Action COST C 26

URBAN HABITAT CONSTRUCTIONS UNDER CATASTROPHIC EVENTS

WG 2: EARTHQUAKE RESISTANCE

Experimental and numerical investigations on the Mustafa Pasha Mosque large scale model

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PROHITECH - *"Earthquake protection of historical buildings by reversible mixed technologies"*

1. Experimental investigations on the Mustafa Pasha Mosque large scale model

Mustafa Pasha mosque (1492), Skopje

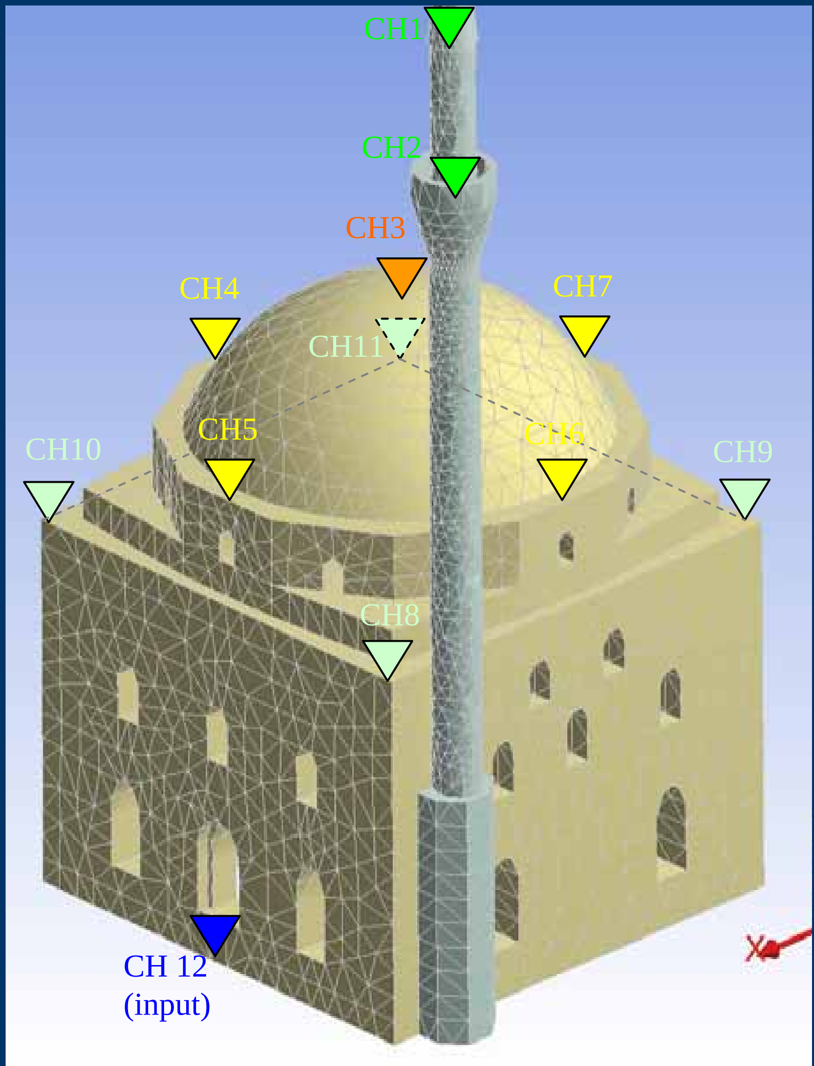
Mosque model, length scale 1:6

- The main objective of this testing was to investigate experimentally the effectiveness of proposed reversible technology for strengthening of this type of historical monuments.

