JOURNAL OF ENGINEERING
annals OF
FACULTY OF ENGINEERING HUNEDOARA
Tome V (year 2007), Fascicole 1, (ISSN 1584 – 2665)

EXPERIMENTAL INVESTIGATIONS ON THE MUSTAFA PASHA MOSQUE LARGE SCALE MODEL

[1]Lidija KRSTEVSKA, [2]Ljubomir TASHKOV, [3]Federico Mazzolani

[1,2]UNIVERSITY "SS. CYRIL AND METHODIUS", SKOPJE, MACEDONIA
INSTITUTE OF EARTHQUAKE ENGINEERING AND ENGINEERING SEISMOLOGY
[3]UNIVERSITY OF NAPLES "FEDERICO II", NAPLES, ITALY
ENGINEERING FACULTY, DEPARTMENT OF STRUCTURAL ANALYSIS AND DESIGN

ABSTRACT:
The experimental results presented in this paper are a part of the activities performed within the Sixth Framework Program PROHITECH - "Earthquake Protection of Historical Buildings by Reversible Mixed Technologies". For the selected prototype structure - historical monument Mustafa Pasha Mosque in Skopje, a 1/6-scale model was constructed and tested on seismic shaking table in several phases. The objective of the experimental model testing was to investigate the seismic stability of the monument after applying a reversible strengthening technology. It was concluded that the behaviour of the strengthened model was evidently different from that of the original model.
KEYWORDS:
Shaking table, scaled model, seismic response, strengthening

1. INTRODUCTION

Shaking table testing of the large-scale model of the Mustafa Pasha mosque in Skopje, (15th century) was performed in the Laboratory of the Institute of Earthquake Engineering and Engineering Seismology in Skopje in the period November-December 2006. The main objective of the tests was to investigate experimentally the effectiveness of the proposed reversible technology for strengthening of this type of historical monuments. The performed testing was a part of the activities within the Sixth Framework Programme PROHITECH - "Earthquake Protection of Historical Buildings by Reversible Mixed Technologies".

2. METHODOLOGY OF EXPERIMENTAL INVESTIGATION

The model of the mosque was constructed to a length scale of 1:6 according to the "gravity forces neglected" modeling principle, using the same materials as those of the prototype: stone, bricks and lime mortar. The experimental testing was performed on the bi-axial seismic shaking table at the IZIIS' Laboratory. Following the main objective, the testing was performed in three phases:
1) Testing of the original model under low intensity level, to provoke small damage;

2) Testing of repaired model and strengthened minaret with FRP, until total collapse of the minaret;
3) Testing of strengthened model with FRP and carbon fiber bars until collapse.

3. INSTRUMENTATION OF THE MODEL

To investigate the model's response during seismic action, different types of transducers were placed at characteristic points - accelerometers, linear potentiometers and LVDTs, as presented in Fig.1.

