THE HAMAM OF IOANNINA: ANALYSIS AND RESTORATION

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ABSTRACT

The methodology applied to the restoration of the Hamam in the city of Ioannina, Greece is presented. The monument is a typical example of Ottoman architecture of the 17th century. At present it is in ruined condition. The restoration study, based on a thorough investigation of the structural system and material properties, includes static and dynamic analyses using FEM. Dynamic analyses take into account not only the code provisions for earthquake design but also selected actual earthquake records. The results point out to the structure's vulnerable areas and give accurate account of actual damages. Moreover, dynamic analyses using selected records of major Greek earthquakes shed light to the behaviour of a complex structure under seismic loads. Overall, the methodology used could function as blueprint for interventions in similar monuments.

1. INTRODUCTION

There is increasing interest lately to establish a framework for interventions on monuments and historical structures, as well as to assess their seismic vulnerability. In a large number of reports and case studies [2, 4], design methodologies that have been applied to important monuments are presented. However there are few published reports regarding historical masonry structures in Greece given the large number and the diversity of these structures.

As the awareness of seismic hazards imposed on historical structures increases and actions for their protection become more intense, the urge to establish this framework is bigger. The study for the restoration of the Ottoman Bath in the city of Ioannina has led to a methodology that may contribute to this purpose.

2. STRUCTURE

The Hamam is a one-storey structure, having dimensions of 25.80 m x 13.30 m.

Figures 1a, 1b. Monument before and after the collapse of the soyunmalik dome.

It was constructed inside the castle of Ioannina at the beginning of the 17th century and consists of four parts [1, 6, 7] as shown on Fig. 2:

a. Soyunmalik (disrobing room): is a square room covered by a dome. The dome, constructed by bricks placed in radial configuration, sits on an octagon, visible only from the outer side. The octagon is supported by a system of squinches and pointed arch pendentives, based on the walls of the room.

b. Soğukluk (tepidarium): is a long and narrow barrel-vaulted room.

c. Sicaklik (hot area): is a square room covered by dome, having similar configuration and structural system as soyunmalik. It has three barrel-vaulted extensions, to the east, south and west. At the corners of the sicaklik four square rooms with sides of 2.40 m, are located. These are the halvet (private rooms), all covered by domes.

d. Kulhan (furnace place): is a longitudinal barrel-vaulted room at the south side of the monument, housing the furnace and the reservoir, covered partly by domes and partly by a barrel vault.

The outer shell of the structure consists of masonry made of stone and has thickness of approximately 1.00 m, while the domes, constructed with bricks, are 0.30 m thick. There is no indication of tie-rods or timber reinforcement embedded in the masonry. The floors of soğukluk, sicaklik and halvet were heated via the use of hypocaust, constructed below slabs made of marble that were placed on cylindrical stone pillars. These floors have been totally ruined. The foundation of the monument consists of strip footings (1.00 m high) made of stone.

3. PATHOLOGY

The monument has been abandoned for many years and is in a ruined condition (Figs. 1b, 2a, 2b, 3). The damages that it has endured can be attributed to weather conditions (humidity and rainfall) and earthquakes. Also, due to the complete lack of maintenance, its condition is rapidly deteriorating. After a thorough structural inspection, carried out by the authors, the pathology was recorded. Structural damages can be divided into two categories: (1) damages of general nature, concerning the disruption of continuity and shape of the structural system (partial

Figures 2a, 2b. Damages at domes and arches.

collapses, extensive cracks) and (2) localized damages concerning the deterioration of building materials (masonry, bricks, mortar).

4. METHODOLOGY OF RESTORATION STUDY

The restoration study was completed in two stages. In the first stage, the original structure was analysed in order to evaluate the safety level and determine the causes and mechanisms of structural damages. It should be noted that the term "original structure" corresponds to the monument after restoration but not reinforced (i.e. reconstruction of collapsed parts, no disruptions or cracks considered in the analysis, mechanical properties of masonry considered as measured).