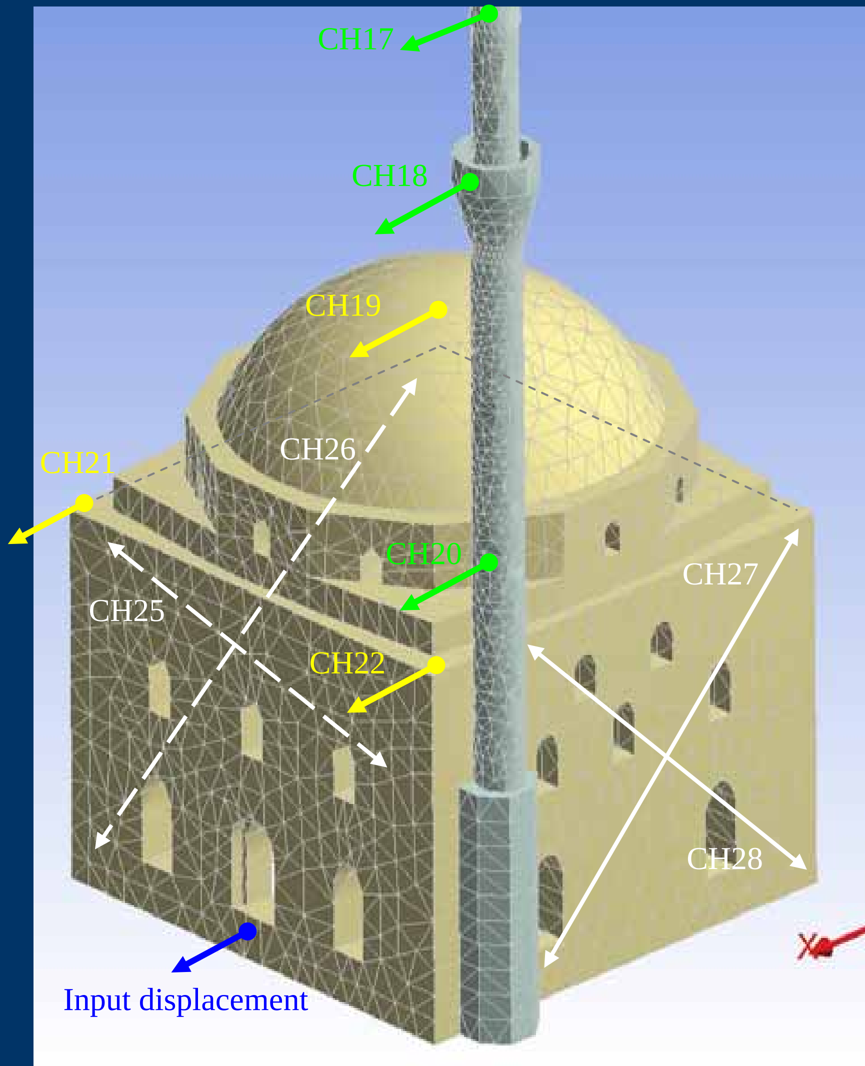
- Bi-axial seismic shaking table in the Dynamic Testing Laboratory of the Institute for Earthquake Engineering and Engineering Seismology in Skopje.

-"gravity forces neglected" modeling principle, using the same materials as in the prototype: stone, bricks and lime mortar.