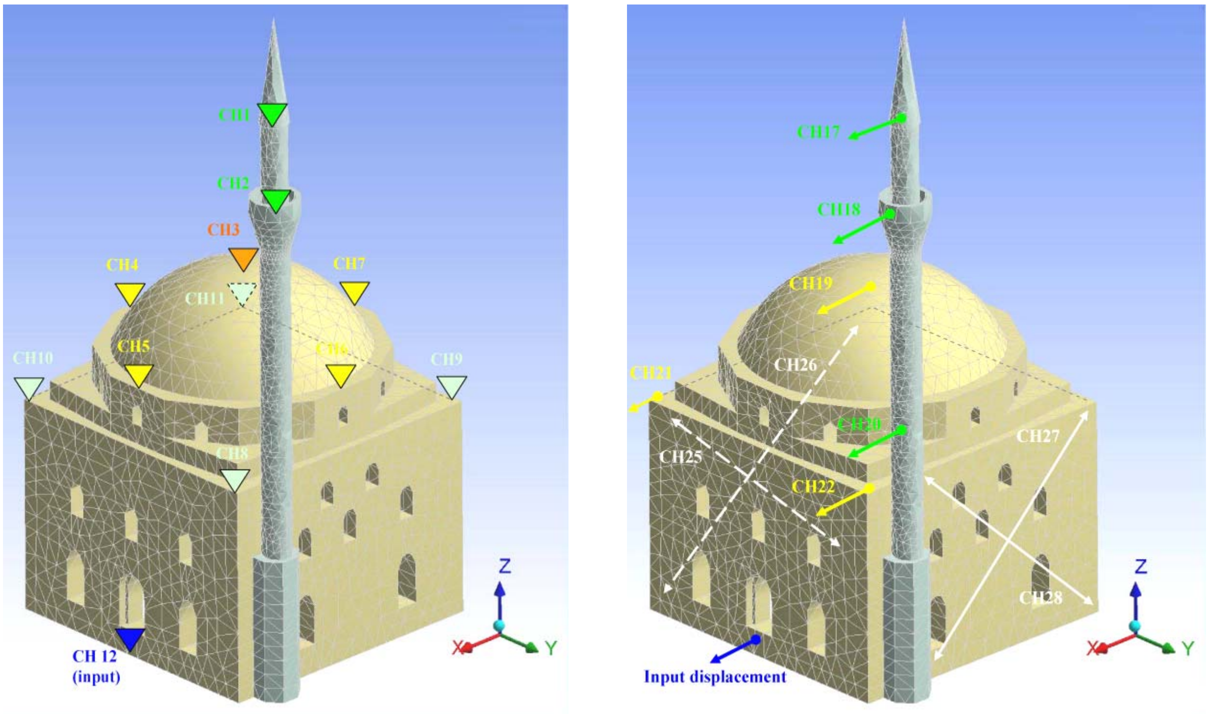

Figure 1. Instrumentation of the mosque model with accelerometers and displacement transducers

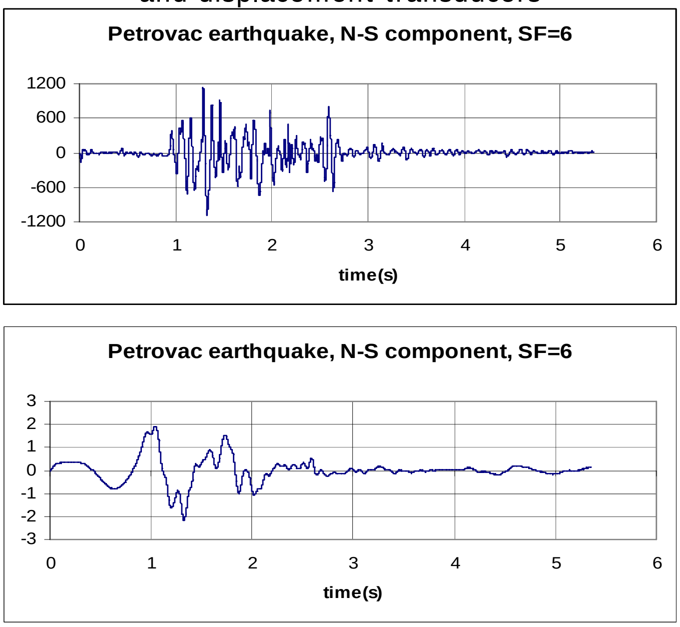

Figure 2. Time histories of acceleration and displacement, earthquake excitation Petrovac, N-S component

4. PHASE 1- TESTING OF THE ORIGINAL MODEL

Before starting the seismic testing, the dynamic characteristics of the model were defined by means of ambient vibration method as well as by low intensity random excitation within the frequency range of 0.1-50 Hz [1]. The accelerogram of the Montenegro earthquake of 1979 (Petrovac N-S component) was selected as a representative earthquake excitation. The acceleration and displacement time histories of the input excitation are given on Fig. 2.

The earthquake time histories were scaled (compressed) 6 times, according to the similitude requirements and several tests were performed with intensity of 0.01- 0.10g. Under input intensity of 2%g, the first horizontal crack appeared at the base of the minaret. In the next tests performed under intensities of up to 10%g, damage occurred on the mosque, too. The reason of this was the frequency content of the applied excitation, which was close to the natural frequencies of both the minaret and the mosque. The damaged model is presented in Fig. 3, while some representative response parameters for input intensities of 2%g and 10%g are given in Fig. 4.

