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P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

FRP Mesh Technique for Retrofitting Historical Structures: A Proposal

H.C. Uzoegbo
University of Wits, School of Civil Engineering, Johannesburg, South Africa

R. Senthivel
University of Minho, Department of Civil Engineering, Guimarães, Portugal

A. Madan
Department of Civil Engineering, Indian Institute of Technology, Delhi, India

ABSTRACT: Shaking table tests is the most powerful method for assessing the seismic capacity of buildings. The tests can avoid a series of technical difficulties such as the establishment of motion equations of the non-linear system and their solutions. Not only the seismic responses of buildings were obtained from the test but the damages of buildings can be visually observed. A single story dry stack interlocking block masonry building system was designed, constructed on a specially designed shaking table at the Spoornet Laboratory in Johannesburg, South Africa. The building was subjected to a series of simulated earthquake ground motions ranging from minor to severe. The damaged building was repaired and retrofitted using fibre reinforced polymer (FRP) mesh technique, and retested under the similar loading conditions. It was found that the retrofitted structure exhibited more ductile response and better resistance to dynamic (seismic) loading. This paper presents experimental test program, test results, evaluation and conclusions. Based on the test results and performance of the present technique, recommendations are made to extent this technique to retrofit the historical structures.

1 INTRODUCTION

The primary function of masonry elements is to sustain vertical gravity load. However, structural masonry elements are required to withstand combined shear, flexure and compressive stresses under earthquake or wind load combinations consisting of lateral as well as vertical loads. A large number of historical masonry buildings in Portugal are built with dry stacking technique (without bonding mortar). The technique of dry stacking in construction has existed in Africa for thousands of years. The Egyptian pyramids and the Zimbabwe ruins, a capital of ancient Shona Kingdom around 400AD, are good examples. Recent and past earthquakes have shown that dry-stack mortarless historical masonry buildings are seismically most vulnerable; therefore, the demand for retrofitting strategies of these buildings has become increasingly stronger in the last few years. Numerous conventional techniques have been applied for retrofitting of existing masonry buildings (ElGawady et al. 2004a and 2004b). Potential disadvantages of these techniques (e.g. heavy mass, limited efficiency, etc.) have been reported. Most of the existing retrofitting solutions require significant investment and major structural changes which makes owners reluctant to install any form of protection against earthquakes. FRP retrofitting techniques is one of the commercially available techniques and this technique provides a very simple method of installing the ultimate earthquake protection system for a relatively low investment and unparalleled protection against earthquakes when masonry is both retrofitted and reinforced using stiff polymer grid. To evaluate the structural performance of this technique, a single story dry stack masonry building system was designed, constructed on a specially designed shaking table at the Spoornet Laboratory in Johannesburg, South Africa. The building was subjected to a series of simulated earthquake ground motions ranging from minor to severe. The damaged building was repaired and retrofitted using the FRP technique, and retested under the similar loading conditions. It was found that the retrofitted structure exhibited more ductile response and better resistance to dynamic (seismic) loading. This paper presents experimental test program, test results, evaluation and conclusions. Based on the test results and performance of the FRP technique, recommendations are made to extent this technique to retrofit the historical structures.

2 EXPERIMENTAL TEST PROGRAM

2.1 Test Structure

Typical interlocking blocks used in this experimental investigation are shown in Figure 1 (Hydraform 1996). The wall structures were built according to the guidelines given in the Hydraform user manual (Hydraform, 1996). A uniformly distributed roof load of 0.75 kN/m^2 was simulated by placing reinforced concrete (RC) beams on top of the in-plane walls. The test structure before testing is shown in Figure 2a. More details about the test structure can be found elsewhere (Senthivel 2004).

2.2 Retrofitting of Tested Structure

The structure shown in Figure 2a was tested under series of simulated earthquake ground motions up to failure. Figure 2b shows the structure after the test. The failure was by falling of blocks in the top area and bending. The damaged top courses from the lintel level were completely removed and the mid courses were set right from the out of plumb using a soft hammer, and then top courses from the lintel level were replaced, and retrofitted with a commercially available fibre reinforced polymer mesh/ grid. The mesh was wrapped around the top courses and nailed to the wall using special nails supplied by the manufacturer and plastered. Figure 3 shows a typical method of retrofitting with fibre reinforced polymer mesh/ grid retrofitting Techniques. More details about the retrofitting procedures can be found elsewhere (Richter-Gard^{TM}, 2006). The roof load was simulated with the same RC beams and railway sleepers used in the virgin test structure. The retrofitted structure before testing is shown in Figure 4a.