In the second stage, the reinforced structure was analysed. Strengthening the monument was accomplished by improving the mechanical properties of the
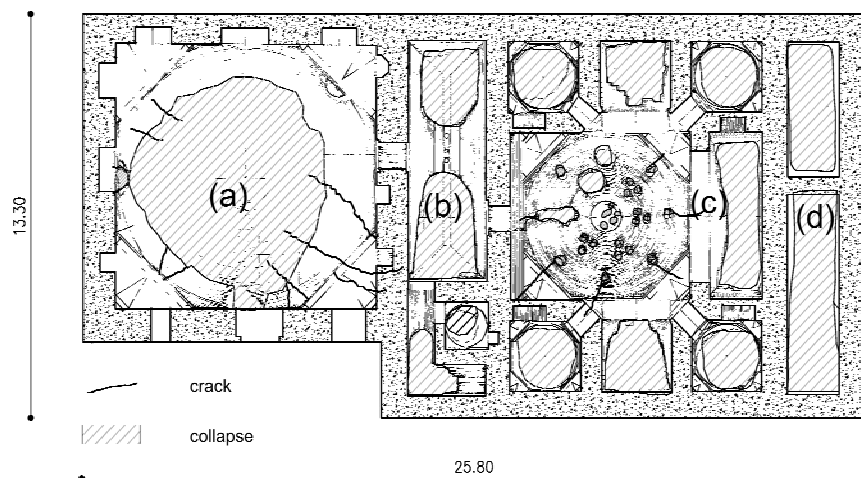

Figure 3. Ceiling plan: cracks and collapses are denoted.

masonry (by use of wall ties for the cracks, grouting, repointing of existing masonry, removal and replacement of decaying material, reinforced coatings) and the use of tie-rods. To determine the best restoration proposal, analyses were performed on a series of structural models gradually increasing the degree of intervention, by placing tie-rods. The final proposal, presented here, corresponds to the minimum possible intervention.

5. STRUCTURAL INFORMATION

This study is based on the systematic investigation of the structural system and the material properties carried out by the authors.

5.1. Material properties
The outer shell of the monument consists of stonework of limestone origin, while the domes are constructed with bricks. Stones are of small size while bricks are solid with wide surface and small thickness (3 cm). The mortar is divided in three categories based on its use (dome construction, wall construction, plumbing installations). Laboratory tests revealed the mechanical properties of materials (stone, brick, mortar) and masonry (masonry from semi-carved stones, masonry from carved stones, masonry from bricks).

Regarding the properties of stone and brick, measured quantities included bulk density, flexural and direct tensile strength. Tensile strength of mortar used in stonework and domes was also measured.

For the mechanical properties of masonry, measured quantities included bulk density, elastic constants (modulus of elasticity, shear modulus and Poisson's ratio), compressive and tensile strength, normal and parallel to bed joints, and shear strength.

5.2. Soil
The monument rests on stiff soil, classified as category A, both from Greek Seismic Code 2000 (GSC-2000) and EC-8.

5.3. Loads
Regarding dead loads, self-weight of the structure is fairly well estimated from the data collected from the investigation of the structural system. The accuracy of the information regarding geometry (cross-sections, fillings) and materials helps to properly define actual loads. In addition to dead loads, seismic, snow and wind loads were considered. Seismic loads are described in the following section. Snow and wind loads were estimated according to the provisions of EC-1.

6. SEISMIC HAZARD

As can be derived from the available seismological data [3, 5] there was remarkable seismic activity in the region in the past. In Table 1, ample historic

Table 1. Historic earthquakes at Ioannina during the lifespan of the Ottoman Bath.