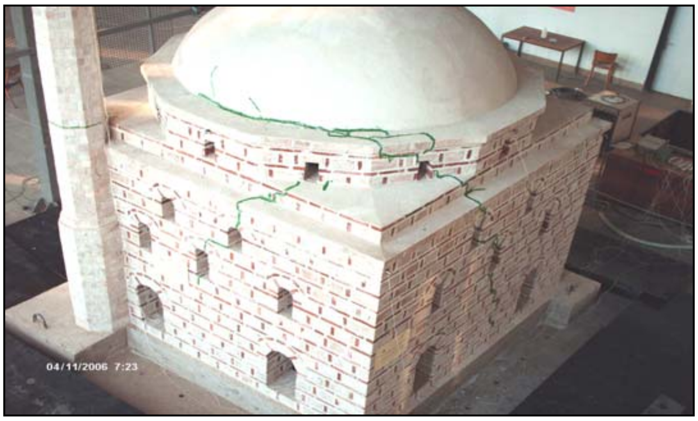

Figure 3. Damage to the minaret (horizontal crack) and the mosque after phase 1

5. STRENGTHENING OF THE MINARET

After performing the seismic tests on the original model of the mosque, the damaged model was repaired by crack injection and the minaret was strengthened by application of CFRP wrap [2], cut to have the corresponding width and applied upon a layer of epoxy glue, Fig. 5. The obtained strips with a width of 15 cm were placed on four sides along the length of the minaret in vertical direction for the purpose of its stiffening. To confine the structure, strips with a width of 10 cm were placed at four levels along the height of the minaret in horizontal direction, while a strip with a width of 20 cm was placed at its base.

6. PHASE 2 - TESTING OF REPAIRED MODEL AND STRENGTHENED MINARET

Before the seismic tests, the dominant frequencies of the model were checked by random excitation. The dominant frequency of the minaret was 4.7Hz, while the dominant frequencies of the mosque were f=7.4Hz and f=9.6Hz.

During this testing phase, 11 tests were performed with input acceleration between 0.2g to 1.5g. The first cracks on the minaret occurred under input intensity of 0.34g, which indicated that the applied strengthening enabled stiffening of the minaret and increasing of its bending resistance.

