Strengthening of the "Rotonda" monument in Salonica

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Renforcement du monument «Rotonda», Salonique

Verstärkung des Monumentes «Rotonda» in Saloniki

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SUMMARY

An effort is made to outline briefly the in situ measurements and laboratory tests that were necessary together with the analytical work for the strengthening procedures of the Monument «Rotonda» in Salonica that was affected by earthquakes in 1978.

RESUME

Le rapport décrit la recherche expérimentale, sur place et au laboratoire, ainsi que les calculs analytiques nécessaires au choix des méthodes appropriées pour le renforcement du monument «Rotonda» à Salonique. Ce monument a été endommagé lors de tremblements de terre en 1978.

ZUSAMMENFASSUNG

In dieser Veröffentlichung sind die in-situ Messungen und die Laborversuche kurz präsentiert, die zusammen mit der analytischen Berechnung für die Verstärkung des durch das Erdbeben von 1978 beschädigten Monuments «Rotonda» in Saloniki notwendig waren.

1. INTRODUCTORY REMARKS

Rotonda of Salonica is one of the older and more splendid monuments of the City (Fig.1,Fig.2). Its core had been built as a part of the Roman Imperial palace layout about 300 A.D. Covered by a huge dome 24.5m in diameter it is an imposing circular building. Eight barrel-vaulted niches lighten the thickness of its 6.25m walls. About 400 A.D. Rotonda was turned into a church. A vaulted chancel and apse were added. So the middle and a part of the upper ring of the cylindrical wall was also cut for connection of the chancel with the main core, an intervention which has caused many structural problems to the monument.

During the course of the monuments' life, the christian intervention, the successive earthquakes and the time have caused extended damage to it as no serious attempt for strengthening had been made for many centuries. The earthquake of June 20, 1978 made the whole situation worse. The main crack due to shear at the