Instrumentation of the model



accelerometers



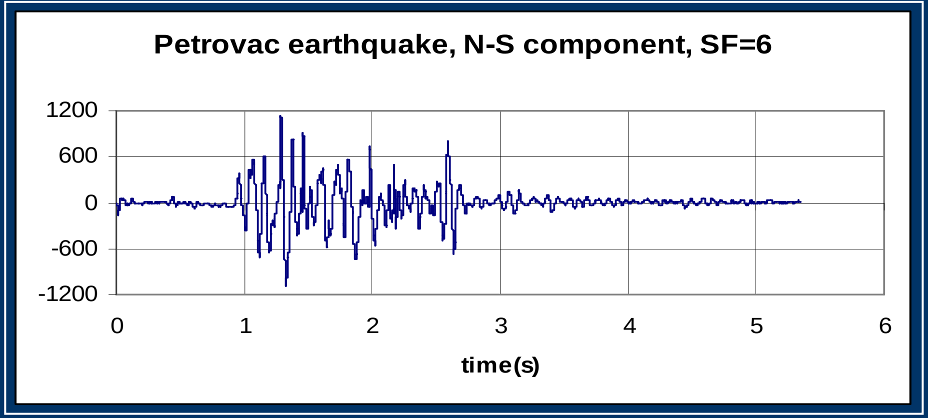
displacement transducers

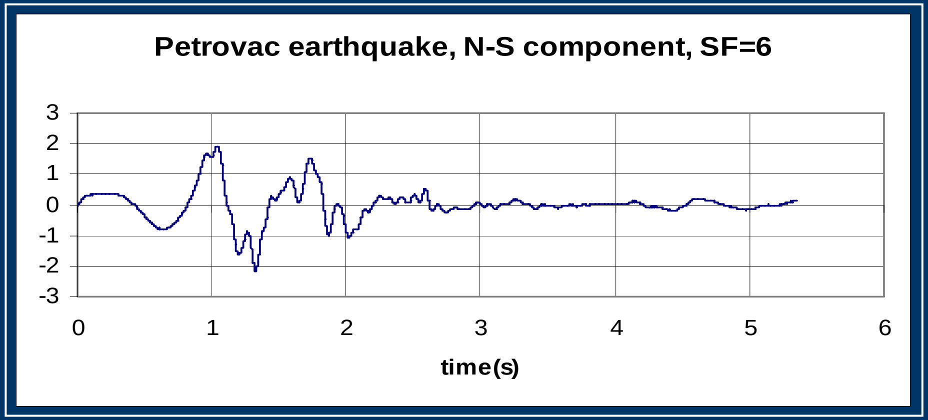
Testing phases:

1) Testing of the original model for low intensity level, to provoke small damage;

2) Testing of repaired model and strengthened minaret, until total collapse of the minaret;

3) Testing of strengthened model until collapse.





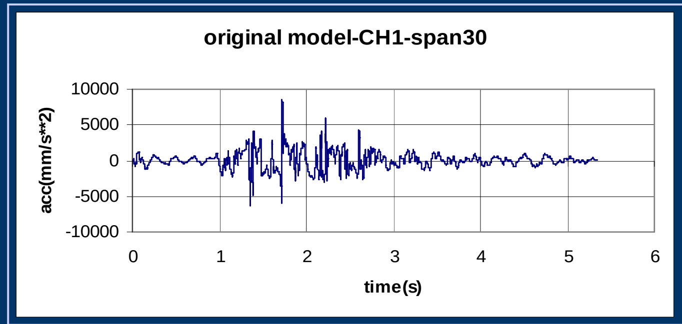
Time histories of acceleration and displacement, earthquake excitation Petrovac, 1979, N-S component , scaled by 6

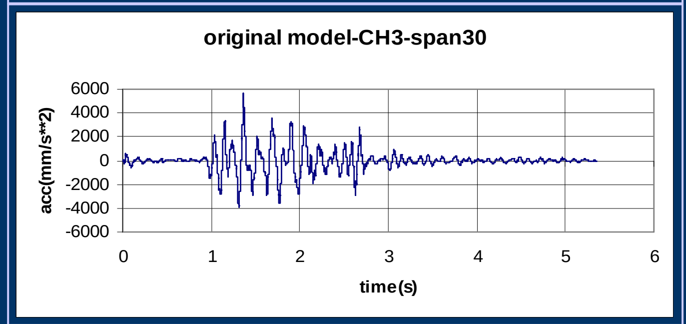
Phase 1 - Testing of the original model for low intensity level, to provoke small damage

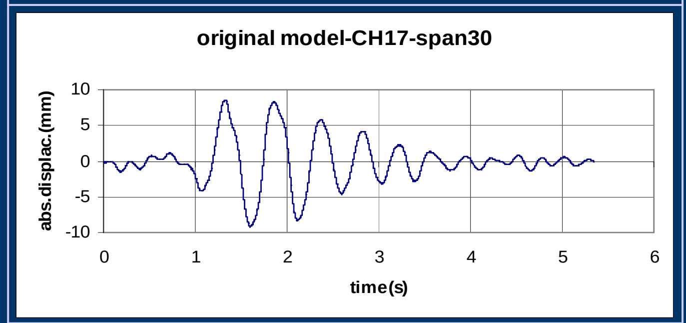
test No.	excitation	span of the table	input acc (%g)	acc - CH1 (%g)	comment
1	Random (0.1-50 Hz)	5	2	20	$f_{minaret}$ = 4.5Hz f_{mosque} = 8.2Hz
2	Montenegro-Petrovac N-S	5	1	15	
3	El Centro	5	0.4	7.5	
4	Montenegro-Petrovac N-S	10	2	20	first cracks-minaret
5	El Centro	20	4	20	
6	Montenegro-Petrovac N-S	20	6	40	
7	El Centro	30	6	30	
8	Montenegro-Petrovac N-S	30	10	70	
9	El Centro	40	9	90	