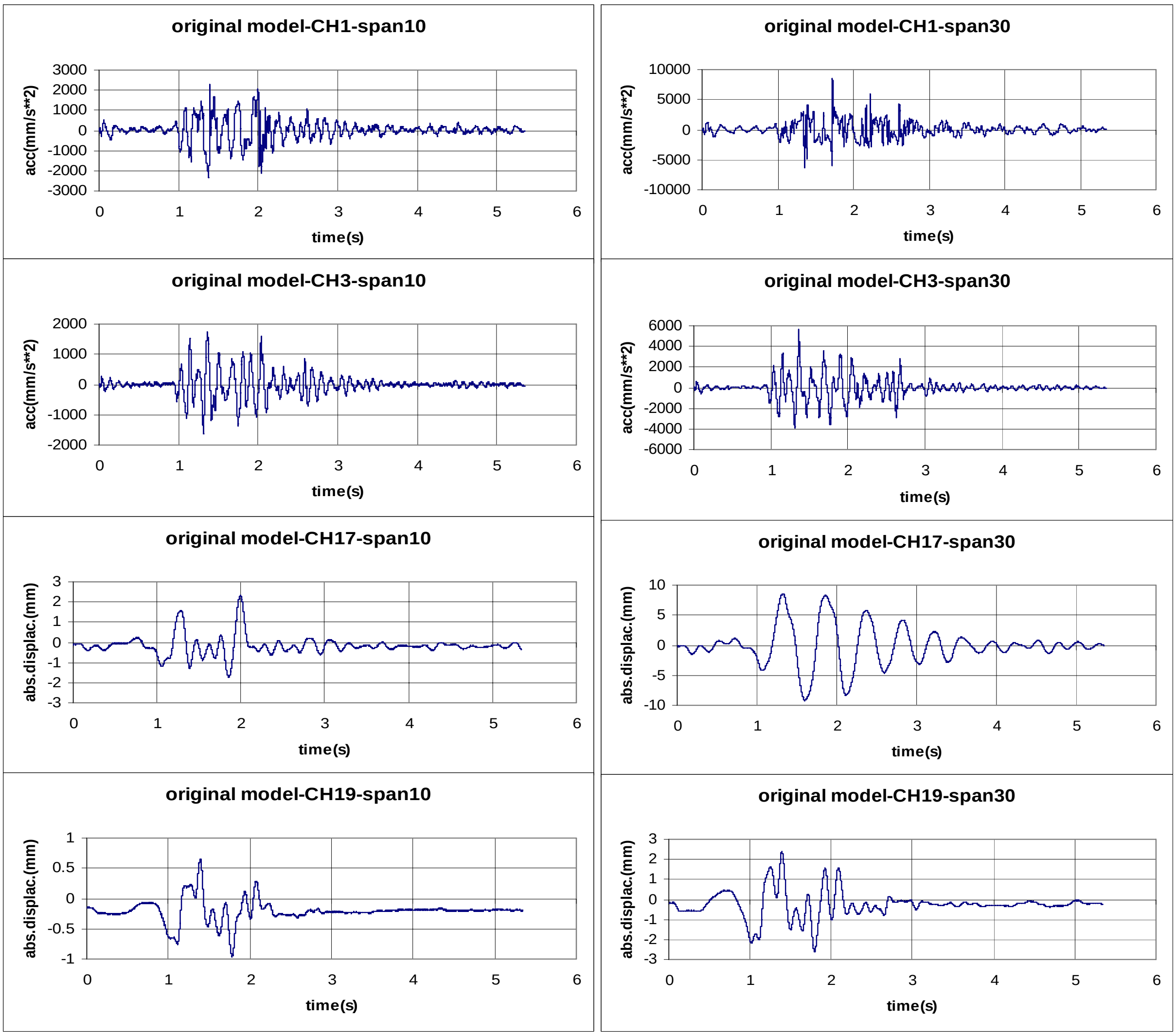

Figure 4. Characteristic response time histories under input intensity of 2%g (left) and under input intensity of 10%g (right), original model

Figure 5. Repaired model and strengthened minaret after phase 1 testing

The initial cracks in the mosque appeared under input intensity 0.42g. During the next tests, the cracks developed and at input level of 0.49g, the upper part of the minaret totally collapsed, Fig. 6. After reaching the max input acceleration of 1.5g, the mosque model was heavily damaged and the testing was stopped. There were cracks in the walls and also in the dome. Some details of the damage are presented on the photos displayed in Figs. 7 and 8. The characteristic response parameters during the seismic tests are given in Table 1, while the representative time histories for the test with intensity of 0.34g and for the final test with an input intensity of 1.5g are given in Figs. 9 and 10, respectively.

Table 1. Performed seismic tests, phase 2

Test No	Inp. acc (g)	Top acc. (minaret)	Top acc. (dome)	Input displ. (mm)	Top displ. (dome)
1	0.2	0.65	0.4	2.24	2.3
2	0.28	0.82	0.6	3.3	3.3
3	0.34	1.7	0.7	4.0	4.0
4	0.42	-	1.0	4.7	5.0
5	0.49	-	0.88	5.48	6.4
6	0.53	-	0.9	6.1	7.5
7	0.58	-	1.0	7.0	8.9
8	0.65	-	0.96	9.1	12.4
9	1.05	-	1.1	11.4	14.7
10	1.4	-	0.7	13.9	18.8
11	1.5	-	0.54	15.3	22