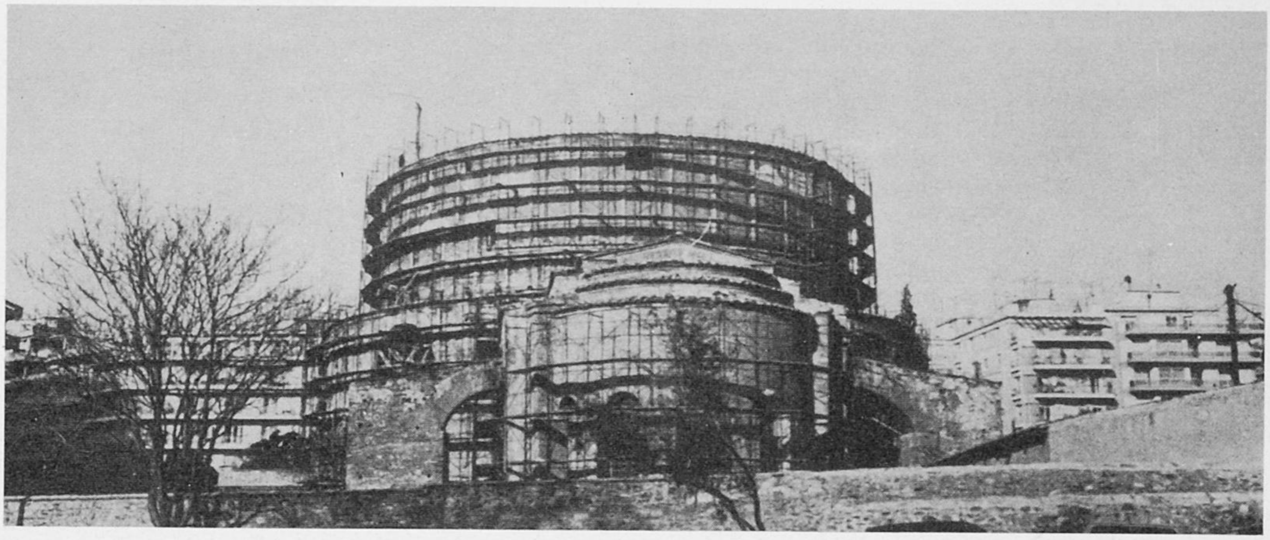

Fig.1 General view of Rotonda

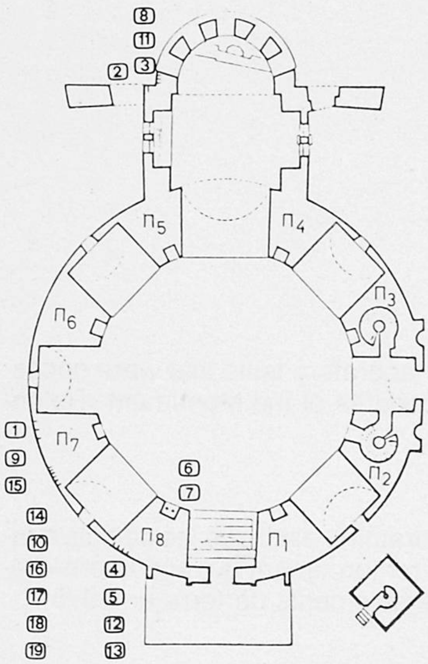

Fig.2 Locations of core-taking on the Monument

southern piers Π_2,Π_3 appeared a widening of 1mm per month indicating that the part of the dome bound by these piers had began slowly to slide.

The Working Group which was assigned the supervision of the restoration and strengthening of Rotonda after the earthquake of June 20,1978 was at first concerned with the immediate remedial measures that were necessary to prevent the collapse of the monument. At the same time with the works of the temporary shoring the study for the final repair and strengthening was started.

In order justified decisions to be made about an intervention in the monument, all the available means of research were used.This research covered three areas:

- In situ investigations
- Laboratory tests
- Analytical research with the aid of computers

In the present paper the in situ investigations and the lab.tests used as basis for the repair and strengthening of the Monument are briefly outlined.

2. IN SITU INVESTIGATIONS

The in situ investigations covered the following areas:

2.1 Geometrical and constructional surveying of the Monument

This included:
- The geometrical surveying of the superstructure carried out with standard as well as photogrammetric methods
- The geometrical and constructional surveying of the foundation carried out through four ground cuttings at the immediate neighborhood of the foundation
- The geometrical and constructional surveying of the cover and the dome carried out through ten cuttings at the cover and
- The constructional surveying of the piers carried out through inspections on their external surface and on the ruins of buildings built at the same period with the same external type of construction.

2.2 Surveying of the damage

The surveying of damages includes, first, a detailed surveying of the cracks, of their width, of the relative displacement of their edges both in the direction of the crack and vertically to it, as well as of their depth. It also includes a photographic surveying of the main cracks. The surveying of the cracking was done by means of geometric methods. The depth was determined using special rods that were forced into the cracks.

Together with the surveying of damage we should include the continuous recording of the variation in the crack widths by means of 11 velometers installed at the main cracks of the Monument. The recording of these movements serves as an additional indicator of the Monument's trend to collapse. It also serves as a basic indicator for the effectiveness of the final strengthening procedure under consideration. Actually, the cease of the crack propagation and the reversing of the relative movement in some of them, after the partial (measured with velometers) prestressing of the rings of the temporary shoring of the Monument, convinced that this type of strengthening has to be a positive one for the final restoration of the Monument (Fig.3). Finally, in the procedure of surveying the damage the measurement of the deviation of the piers from the vertical position should be included (Fig.4).

2.3 Core-taking and non destructive tests

In order to determine in the laboratory the mechanical constants of the Monument, an amount of 19 cores of 10cm diameter was taken from various locations on the Monument (Roman and Christian) (Fig.2). It is beyond any doubt that this limited number of specimens can not give credible values of the mechanical constants for the whole structure. On the other hand, an unlimited number of core could not be taken because of the risk to cause extended damage to the Monument due to core-taking. Therefore the cores were combined to N.D.T. i.e. wide range hammer tests (600) as well as ultrasonic measurements (300) which were extended on the whole surface of the Monument. The correlation of hammertesting to the corresponding compressive strengths found in the laboratory, through D.T. was found to be very satisfactory (correlation rate equal to 0.867). The correlation of ultrasonic measurements to the corresponding compressive strengths determined through D.T. at the locations of core-taking did not provide satisfactory results (correlation rate $r < 0.500$). Anyhow ultrasonic measurements have given very good correlation results, concerning the dynamic modulus of elasticity, which is a quantity indispensable to the analysis as well as to the choise of the type of the grout for the repair.