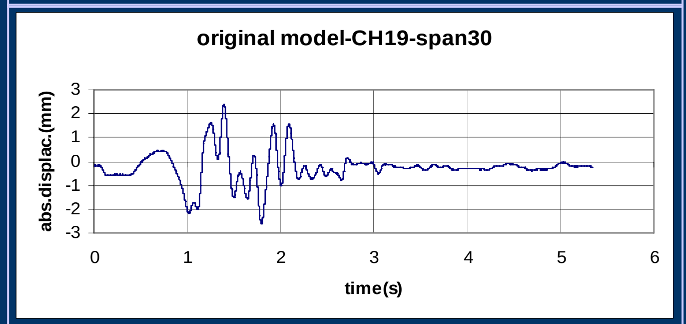
Details of damage – phase 1

Response parameters - test with input intensity 10%g









STRENGTHENING OF THE MINARET

Application of CFRP wrap upon a layer of epoxy glue:

- on four sides along the length of the minaret in vertical direction;
- at four levels along the height of the minaret in horizontal direction;
- at the minaret base

Such a strengthening enabled stiffening of the minaret and increasing of its bending resistance

Repairing of the mosque by crack injection

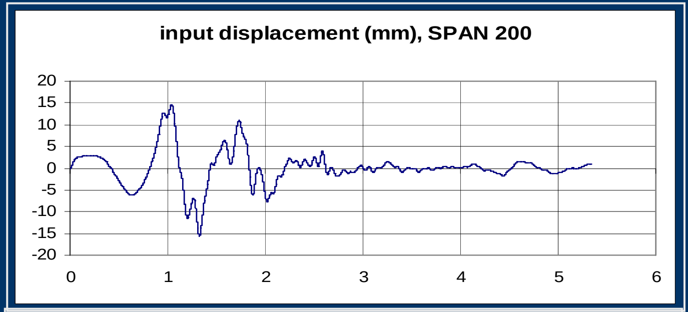
Phase 2 - Testing of the model with strengthened minaret until collapse

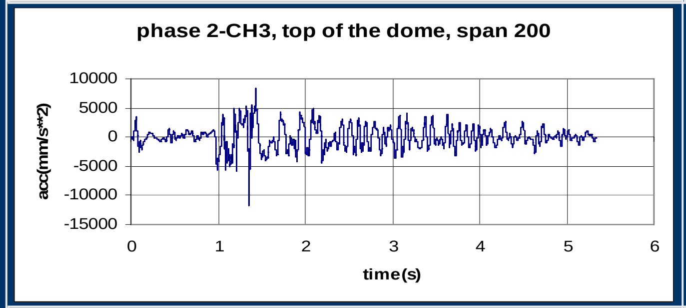
test No	span	input acc (g)	top acc. (minaret)	top acc. (dome)	input displac. (mm)	top displac. (dome)	comment
1	30	0.2	0.65	0.4	2.24	2.3	
2	40	0.28	0.82	0.6	3.3	3.3	
3	50	0.34	1.7	0.7	4.0	4.0	Cracks on the minaret
4	60	0.42	-	1.0	4.7	5.0	First cracks on the mosque
5	70	0.49	-	0.88	5.48	6.4	Collapse of the minaret
6	80	0.53	-	0.9	6.1	7.5	
7	90	0.58	-	1.0	7.0	8.9	
8	120	0.65	-	0.96	9.1	12.4	
9	150	1.05	-	1.1	11.4	14.7	
10	180	1.4	-	0.7	13.9	18.8	
11	200	1.5	-	0.54	15.3	22	Heavy damage of the mosque

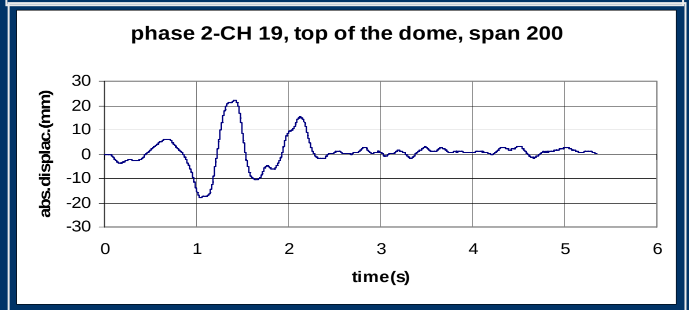
Collapse of the upper part of the minaret