Event/Date	Magnitude	Max Intensity (MM)	Losses
1740 Ioannina	6.2	VIII (Ioannina)	Extensive building damage
1743 Corfu	7.0	VIII (Ioannina)	Serious damage in most buildings
1813 Ioannina	6.2	IX (Ekklisohori)	Minor building damage in the city, Building collapses in neighbor cities
1823 Sagiada	6.4	IX (Sagiada)	Building collapses on the axis Ioannina-Sagiada
1858 Ioannina	6.0	VIII (Ioannina)	Extensive building damage
1867 Ioannina	6.2	VIII (Ioannina)	Extensive building damage
1898 Ioannina	6.3	VIII (Ioannina)	Building collapses

evidence for earthquake-induced destructions in Ioannina during the lifespan of the monument is presented. It can be noticed that these earthquakes are important in magnitude (as estimated from correlations with intensity [3, 5]) and may have been the cause of some of the structure's damages. However on recent years seismic events in the area were moderate.

According to seismic hazard zonations of Greece, the specified design ground acceleration for the region is 0.16g. This value should be multiplied by importance factor 1.3 assigned to monument structures according to GSC-2000. To evaluate the safety factor of the structure, not only the above code provisions were considered but also actual earthquake records from major Greek earthquakes. These motions (Table 2) were selected to correspond to the seismic profile of the region regarding soil conditions (stiff soil), distance from epicenter and magnitude of event.

7. ANALYSIS PROCEDURE

7.1. Modeling

A 3-D finite element model of the structure was created (Figs. 5, 6), following the available information regarding geometry and load bearing mechanism. Computer code ETABS was used. The complexity of the structure (domes, squinches and pointed arch pendentives) has imposed the use of a large number of elements (8400 approximately). The model was restrained both vertically and horizontally at the foundation level. Analyses assume elastic behaviour. Results include normal stresses, parallel and normal to bed joints S_{11} and S_{22} respectively, shear stresses, S_{12}, S_{23}, and S_{13} and principal stresses S_{max} and S_{min}. For each element two groups of stresses were obtained: one for the inner and one for the outer side.

Table 2. Selected major Greek earthquakes recorded on stiff soil.

Event/ Date	Station	Magnitude (M_s)	Epicentral Distance (km)	Distance from Rupture (km)	Orientation		PGA (g)
Kalamata 13/09/1986	Kalamata (OTE bldg)	5.8	10	5	˥ ˩	N265 N355	0.22 0.30
Egion 15/06/1995	Egion (OTE bldg)	6.2	18	4	˥ ˩	N-S E-W	0.54 0.49
Athens 07/09/1999	Athens (Syntagma)	5.9	17	13	˥ ˩	N10 N100	0.15 0.23

7.2. Response spectrum analysis

Analysis was performed following the provisions of EC-6 for the design of masonry structures and GSC-2000 (similar to EC-8). The load combinations of these codes for gravity and seismic loading were considered.

In order to further investigate the behaviour of the monument and check the performance of the reinforced structure under selected earthquake motions of Greek territory (Table 2), the corresponding response spectra in both horizontal directions were considered in the analysis. In Fig. 4, the response spectrum of the dominant direction of each motion is plotted and compared with that suggested by GSC-2000. It should be noted that the behaviour factor of the structure was taken as 1.0, i.e. no ductility or overstrength were considered.

8. STRUCTURAL ANALYSIS OF THE ORIGINAL STRUCTURE

In the first stage, the original structure, corresponding to the monument after restoration but without strengthening, was analysed. The fundamental period of the monument is approximately 0.05 s, in both the longitudinal and transverse axis verifying the high stiffness of the structural system. Examining the results, it can
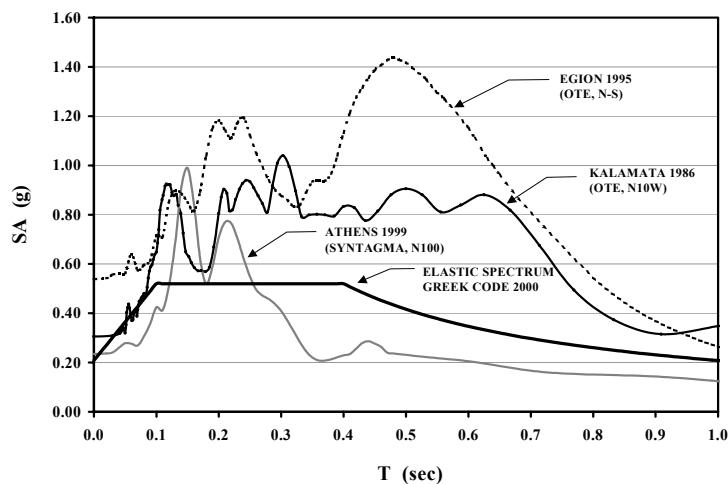

Figure 4. Acceleration response spectra (ζ=5%).