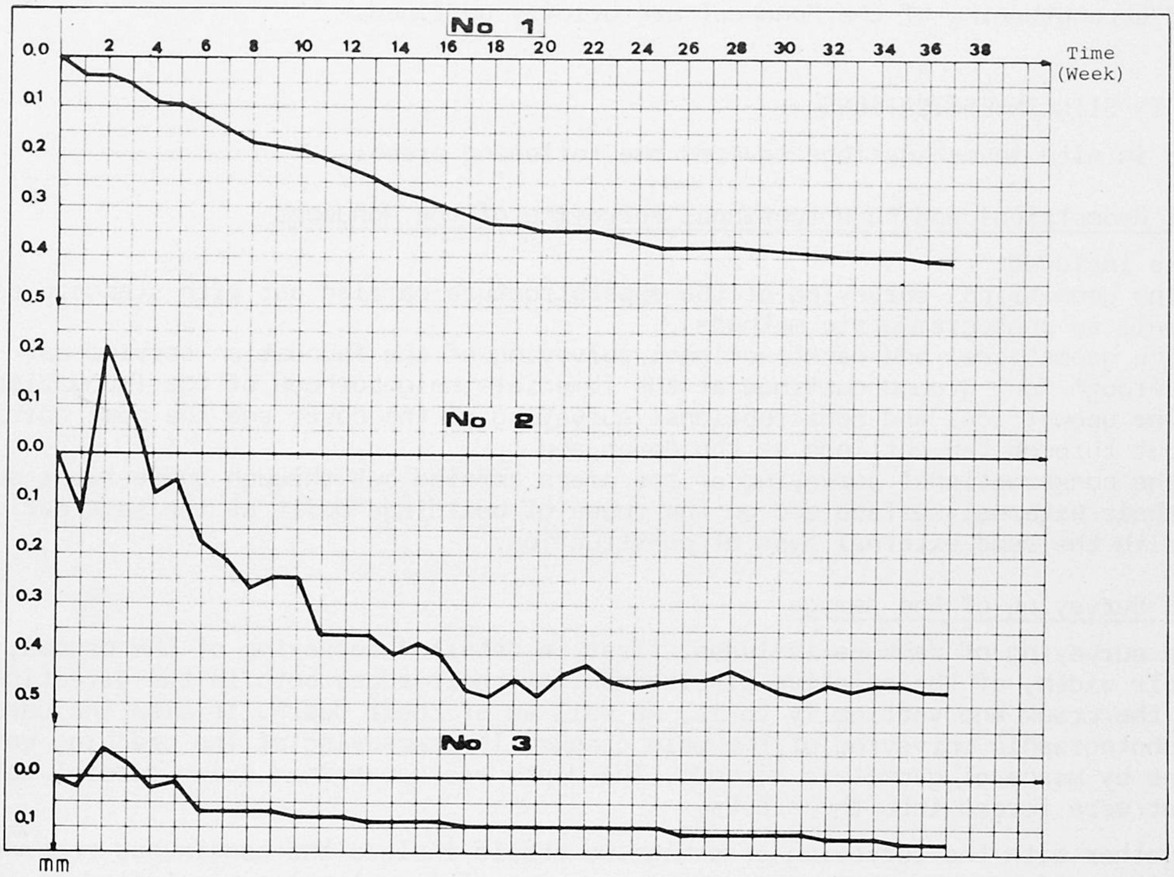

Fig.3 Variation of crack width with time

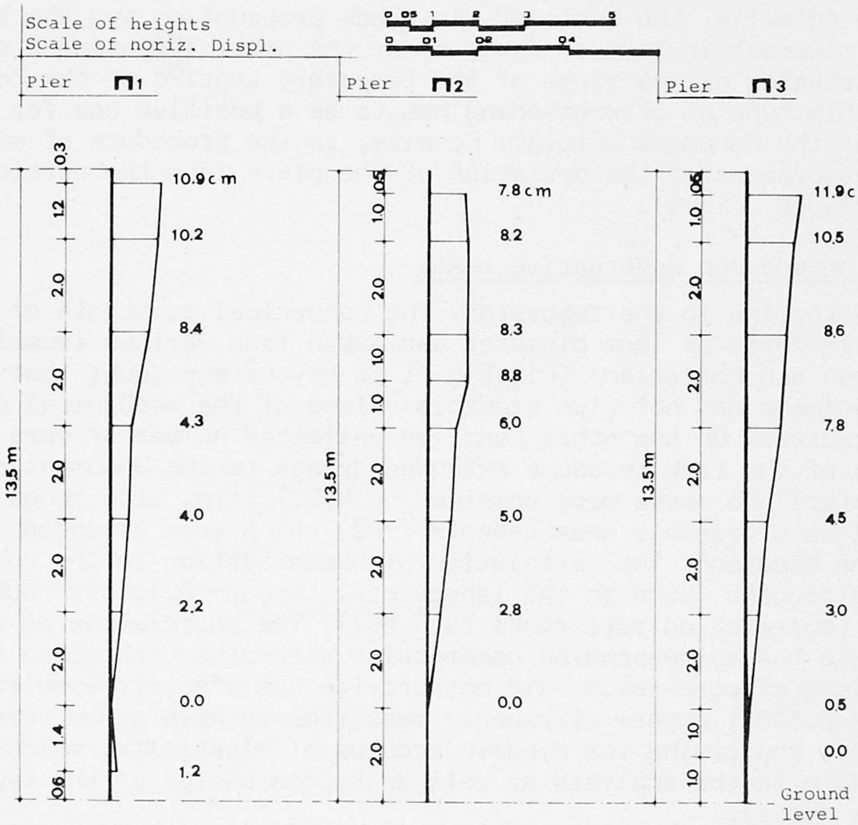

Fig.4 Horizontal displacements of the piers

The materials of the cores were also used in the chemical analyses for the determination of the composition of the structural materials of the Monument.

2.4 Natural period and degree of damping of the Monument's dynamic response

For the determination of the natural period of the Monument ambient vibration measurements were carried out in cooperation with the Laboratory of Engin.Seismology and Aseismic Structures, Nat. Tech. Univ. of Athens. Forced vibration measurements are also under way. The conclusions of these measurements are in a very good agreement to the analytical estimation of the natural period determined through the Rayleigh Method. So while the foundamental period according to ambient vibration measurements was found to be T_1=0.42sec., the analytical approach gave for T_1 prices between 0.53 and 0.33sec.

2.5 Soil borings

For the evaluation of the influence of the soil on the existing damage, four borings were carried out at a depth of approximately 25.0m. The results of the soil exploration were also used for the estimate of the soil conditions influence on the seismic loads (base shear) to be used in the strengthening procedure.