Figure 6. Collapse of the upper part of the minaret

Figure 7. Damaged model after phase 2 testing

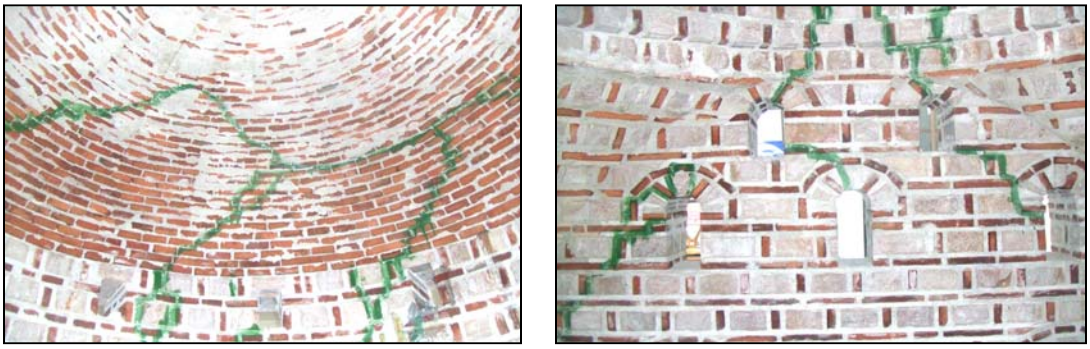

Figure 8. Damage of the mosque, interior

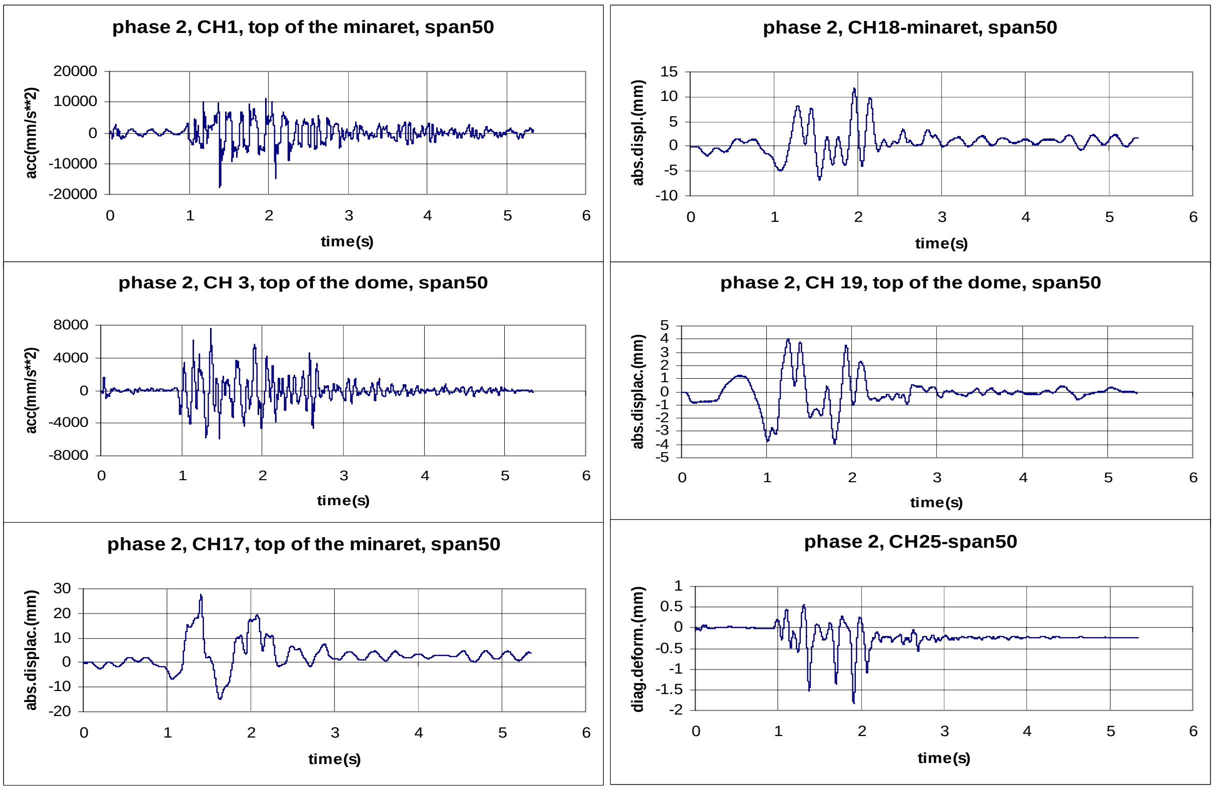

Figure 9. Characteristic response time histories for input intensity 34%g, phase 2