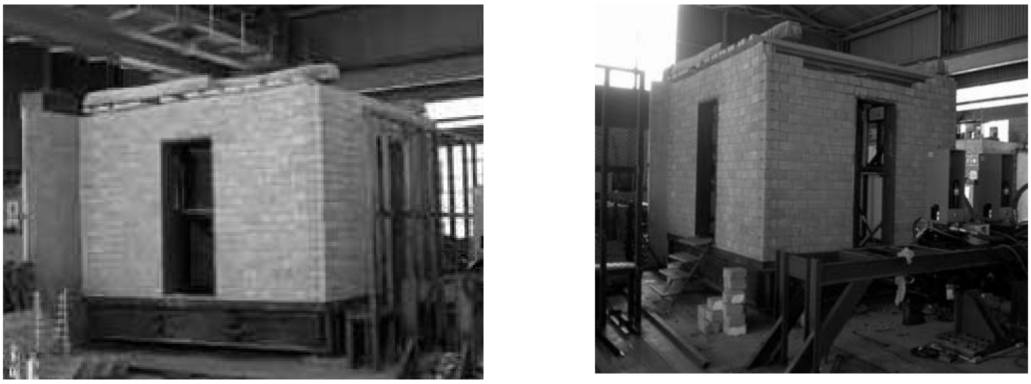
2.3 Instrumentation and Data Acquisition

A uniaxial shaking table has been designed, fabricated and mounted on recirculation roller type linear bearing at the Spoornet laboraroty of the South African Railway Corporation in Johannesburg. The size of the square table is 4m x 4m and 0.5 thick with associated hydraulic actuator and control system supplied by Material Testing System (MTS) Corporation. The test structures were instrumented with LVDTs (Linearly Variable Differential Transducers) and Accelerometers to measure the response of the structure at the bottom, middle and top of both in in-plane and out of plane walls. Figure 5 shows the numbering of the measuring points and loading direction. At each point, there is an Accelerometer and a LVDT named A and L respectively. Accelerometers were fixed to the wall to measure the vibration of the structure. LVDT measures the displacement. Displacement of the structures relative to the shaking table was measured from the rigid octagonal reference frame located inside the structure. The frame was well braced and extremely stiff. A Pentium based real time data acquisition and control software system called TLC was used to display, monitor and record the load/ stroke, displacement and acceleration measurements in real time.

2.4 Test Procedure

The structures were subjected to a series of unidirectional base motions for twenty seconds each which varied in intensity from minor (0.05g) to extremely sever (>0.6g). The shake table runs records for non-retrofitted and retrofitted test structures are given in Table 1. Figure 6 shows a typical displacement and acceleration histories of shaking table at 1 Hz and 0.3 g.