3. LABORATORY TESTS

The laboratory tests covered the following areas:

3.1 Chemical analyses

The chemical analyses had the following tasks:
- The determination of the proportions between the paste and the aggregates in the construction mortar.
- The determination of hydraulic elements into the mortar. So, for the Roman part it was concluded that the existing hydraulic materials were due to the brick powder while for the Christian part they were due to addition of pozzolanic ash together with the brick powder (Table 1).

Composition	First analysis with coarse ceramic material			Second Analysis without coarse ceramic mater		
	Determined values			Determined values		
	(gr)	%	%	(gr)	%	%
Burning loss	2.672	12.78		4.3045	21.52	
Insoluble compounds	13.852	66.30		8.989	44.94	
Soluble compounds	(4.372)	(20.92)	Composition of compounds	(6.71)	(33.54)	Compo - sition of compounds
SiO_2	0.540	2.58	12.35	0.640	3.20	9.53
R_2O_3	0.673	3.22	15.39	0.775	3.87	11.55
CaO	2.988	14.31	68.36	5.10	25.48	76.00
MgO	0.107	0.51	2.44	0.1175	0.59	1.75
SO_3	0.029	0.14	0.67	0.029	0.14	0.44
Na_2O	-	-	-	0.0060	0.03	0.09
K_2O	-	-	-	0.0400	0.20	0.59
Not determined	0.035	0.16	0.79	0.0025	0.03	0.05
Total	20.896	100.00	100.00	20.003	100.00	100.00