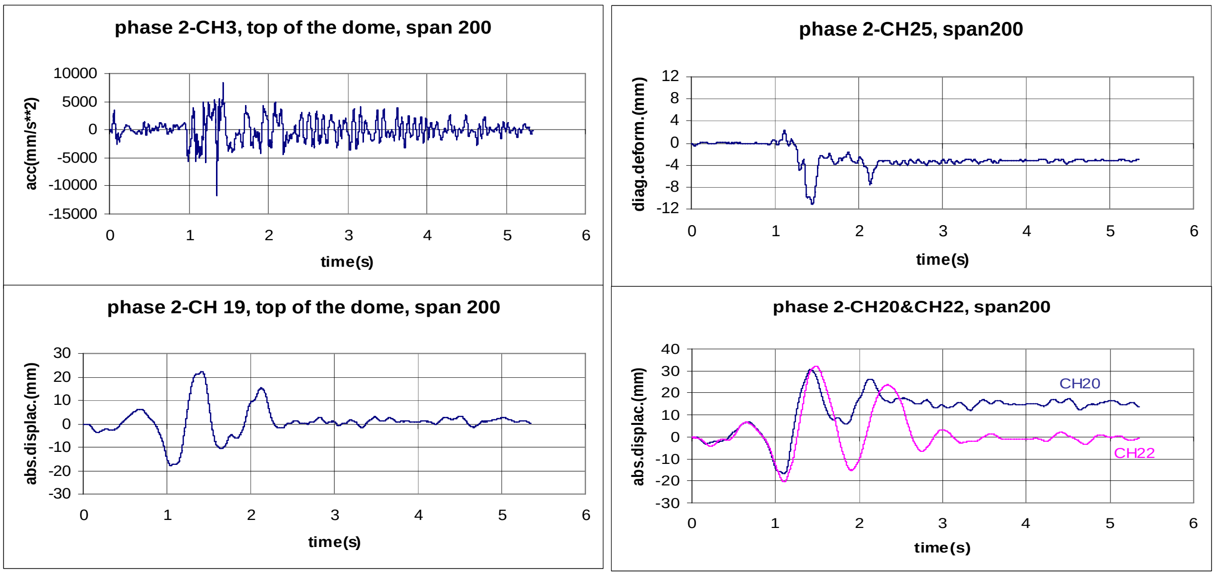

Figure 10. Response during the test with intensity 1.5g, phase 2

7. STRENGTHENING OF THE MOSQUE MODEL

After the final test of the model in phase 2, the minaret was removed and the damaged parts of the mosque were rebuilt, Fig. 11. Then the model was strengthened [3]. The main adopted principle in strengthening of the model was that the methodology to be applied be reversible and invisible. Hence, the cracks in the damaged model were not repaired by injection, but a concept was adopted that the model be strengthened to the conditions after the preceding tests.

The strengthening consisted of incorporation of horizontal belt courses for the purpose of increasing the integrity of the structure at those levels and providing as better as possible synchronous behaviour of the bearing walls:

- Incorporation of carbon rods in two longitudinal mortar joints around the four walls at two levels: the level above the openings and at the top of the bearing walls, immediately below the tambour. For that purpose, the mortar in the joints was first of all grooved down to the depth of 1.5 to 2 cm and such an obtained surface was fixed by a corresponding material (primer). After curing, longitudinal carbon rods were placed in the joints of each facade of the bearing walls. At both ends, these rods were cantilevered for about 25 cm in order that they could cautiously be bent and attached to the rods of the adjacent walls. Then the grooved part of the joint was filled with epoxy resin. To strengthen the corners where the carbon rods are bent and have a lower bearing capacity, a carbon strip with a length of 25 cm was placed upon the resin. With the incorporation of these carbon rods, a horizontal belt course was formed whereby the tensile resistance of the wall was improved and synchronous behaviour of the bearing walls was achieved.
- Formation of a horizontal belt course around the tambour by applying a CFRP wrap with a width of 10 cm. After the application and the drying of the layer used for fixation of the masonry (primer), a thicker layer of epoxy glue (~3-4 mm) was applied for gluing the CFRP wrap upon it. To impregnate the strip, it was cautiously glued to the lower layer of resin by means of rollers. Finally, another layer of epoxy glue was applied and the entire surface was treated with the roller again.
- Formation of a horizontal belt course at the base of the dome by use of a CFRP wrap. The procedure for the formation of this belt course was identical to that used for the tambour except that the wrap had a width of 50 cm.

