top and middle height of the wall panel. Vertical mesh strips were fixed on the corners, the free ends of the wing walls and middle part of the long wall. With consideration of applying the reinforcement to existing earth buildings the vertical mesh strips were not fixed to concrete wall foundation but extended to the bottom of the earth wall.

Description of Dynamic Testing

The wall panels were subjected only to uniaxial motion to study the behavior of out-of-plane long wall and in-plane wing walls. Both the specimens were shaken in an east-west direction. The earthquake motion used in the tests was based on the El-centro earthquake wave (1940).

In order to study the behavior and performance of the structures at different load levels in terms of peak acceleration, each specimen was subjected to a series of simulated earthquake acceleration motions with varying acceleration intensities. The peak acceleration of each subsequent acceleration motion was 0.05g to 0.1g larger than the previous one. The tests were stopped when the wall panel nearly collapsed.

Test Results

Specimen A was an unreinforced wall panel, tested to demonstrate the vulnerability of unreinforced rammed earth walls. Table 2 gives the description of the performance at different load levels. Cracks began to form during the load level of 0.30g. The crack pattern was apparent during load level of 0.4g with the vertical crack formed of horizontal flexure in out-of-plane wall, horizontal shear cracks in the in-plane wing walls and vertical cracks in the inner corners. During the load level of 0.45g the cracks developed very fast and divided the wall panels into several sections with the cracks extending around the entire wall panel and nearly fell down and this condition is typical failure of earth structure in earthquake which can lead to life loss. The wall panel was severely damaged during the last load level as Fig. 2.

Table2 the performance of specimen A at different load levels

Peak acceleration of the input motion	*Performance comments*
0.05g~0.25g	No damage.
0.30g	Horizontal cracks initiation primarily in the middle and lower portion of the in-plane wing walls, also in the lower portion of the out-of-plane wall.
0.4g	Vertical crack in the middle of the out-of-plane wall which is typical of flexural cracking of long wall. Vertical and diagonal cracks in the corners of walls. Additional horizontal cracks formed in walls. A complete crack pattern was apparent.
0.45g	All the cracks were fully developed. The horizontal cracks extended around the entire wall panel. The vertical cracks in the out-of-plane wall and the corners extended to the bottom of the walls. Damaged in corners. The out-of-plane wall was divided into several sections and neatly collapsed. The wall sections would have fallen if not being supported and stopped test.

Specimen B As expected, the performance of the reinforced wall panel specimen B was much better than specimen A. Table 3 gives the performance of specimen B during the test. The reinforcement worked effectively to prevent and delay the cracks from forming and developing. The movement of the wall panel was restrained by the reinforcement. The ratios of maximum displacement of the top/mid-span of the out-of-plane wall (relative to shake table) of specimen B to specimen A are 60%-70% at each test level of 0.1g, 0.15g, 0.3g and 0.45g. The vertical and horizontal reinforcement helps to restrain the out-of-plane bending and in-plane shear, as well as restraining the shear stresses in the corners between adjoining walls and minimizing crack propagation. By contrast with specimen A, cracks in specimen B developed slower and most of the cracks were not severe and were seen only on one side of the wall. No severe cracks appeared in the corners of the walls for the well effectiveness of the reinforcement applied to the corners. The vertical crack appeared in the out-of-plane during the test level of 0.6g remained unchanged till the end of the test for the horizontal reinforcement preventing crack propagation. The location of the main horizontal cracking in the out-of-plane wall was generally consistent with that observed in specimen A, but the cracks were slight and discontinuous for the vertical reinforcement applying in the wall. One notable horizontal crack formed in the north wing wall for the poor bond between the mesh and the earth wall in this area, whereas only one slight crack in the south wing wall was seen till the end of the test. The cracks along the foundation opened up and the wall panel nearly overturned for during the last load level of 0.7g but the wall panel maintained as a monolithic element. Figure 3 shows the cracks in specimen B after the test.

Table3 the performance of specimen B at different load levels

Peak acceleration of the input motion	*Performance comments*
0.05g~0.25g	No damage（Note：there was 3 mm wide vertical shrinkage near the bottom of the out-of-plane wall before the test）
0.3g	Slight crack along the foundation of the south wing wall was seen
0.4g	Minor horizontal crack was seen on the outer surface of the corner
0.45g	In the lower portion of the out-of-plane wall a short minor horizontal crack was seen on the inner surface.
0.5g	Horizontal cracking in lower portion of the north wing wall (Note: in this area around 15 cm length of mesh strip was not nailed up in the wall for construction neglect). The horizontal crack initiated during the previous load level was developed and another horizontal crack was seen in the lower portion of the out-of-plane wall. Crack pattern was nearly complete.
0.6g	The mesh strip in lower portion of the north wing wall was separated from the earth wall and the crack began to open up; Minor vertical crack on the outer surface of out-of-plane wall, which was a continuation of the existing shrinkage vertical crack. Fewer slight cracks on the render surface of the reinforcements
0.7g	The horizontal cracks in the out-of-plane wall were developed; a section in the upper corner of the north wing wall dislodged and a wide diagonal crack formed extending to the foundation, the north wing wall was damaged. More horizontal cracks formed in the out-of-plane wall. The out-of-plane wall rotated about the foundation. Cracks formed and developed along the foundation of the walls. The wall panel would have overturned outward holistically if not stopped test whereas the wall panel still kept integrity.

Figure 2: specimen A after test

Figure 3: specimen B after test

Conclusion

In exploring the seismic behavior of the rammed earth wall panels and evaluating the effectiveness of the reinforcement, the following conclusions were drawn from the tests:

The shake table testing proved the reinforcing method used in specimen B to be an effective means of improving the seismic capacity of rammed earth wall panel. Specimen B performed much better than specimen A, passing higher load levels and exhibiting less movement and slighter cracks. Both of the stability and integrity of the wall panel were improved with the reinforcement applying. The wall panel was divided to several cracked sections and nearly fell down when the cracks fully developed in the specimen A, whereas specimen B maintained monolithic till the end of the test.

In specimen B the reinforcement was not tied to the foundation, leading to the last failure during the last load level test. In practice the vertical reinforcement strips should be extended and fixed to the wall foundation when building new earth houses in order to be more effective on preventing overturning or sliding on the interface between the earth wall and the foundation.

In both specimens all the severe horizontal cracks were located in the interface between the rammed earth layers for lack of cohesion and friction, thus for traditional rammed earth construction small vertical interior reinforcement element such like wood is recommended to be applied to interlock the adjacent earth layers.

In addition to the effectiveness of improving the seismic capacity, the reinforcing measure is simple and low-cost, which makes it applicable for the rammed earth house reinforcing in rural poor area.

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