Table 1 Chemical components of the Roman mortar (mortar specimens, from core 10)

- The determination of the composition of the structural bricks and more specifically whether they were of the same composition with the mortar's brick powder and whether they have incorporated hydraulic materials. So, for the bricks of the Roman part it came out that they have hydraulic components, while for the bricks of the Christian part it came out that the hydraulic components are transformed to ceramic compounds because they were burned in high temperatures On the other hand, it was concluded that the mortars both in Roman and Christian part contain brick powder of the corresponding parts, both hydraulic active, a conclusion that was cross checked with the archaeological evidence.
- The chemical analysis of the materials that could be possibly used for the composition of grouts, i.e. hydrated lime, pozzolanic ash,cement and brick powder.

3.2 Mechanical properties of the structural materials of the Monument

Using the cores taken from the two parts of the Monument, the Roman and the Christian, mortar specimens were prepared in the Laboratory of Reinforced Concrete, Univ. of Thessaloniki, and their flexural strength was determined as well as the compressive strength, the modulus of elasticity of the mortar and the bond strength between the bricks and the mortar.

Brick specimens were also prepared and the bricks compressive strength as well as modulus of elasticity were determined. As we have already mentioned, the number of specimens was limited and was used for the calibration of the N.D.T. instruments by means of which the in situ investigation was extended all over the Monument (Table 2). As it is clear, from the above laboratory tests, completely reliable data were provided, concerning the structural materials-especially the mortar-which are necessary for the preparation of the grouts.

Constr. Phase	Location of Tests	Number of Tests	Mean value μ	Standard deviation σ	Lower 5% fractile $\mu-1,645\sigma$	Upper 5% fractile $\mu+1,645\sigma$	Minimum value	Maximum value
			(kg/cm^2)	(kg/cm^2)	(kg/cm^2)	(kg/cm^2)	(kg/cm^2)	(kg/cm^2)
Roman	Π_1	54	28,33	4.61	20,75	35,91	17,80	39,40
	Π_2	54	29,96	6,91	18,59	41,33	19,19	44,94
	Π_3	54	26,04	5,54	16,92	35,16	15,16	42,93
	Π_4	54	32,36	5,89	22,67	42,05	15,16	42,93
	Π_5	54	29,67	6,64	18,75	40,59	15,16	49,08
	Π_6	54	28,23	6,35	17,78	38,68	17,13	39,99
	Π_7	54	28,13	6,44	17,54	38,72	13,90	39,04
	Π_8	54	27,34	7,57	14,89	39,79	11,51	48,03
	Top	144	32,44	6,34	22,01	42,87	15,16	49,08
	Midhight	144	28,27	5,04	19,98	36,56	17,80	39,04
	Bottom	144	25,56	6,13	15,48	35,64	11,51	42,93
	Inside	216	27,36	5,25	18,72	36,00	15,16	42,93
	Outside	216	30,16	7,29	18,16	42,16	11,51	49,08
	Total	432	28,76	6,50	18,07	39,45	11,51	49,08
Christian	Top	54	36,96	11,60	17,87	56,05	15,81	60,16
	Midhight	54	37,39	11,15	19,05	55,73	19,19	59,00
	Bottom	60	39,88	14,32	16,33	63,43	13,90	69,77
	Inside	72	33,91	11,25	15,40	52,42	13,90	59,00
	Outside	96	41,32	12,51	20,74	61,90	15,81	69,77
	Total	168	38,14	12,50	17,57	58,71	13,90	69,77

Table 2 Statistical evaluation of the values compressive strength of the mortar

These data also used for the indirect determination of the compressive strength and of the modulus of elasticity of the compound masonry,using semiempirical relations established by current Codes together with destructive measurements on masonry cores.

3.3 Mix design of the grouts and testing of their properties

Based on the chemical analyses and the tests for the determination on the mechanical properties of the Monument's mortars, the composition of grouts was attempted in the Laboratory of Reinforced Concrete, Univ. of Thessaloniki, using traditional materials, compatible to the mechanical properties of the construction mortar of the Monument. Meanwhile, the chemical analyses and the testing of the machanical properties for a whole series of Byzantine Monuments carried out in the same Laboratory, led to the thought that this research had to be carried out in a uniform way for all the Monuments, in order to avoid unnecessary repetitions. So, a whole series of mixes was tested and we chose those that fulfilled the current specifications for grouting injections, as far as the fluidity, the bleeding, the shrinkage and the sedimentation are concerned (Table 3); from these mixes the choise of the appropriate grout for every Monument was made, according to the strength of the mortar and to its modulus of elasticity.