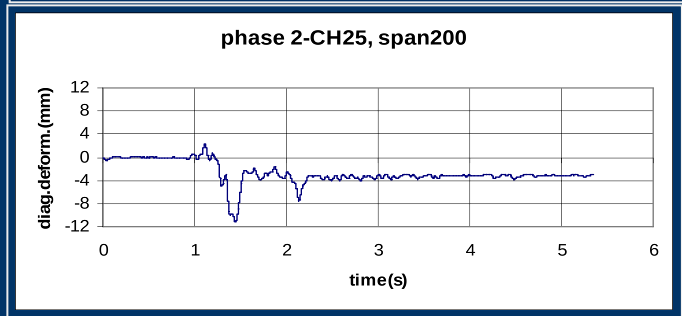
Details of damage – phase 2

Response parameters - test with input intensity 1.5g









Rebuilding of the damaged part after phase 2 testing

STRENGTHENING OF THE MOSQUE MODEL

- The main adopted principle in strengthening of the model was that the methodology to be applied be reversible and invisible.

• Incorporation of carbon rods in two longitudinal mortar joints around the four walls at two levels ;

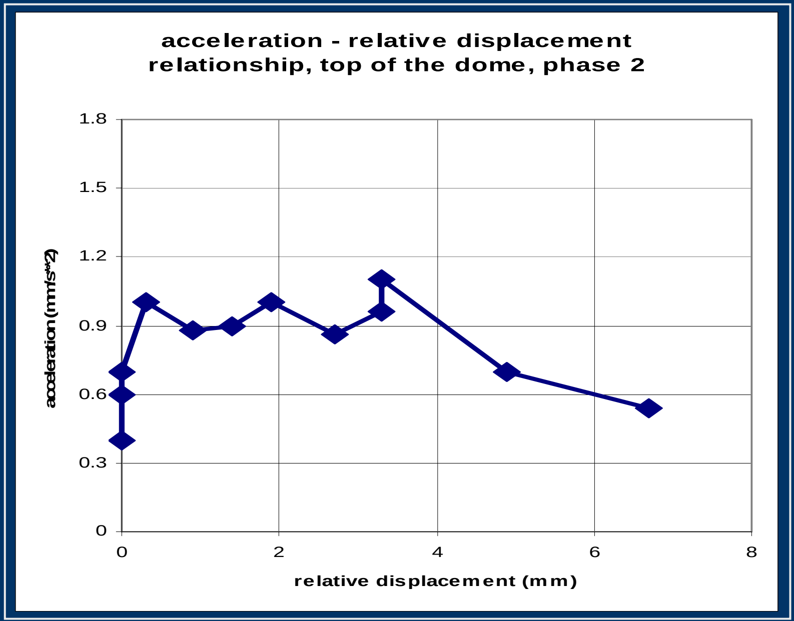
the grooved part of the joint was filled with epoxy resin

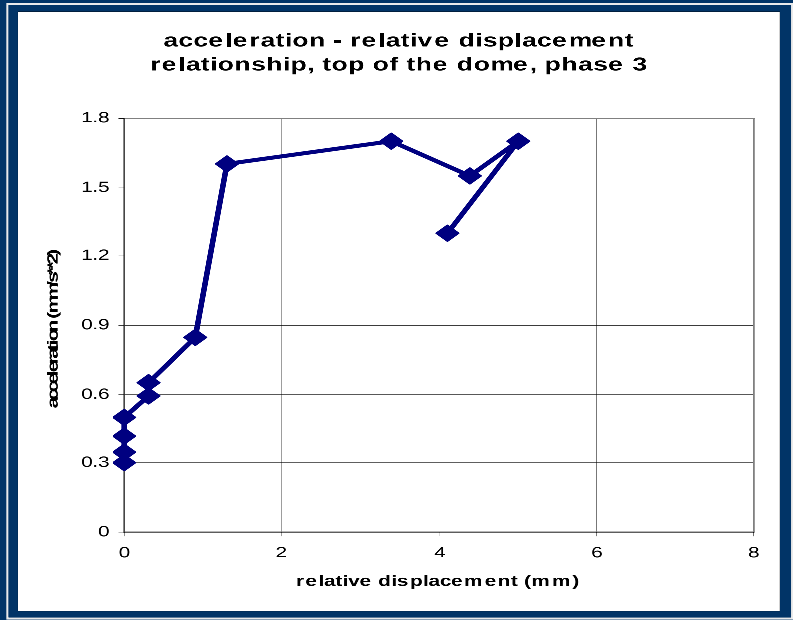
• Formation of a horizontal belt course at the base of the dome by use of a CFRP wrap