(a) block type-I (b) block type-II
Figure1 : Dry-stack block units



(a) before testing (b) after testing
Figure 2 : Non-retrofitted test structure

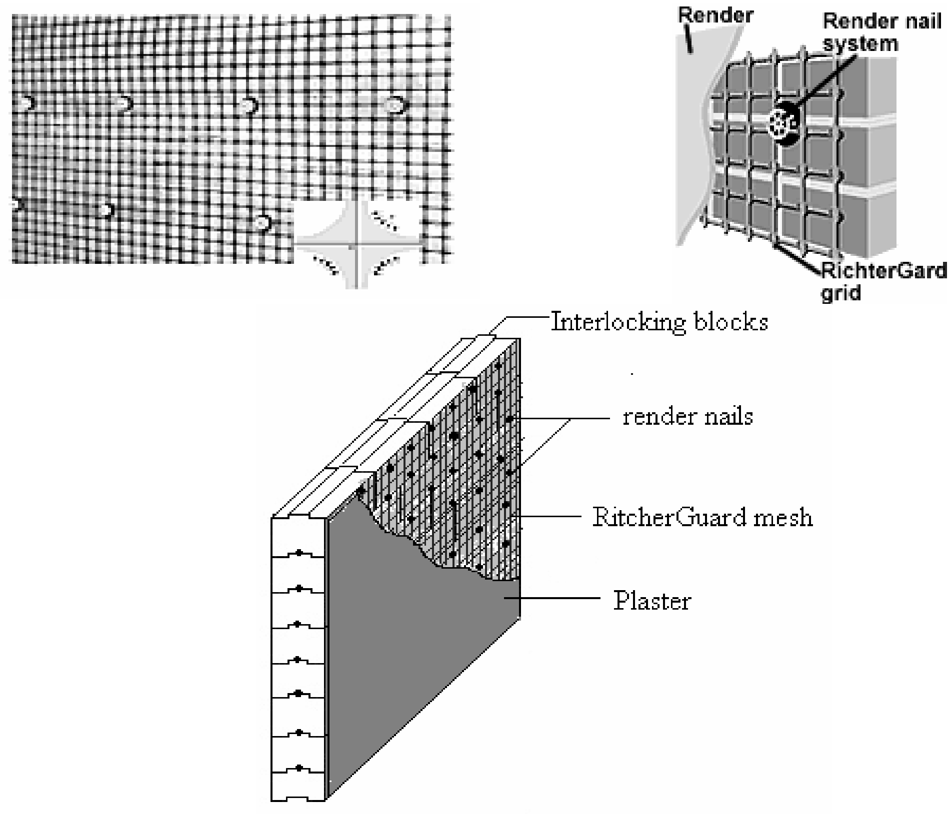


Figure 3 : Details of FRP Retrofitting Techniques

(a) before testing

(b) after testing

Figure 4 : Retrofitted test structure

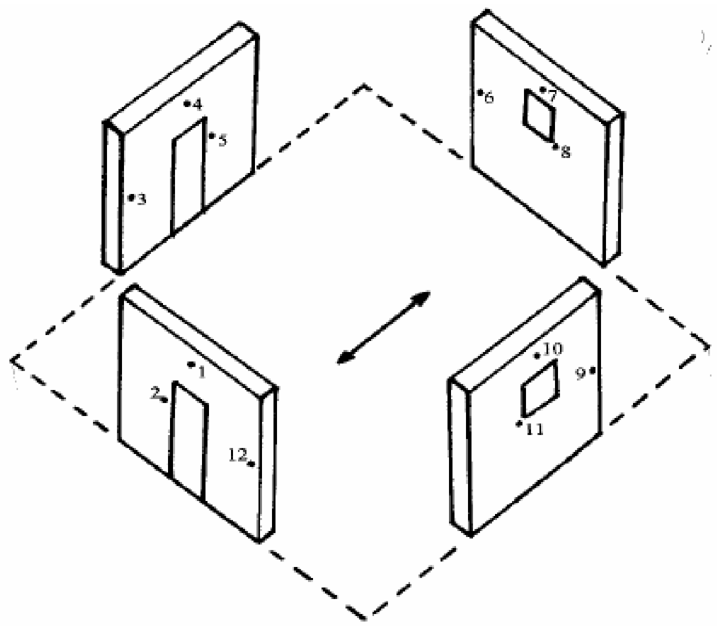


Figure 5 : Instrumentations and loading direction

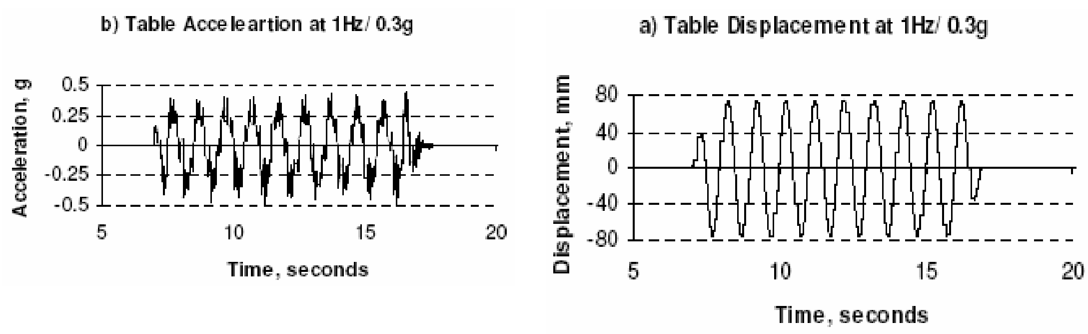
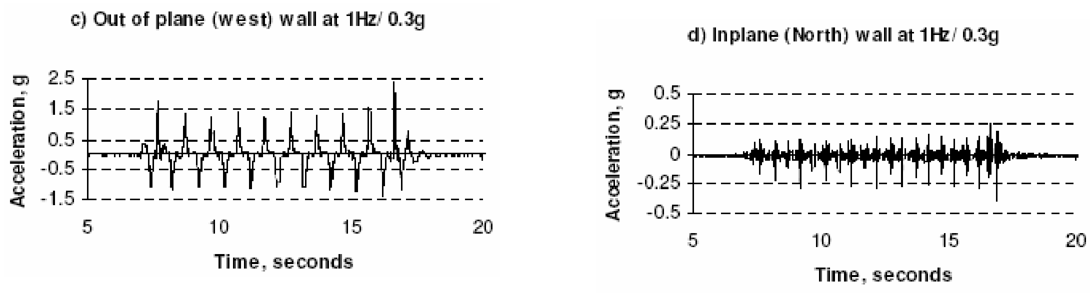


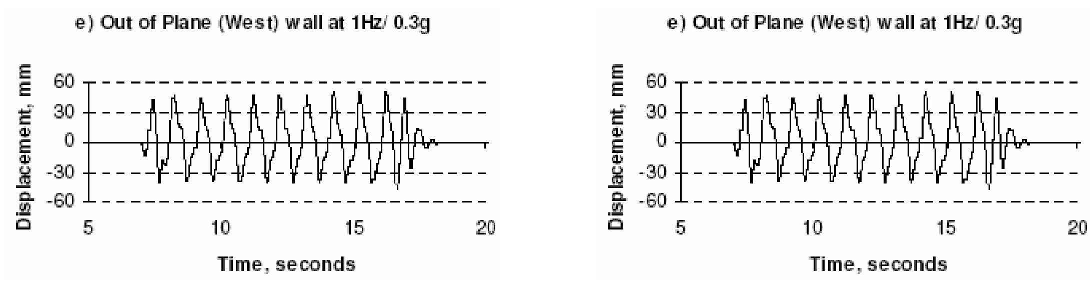
Figure 6 : Acceleration and displacement history of shake table

3 TEST RESULTS AND PERFORMANCE EVALUATION

It can be seen from the Table 1 that the tests were generally conducted in changing the table displacement with different frequency and acceleration. A trial test shows that the natural frequency of the structure is about 10 Hz. The non-retrofitted structure shown in Figure 2a was subjected to 31 test run as summarized in Table 1a. Test runs 1-7 caused no visible damage. Test run 8 produced hairline cracks on the plastered surface of the out of plane walls. Falling of plaster in some places of out of plane wall was observed after test run 18. Test run 23 caused a diagonal crack on the in plane wall. Widening of the diagonal crack was noticed for the rest of the test runs. Failure in the top courses and falling of units from the out of plane walls was occurred during test runs 30-31 and the test was concluded. Figure 2b shows the structure after the last test run. Figure 7 shows the displacement and acceleration history of in plane and out of plane wall at just one run before failure i.e. frequency, 1 Hz and acceleration, 0.3 g. The damaged structure was retrofitted (Figure 4a) and subjected to 41 test runs as summarized in Table 1b. Test runs 1-13 caused no damage. Initial failures of bond due to excessive deflection at mid span of out of plane walls were observed after test run 14. Openings in the head joint in some places of in plane and out of plane walls were observed after test run 22. The progress of above failure was seen in the subsequent test runs. Major bond failure and separation of mesh and the out of plane wall were seen after test run 41 and the test was concluded. Figure 4b shows the retrofitted test structure after the last test run. Table 2 shows the structural response including peak displacement and acceleration of the structure before and after retrofitting.