Grouting		Mixing Proporsions (parts by weight)								Sinking
Category	Label	Pozzolanic Ash	Lime	Cement	Ceramic powder 900°	Ceramic powder 650°	Sand	Water	Tricosal	time (sec.)
I	E_1	10	5	-	-	-	-	15,50	-	33
	E_1	10	5	-	-	-	-	12,00	0,15	30
	E_2	10	8	-	-	-	-	12,50	0,18	32
	EΠ2	6	4	-	5	-	-	13,50	0,15	28
	$E\Pi_4$	6	4	-	-	5	-	14,50	0,15	29
	K_{1-1}	10	5	-	-	-	15	17,50	0,15	28
	K_{1-2}	10	5	-	-	-	30	18,75	0,15	26
	K_{1-3}	10	5	-	-	-	45	20,50	0,15	27
II	ET_1	10	5	1	-	-	-	12,50	0,16	32
	ET_2	10	5	2	-	-	-	12,50	0,17	34
	ET_3	10	5	3	-	-	-	12,75	0,18	34
	ET_4	10	5	4	-	-	-	14,00	0,19	28
	ET_5	10	5	5	-	-	-	14,50	0,20	30
	ET_6	10	5	6	-	-	-	14,00	0,21	32
	ET_7	10	5	7	-	-	-	15,00	0,22	
	ET_8	10	5	8	-	-	-	15,50	0,23	33
	ET_9	10	5	9	-	-	-	16,00	0,24	31
	ET_{10}	10	5	10	-	-	-	16,50	0,25	
III	KT_{1-1}	10	5	2	-	-	17	15,75	0,17	32
	KT_{1-2}	10	5	2	-	-	34	20,00	0,17	29
	KT_{1-3}	10	5	2	-	-	51	22,50	0,17	30
	KT_{2-1}	10	5	4	-	-	19	18,00	0,19	23
	KT_{2-2}	10	5	4	-	-	38	21,00	0,19	
	KT_{2-3}	10	5	4	-	-	57	25,00	0,19	31
	KT_{3-1}	10	5	6	-	-	21	18,50	0,21	
	KT_{3-2}	10	5	6	-	-	42	23,00	0,21	30
	KT_{3-3}	10	5	6	-	-	63	25,50	0,21	32
	KT_{4-1}	10	5	8	-	-	23	19,50	0,23	33
	KT_{4-2}	10	5	8	-	-	46	23,00	0,23	30
	KT_{4-3}	10	5	8	-	-	69	29,50	0,23	28
	KT_{5-1}	10	5	10	-	-	25	19,00	0,25	31
	KT_{5-2}	10	5	10	-	-	50	23,50	0,25	30

Table 3 Mixing proportion of the grouts

The materials used are the following: Hydrated lime, pozzolanic ash, brick powder, cement and fine sand.

For each mix the water content was such that the time of sinking in the corresponding apparatus of the German specifications varied between 30″ and 32″,which ensures the entering of the injected mortar into the cracks.

In addition, the sample was tested to find whether it could be pumped in a hand-

-operated pump used for grouts.

For each mix, specimens were prepared according to current specifications and the volume reduction during coagulation was determined, as well as the shrinkage, the flexural strength, the compressive strength, the bond between the bricks and the grout and the modulus of elasticity. The strength tests for each composition covered a period up to nine months.

3.4 Soil tests

Based on the soil samples taken from the borings and the in situ collected data (soil profile, standard penetration tests, water table) lab. tests were carried out for the determination of the soil properties.

4. CONCLUSIONS

It is obvious from the above presentation that for a well justified repair and strengthening of a monument of world wide importance a very comprehensive investigation is necessary. The in situ investigations and the laboratory tests consist a very important part of the whole task necessary for the following steps in the intervention procedure.

5. ACKNOWLEDGEMENT

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