The formation of these horizontal belt courses enabled better integrity of the tambour and the dome base and prevented “opening” of the dome which was the most common reason for occurrence and prolongation of cracks in the bearing walls. The strengthened model and some details of strengthening are presented in Fig. 12.

Figure 11. Re-built part of the model after removal of the minaret

Figure 12. Details of strengthening and strengthened model ready for testing, phase 3

8. PHASE 3- TESTING OF STRENGTHENED MOSQUE MODEL

Before the seismic tests, the dominant frequencies of the model were checked. The resonant frequency of 9.2 Hz was obtained and it was compared to the frequency of 8.6Hz measured after the last test of testing in phase 2. This pointed out that strengthening had increased the resonant frequency of the model for about 8%, meaning that the stiffness of the model hadn't been recovered completely compared to the initial state.

Figure 13. Damage of the model after phase 3 tests accomplishement

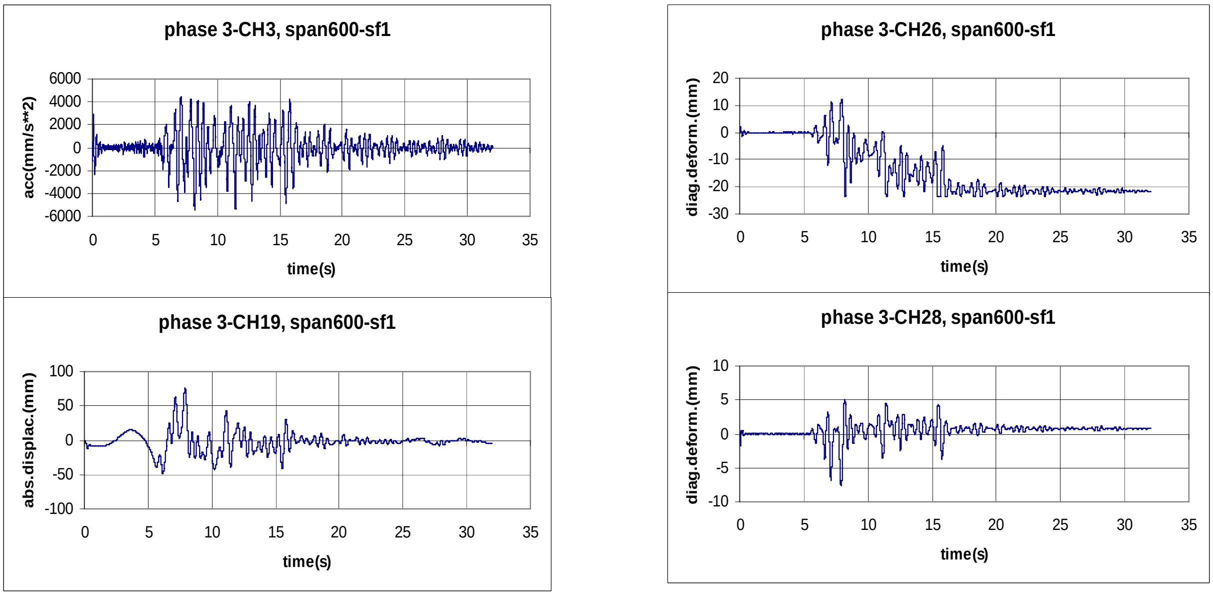

Figure 14. Response of the model during the last test with intensity 0.35g, scaling factor 1, phase 3

During this phase, 24 tests were performed under input acceleration between 0.15g to 1.5g [4]. The accelerogram of the Petrovac earthquake (N-S component) was scaled by 6 (compressed) in the first 15 tests. During the tests performed under input intensities between 0.15g and 0.40g. the model's behaviour was stable, without provocation of large cracks. In the next 6 tests carried out under input acceleration of 0.60-0.80g, the dome experienced sliding at a visible horizontal crack at its base. To provoke more intensive response of the model, in the next tests, a time scaling factor of 3 was used, producing an input acceleration of 0.46-1.5g. In this series of tests, many new cracks appeared in the walls as well as in the dome, decreasing the dominant frequency of the model to f= 4.4Hz. This value was more than twice lower compared to the initially measured frequency of 9.2 Hz, thus indicating a pre-collapse state of the model.