• Formation of a horizontal belt course around the tambour by applying a CFRP wrap

Phase 3 - Testing of the strengthened model until collapse

Scal. fact.	test no	excitation	span	input acc (g)	top acc. (g)	input displ. (mm)	top displ. (mm)	relat. displ. (mm)	comment
	1	random	5						f = 8.2 Hz
6	2	Petrovac	30	0.14	0.30	1.5	1.5	0	
	3		40	0.18	0.35	2.0	2.0	0	
	4		50	0.25	0.42	3.0	3.0	0	
	5		60	0.29	0.50	3.5	3.5	0	
	6		70	0.35	0.59	4.0	4.3	0.3	
	7		80	0.38	0.65	4.7	5.0	0.3	
	8		90	0.40	0.75	-	-	-	
	9		100	0.42	0.85	6.8	7.7	0.9	
	10		120	0.67	1.60	7.2	8.5	1.3	sliding of dome
	11		150	0.87	1.70	10.6	14.0	3.4	
	12		180	0.82	1.55	10.0	14.4	4.4	
	13		200	0.90	1.70	11.0	16.0	5.0	
	14		230	0.80	1.3	12.6	16.7	4.1	
	15	random	10						f = 5.0 Hz





'Push-over' curves obtained for the model in phase 2 and in phase 3

- the strength of the model in phase 3 is larger for about 60%

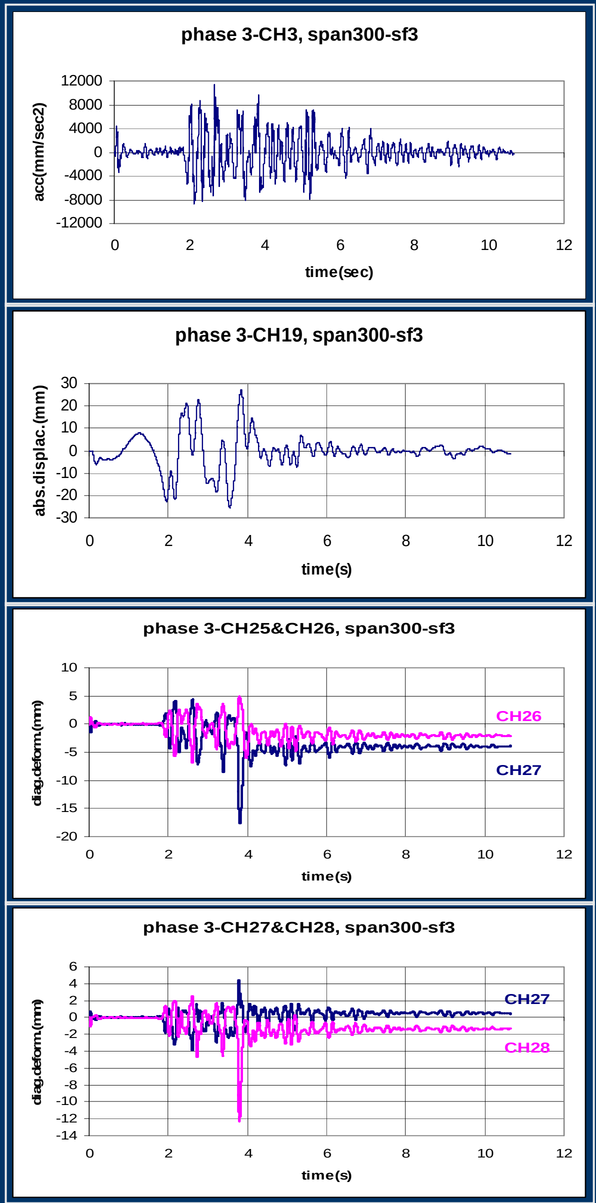
Phase 3 - Testing of the strengthened model until collapse