(a) Acceleration history



(b) displacement history

Figure 7 : Acceleration and displacement history of non-retrofitted test structure

4 DISCUSSION AND CONCLUSIONS

The structure before retrofitting failed at loading of 0.3 g which is equivalent to 4.3-4.8 on the Richter scale and V on the MMI scale. From Table 2, it can be seen that the retrofitting modifies the structural response from brittle to ductile. It is because of the flexible fibre used in retrofitting. The retrofitted structure was elastic and displaces more during shaking and comes back to original position once shaking is stopped. It is capable of resisting acceleration up to 0.7 g which is 7.4-8.1 on the Richter scale and XI on MMI scale. The test results lead to the following conclusions: a) the failure of non-retrofitted structure was due to brittle nature of the masonry block and excessive displacement at the top courses of the out of plane walls; b) the fibre mesh used for retrofitting increases the flexibility of the masonry from brittle to ductile. It acts as a ring beam/ band and holds the structure together; c) retrofitted dry-stack masonry structure can resist earthquakes over 7.4 on the Richter scale.

Table 1a : Shake table test run record for non-retrofitted test structure

Run no.	Peak table acceleration (g)	Frequency (Hz)	Peak table displacement (mm)
1		1	12.67
2		2	3.17
3		3	1.41
4	0.05	4	0.79
5		5	0.51
6		6	0.35
7		7	0.26
8		1	25.33
9		2	6.33
10		3	2.81
11		4	1.58
12		5	1.01
13	0.1	6	0.70
14		7	0.52
15		8	0.40
16		9	0.31
17		10	0.25
18		11	0.21
19		1	50.49
20		2	12.62
21		3	5.61
22		4	3.16
23	0.2	5	2.02
24		6	1.40
25		7	1.03
26		8	0.79
27		9	0.62
28		10	0.50
29		11	0.42
30		30	75.73
31		31	18.93

Table 1b : Shake table test run record for retrofitted test structure

Run no.	Peak table acceleration (g)	Frequency (Hz)	Peak table displacement (mm)	Run no.	Peak table acceleration (g)	Frequency (Hz)	Peak table displacement (mm)
1	0.05	1	12.67	22		2	25.24
				23		3	11.22
2		1	25.33	24		4	6.31
3		2	6.33	25		5	4.04
4		3	2.81	26	0.4	6	2.80
5		4	1.58	27		7	2.06
6	0.1	5	1.01	28		8	1.58
7		6	0.70	29		9	1.25
8		7	0.52	30		10	1.01
9		8	0.40				
10		9	0.31	31		3	14.02
11		10	0.21	32	0.5	4	7.89
				33		5	5.05
12		1	75.73	34		6	3.51
13		2	18.93	35		7	2.58
14		3	8.41	36		8	1.97
15		4	4.73				
16		5	3.03	37		3	16.83
17	0.3	6	2.10	38	0.6	4	9.47
18		7	1.55	39		5	6.06
19		8	1.18	40		6	4.21
20		9	0.93				
21		10	0.76				
				41	0.7	3	19.63

Table 2 : Response of in-plane (IP) and out of plane (OP) walls

	Non-retrofitted			Retrofitted test structure				
	1 Hz @ 0.3 g			1 Hz @ 0.3 g		3 Hz @ 0.7 g		
	Table	OP wall	IP wall	OP wall	IP wall	Table	OP wall	IP wall
Peak displacement (mm)	75.73	50.5	0.70	96.63	1.42	19.63	23.73	1.91
Peak acceleration (g)	0.45	2.37	0.30	1.86	0.75	1.36	2.5	1.91

The basic philosophy of retrofitting is to improve ductility within masonry structures. Ductility is, according to Eurocode 2, the extra reserve within a structure. This is particularly relevant in critical conditions such as earthquakes. Dry stack historical masonry structures are commonly built of blocks without bonding mortar, which has no ductility at all. This makes the potential problem even more severe. FRP provides a major improvement to the ductility of masonry structures, greatly increasing the level of safety. The polymer grids have unique properties due to its patented production method. This result in an almost perfect shape, according to Bernoulli's principle, giving the following combination of properties: a) High strength at low strain, b) High junction strength, c) Stiff apertures and ribs and d) Rectangular rib shape. This results in a particularly high torsional stiffness, which provides major load distribution through the junctions and the ribs thus preventing high local stresses which cause initial failure of the masonry, causing a chain reaction. FRP can provide all the resistance required for sound antiseismic design, but its application does not exclude cooperation with other structural systems. Resulting configurations can enhance safety and cost effectiveness.

Based on the above experimental test results and structural performance of the FRP technique, it is recommendation by authors to extent this unique technique to retrofit the historical structures located in earthquake prone areas.

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