Table 2. Performed seismic tests, phase 3

Scaling factor	Inp. acc (g)	Top acc -dome	Inp. displ.(mm)	Top displ.(mm)
6	0.14	0.30	1.5	1.5
	0.18	0.35	2.0	2.0
	0.25	0.42	3.0	3.0
	0.29	0.50	3.5	3.5
	0.35	0.59	4.0	4.3
	0.38	0.65	4.7	5.0
	0.40	0.75	-	-
	0.42	0.85	6.8	7.7
	0.67	1.60	7.2	8.5
	0.87	1.70	10.6	14.0
	0.82	1.55	10.0	14.4
	0.90	1.70	11.0	16.0
	0.80	1.3	12.6	16.7
3	0.20	0.60	7.8	13.0
	0.46	0.93	15.0	22.0
	1.20	1.10	25.0	26.8
	1.5	1.0	30.0	40.0
2	0.15	0.40	8.4	12.0
	0.75	0.70	27.0	35.0
	1.00	0.80	45.0	52.0
1	0.35	0.53	58.0	75.0

The next two tests were performed by a scaling factor of 2, under an input acceleration 0.75-1.0g. Progressive cracks appeared, but still without collapse. The final test was performed by a scaling factor of 1, under an input acceleration of 0.35g. Heavy damage occurred in many places on the dome and around the openings as well as big cracks and inclination of one corner of the model, including damage to the strengthening FRP belt at the lower level of one of the walls, after which the testing was stopped.

The damaged model and some details of damages are presented in Fig. 13. The characteristic response parameters during the seismic tests are given in Table 2. The representative time histories in the final tests are given in Fig. 14.

8. CONCLUSIONS

The experimental testing of Mustafa pasha large scale model was performed to investigate the seismic stability of the monument after applying a reversible strengthening methodology, both for the minaret and for the mosque.

The strengthening applied to the minaret enabled stiffening and increasing of its bending resistance.

The mosque model's behaviour after strengthening was evidently different in respect to that of the original model. Under tests of moderate intensity, the existing cracks were activated but during the subsequent more intensive tests, the failure mechanism was transferred to the lower zone of the bearing walls, in the direction of the excitation, where typical diagonal cracks occurred due to shear stress.

ACKNOWLEDGMENTS

It is significantly acknowledged the financial support of the European Commission (grant No. INCO-CT-2002-509119), for funding the research project PROHITECH (Earthquake PROtection of HIstorical Buildings by Reversible Mixed TECHnologies), which is the main framework of the experimental activity presented in this paper.

REFERENCES

[1.] Gramatikov, K., Tashkov, Lj., Krstevska, L.: Preliminary report on testing of Mustafa Pasha mosque model - Phase 1: Testing of original model. FP6-PROHITECH Project, WP7. Skopje, 2006.

[2.] Gramatikov, K., Tashkov, Lj., Krstevska, L.: Preliminary report on testing of Mustafa Pasha mosque model - Phase 2: Testing of repaired model and strengthened minaret with FRP. FP6-PROHITECH Project, WP7. Skopje, 2006.

[3.] Gramatikov, K., Tashkov, Lj., Krstevska, L.: Preliminary report on testing of Mustafa Pasha mosque model - Phase 3: Testing of strengthened model. FP6-PROHITECH Project, WP7. Skopje, 2006.

[4.] Krstevska, L., Tashkov, Lj., Gramatikov, K.: Shaking table testing of Mustafa-Pasha mosque model - Final report. FP6-PROHITECH Project, WP7. Skopje, April 2007.