Table 3. Comparison of normal stresses (S_{11}, S_{22}) at selected points from dynamic analysis using the GSC-2000 elastic response spectrum.

Position	Original Structure				Reinforced Structure			
	S_{11} (KPa)		S_{22} (KPa)		S_{11} (KPa)		S_{22} (KPa)	
	inside	outside	inside	outside	inside	outside	inside	outside
1	-30.0	-60.6	-29.3	-60.3	-25.9	-56.0	-29.2	-60.2
2	52.1	-310.3	-82.1	-393.0	-119.0	-217.1	-45.1	-308.2
3	-89.2	65.9	18.4	-18.4	-99.1	-17.3	10.1	-23.4
4	61.1	-133.2	62.2	-97.9	48.2	-129.9	55.9	-82.7
5	-45.4	-50.7	-30.8	-5.0	-20.3	-116.0	-24.8	-7.9
6	71.0	149.1	88.1	60.2	75.1	151.2	95.3	63.8
7	6.1	11.2	47.9	29.1	8.1	12.8	53.1	36.3

be concluded that compressive stresses are small compared to the strength of masonry. This is not the case with tensile stresses that exceed the capacity of the structure at several points, especially on the upper part of the large domes of soğukluk and sicaklik. On Figs. 5a and 5b, the vulnerable areas of the structure are denoted. In Table 3, normal stresses, parallel and normal to bed joints, S_{11} and S_{22} respectively, on selected points of the structure, denoted on Fig. 5a, are presented. As can be derived by comparing Figs. 5a and 5b to Fig. 3 the results reveal the weak areas of the monument and give an accurate account of the actual partial collapses and cracks. This shows the validity of the model used, crucial to continue to the next stage and also proves that despite the growing use of inelastic methods, elastic analysis can still be a sufficient tool.

9. STRUCTURAL ANALYSIS OF THE REINFORCED STRUCTURE

In the second stage, the reinforced structure was analysed. Strengthening the monument was accomplished by improving the mechanical properties of the masonry
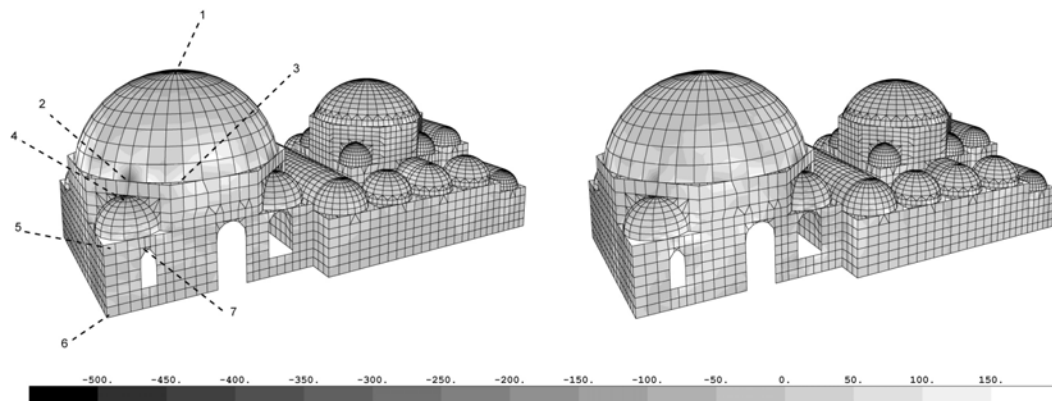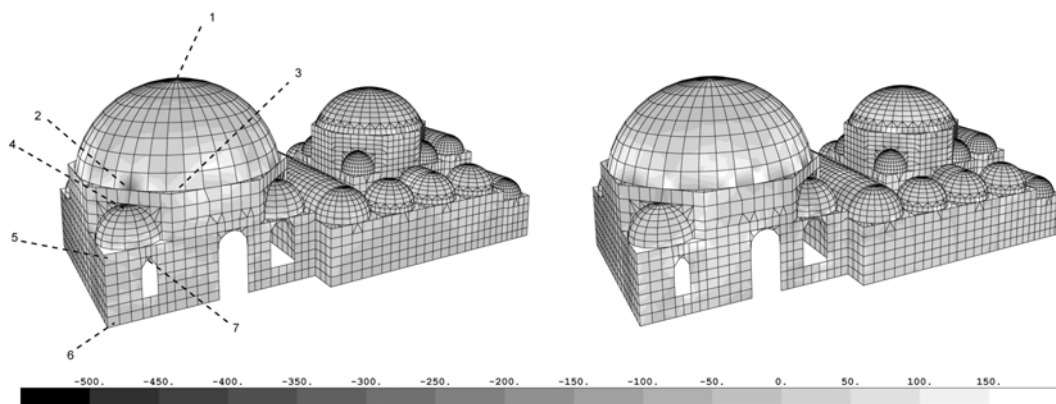