Scal. factor	test no	excitation	span	input acc (g)	top acc. (g)	input displ. (mm)	top displ. (mm)	relat. displ. (mm)	comment
3	16	Petrovac	100	0.20	0.60	7.8	13.0	5.2	
	17		200	0.46	0.93	15.0	22.0	7.0	
	18		300	1.20	1.10	25.0	26.8	1.8	
	19		400	1.5	1.0	30.0	40.0	10.0	
	20	random	20						f = 4.4 Hz
2	21	Petrovac	100	0.15	0.40	8.4	12.0	3.6	
	22		300	0.75	0.70	27.0	35.0	8.0	
	23		500	1.00	0.80	45.0	52.0	7.0	
1	24		600	0.35	0.53	58.0	75.0	17.0	heavy damage

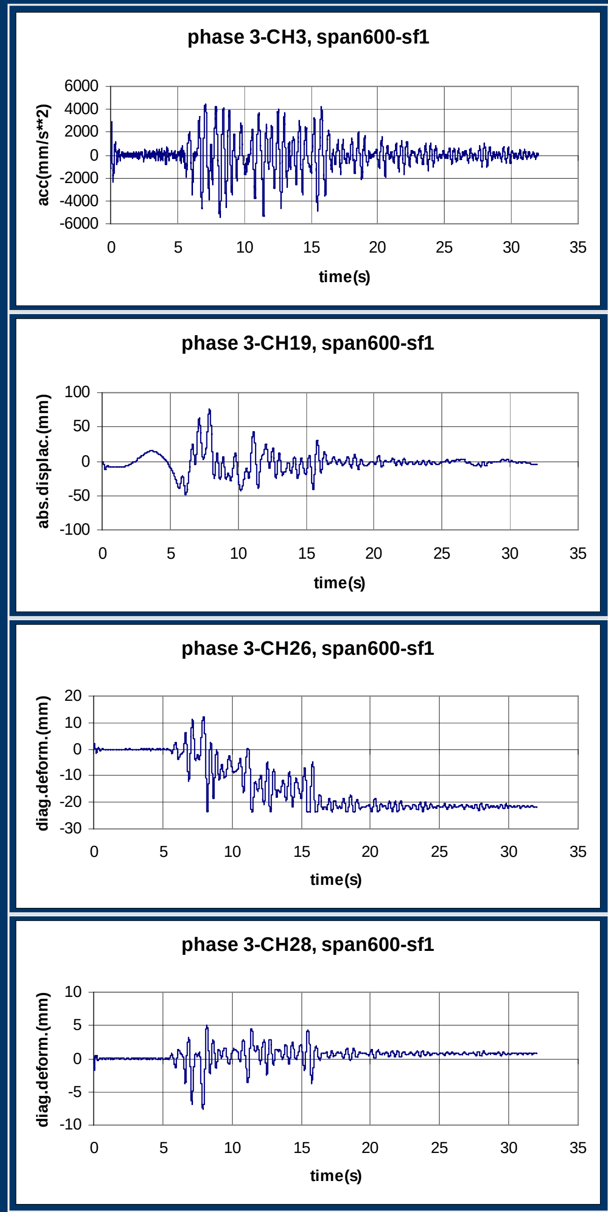
The frequency value was more than twice lower comparing to the initially measured frequency of 9.2 Hz, thus indicating pre-collapsing state of the model.

Detail of damage – phase 3

Heavy damage on many parts of the model was observed: many cracks developed on the dome and on the walls around the openings. Due to the intensive shaking inclination of one corner of the model occurred and at that part damage at the FRP belt developed.



Response of the model during the test with intensity 1.2g, sf3



Response of the model during the final test with intensity 0.35g, sf1

The **main conclusion** after the performed seismic shaking table testing of the Mustafa pasha mosque model in phase 3 is the following:

Although the original model was not repaired after testing in phase 2, **behaviour of the strengthened model 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.

The formation of the 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.