Figures 5a, 5b. Original Structure: maximum principal stresses (KPa)
from gravity and seismic loads respectively.

and using tie-rods. The latter, after taking into account the results of the analysis of the original structure, are placed on the octagonal base of the major domes and on the crown of the perimeter walls. To determine the best restoration proposal, analyses were performed on a series of structural models, gradually increasing the degree of intervention, by adding tie-rods. The final proposal, presented here, corresponds to the minimum possible intervention. The reinforcement does not affect noticeably neither the stiffness nor the mass of the structure, so the fundamental period is the same as in the previous analysis. Principal stresses S_{max} are presented on Figs. 6a and 6b for gravity and seismic load combinations respectively. In Table 3, normal stresses, parallel and normal to bed joints, S_{11} and S_{22} respectively, on selected points of the structure, denoted on Fig. 6a, are presented. It can be concluded that tensile stresses, still located in the same areas of the monument as in previous analysis, have decreased by 10% approximately.

In order to further investigate the behaviour of the monument and check the performance of the reinforced structure, analyses under selected motions of Greek territory (Table 2), were carried out. These motions impose greater actions than the provisions of GSC-2000. Response spectrum analysis using the records of Athens (1999) and Kalamata (1986) earthquakes result in tensile stresses that slightly exceed the strength of the masonry. This is not the case with the severe Egion (1995) earthquake; tensile strength of masonry is surpassed and therefore inelastic analysis would be needed as a further step to predict the monument' s behaviour.

10. CONCLUSIONS

The methodology followed for the restoration of the Ottoman Bath in the city of Ioannina is presented. The restoration, based on a thorough investigation of the structural system and the material properties, includes static and dynamic analyses using FEM. Dynamic analyses take into account not only the code provisions for earthquake design but also selected actual Greek earthquake records.

Figures 6a, 6b. Reinforced structure: maximum principal stresses, (KPa), from gravity and seismic loads respectively.

The study consists of two stages. In the first, the original (unreinforced) structure was analysed and the results point out το the structure's vulnerable areas and give accurate account of the actual partial collapses and cracks. It is concluded that despite the growing use of inelastic methods, elastic analysis can still be a sufficient tool in predicting the behaviour of a complex monument. In the second stage, analyses were performed on a series of structural models gradually increasing the degree of intervention to determine the best proposal (minimum intervention). Comparison of results between the analyses of the final model to the ones of the original structure verifies the correctness of suggested interventions. Moreover, dynamic analyses using selected records of major Greek earthquakes shed light on the behaviour of a complex monument structure under actual seismic loads. Overall, the methodology used, could function as blueprint for the restoration of similar monuments.

ACKNOWLEDGMENTS

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