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ASSESSMENT AND RESTORATION OF THE HISTORIC TEMPLE OF THE DORMITION OF THE THEOTOKOS AND THE PERIMETRIC FORTIFICATION WALLS AT PETRA, LESVOS IN GREECE

Constantine Spyrakos[1,2*], Dimitrios Kokkinakos[1], Dimitrios Chiotis[1]

[1] NTUA
Athens, Greece
cspyrakos@gmail.com

[2] NUP
Paphos, Cyprus
cspyrakos@gmail.com

Abstract

This paper presents the results of the analysis regarding the assessment of the historic temple of the Dormition of the Theotokos at Petra on the island of Lesvos, the perimetric fortification walls as well as the rock on which they are constructed. The temple, the fortification walls and the rock have been declared as monuments.
Both at the temple and the walls as well as at the rock, extensive in-situ and laboratory measurements were performed, such as, (imprint of geometry of the rock and the structures, imprint of rock cracks, mortar analysis, and video endoscopies). The aim of the measurements was the evaluation of the existing materials, the determination of the cause of the existing damage, the estimation of the hazard for future failures and the collection of data to propose proper strengthening measures.
In order to assess the existing condition and indicate the required interventions to restore and strengthen the structures both global and kinematic analyses were applied. Also, slope stability analysis was applied in order to assess the existing condition of the rock and propose the necessary strengthening measures. The study concluded that extensive interventions were required for the structures, such as, jointing, mortar injections, external confinement, application of tie-rods and use of special steel bars for partial mechanism prevention. Also, extensive strengthening measures should be applied for the rock, such as, cavity filling, mortar injections and rock anchoring and steel wire mesh for slope stabilization.

Keywords: Historic Masonry Temples, Historic Masonry Fortification Structures, Assessment of Existing Structures, Kinematic Analysis, Strengthening Interventions, Slope Stability.

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1 INTRODUCTION

The monument, that consists of the Temple of the Dormition of the Theotokos, the perimetric fortification walls and the rock on which they are constructed, is located at the center of the settlement of Petra, at the northern part of the island of Lesvos in Greece. The temple and the walls have been constructed at the top of a rocky outcrop at a height of 40 m, around 1840.

The temple is a two-story structure that has a total area of 212 m^2 and a maximum height of 9.4 m. The fortification walls have the form of a fortress enclosing a total area of 510 m^2, while its total perimetric length is 89 m. The height of the fortification walls varies between 3.2 and 7.35 m and their thickness varies between 0.60 and 0.92 m.

The slopes of the rocky outcrop extend over an area of 1000 m^2 and its dimensions are approximately 100 m length x 50 m width x 40 m height.

The temple, the fortification walls and the rock have been declared as monuments that are in need of special preservation. In Figures 1 – 2 the temple, the fortification walls and the rocky outcrop are presented.

Figures 1 and 2: Temple of the Dormition of the Theotokos, perimetric fortification walls and rocky outcrop.

2 LOAD BEARING STRUCTURES

The load bearing walls of the temple are made of stone masonry. Four (4) different types of stone masonry were observed. The main walls of the ground floor are made of three-leaf stone masonry with a total thickness of 75 and 50 cm. The apse is made of carved stone masonry with a thickness of 35 cm. The perimetric walls of the gallery at the upper floor level are made of three-leaf masonry with a thickness of 35 cm. The colonnade of the west side of the temple that supports the gallery consists of stone columns. At the interior of the temple there is another colonnade that consists of wooden columns made of tree trunks that support the wooden roof. All the load bearing columns are connected with each other and with the walls through iron tie rods.

The perimetric fortification walls are made of rubble stone masonry covered with stone plates at the top and they consist of continuous layers of stone masonry. In Figures 3 – 4 the structural system of the temple and the perimetric fortification walls are presented.

Figures 3 and 4: East view (three-leaf masonry and apse made of carved stone masonry) of the temple. South view of the perimetric fortification walls.

3 INVESTIGATION OF THE CURRENT STATE

3.1 Evaluation of the existing damage of the structures

For the case of the temple, during the on-site investigation the existing damage was examined in order to identify the cause for each case. All observed damages are attributed to two different causes: (a) the age of the structure and its deterioration in time because of environmental factors and (b) previous earthquake actions.

For the case of the temple, cracks were observed at the external and/or internal layer of load bearing walls of the gallery, as well as at the area of the connection between the gallery and the main temple. Cracks were also observed at several wooden columns at the interior of the temple, having approximately vertical orientation. Furthermore, deterioration of material was also observed at other elements of the temple, like, integrated wooden elements at the internal layer of the masonry of the gallery, wooden elements that are forming the cross vaults and iron tie rods that connect the columns between them and with the load bearing walls. In Figures 5 – 6 representative cases of the most significant cracks observed are presented.

Figures 5 and 6: Cracks at the external layer of the masonry of the gallery. Insufficient connection and detachment of the gallery from the main temple.

For the case of the fortification walls, it was found that the existing damage is attributed to the age of the structure and its deterioration in time because of environmental factors. It should be noted that the damages are observed at the external layers of the south, the west and the north side of the fortification walls, where the access is very difficult.

At the external layer of the south, the west and the north side of the fortification walls deterioration of the mortar of the joints is observed. Also, at the north side of the fortification walls the extreme deterioration of the mortar at certain areas has led to disconnection between the stones of the masonry. The most significant damage is the existence of very wide cracks around all the openings of the south side of the fortification walls, as well as at a part of those of the west side. These cracks are observed approximately in the middle of the thickness of the walls, have a vertical orientation and are visible at the left, right and upper side of the openings and their existence indicates the gradual disconnection of the external layer of the masonry from the internal.

In order to distinguish the damage of each area of the fortification walls according to its severity they were separated in three zones: (i) Zone 1 where the damage is less severe in comparison to the other zones, (ii) Zone 2 where the damage is more severe than any other part of the structure and (iii) Zone 3 where the damage is more severe than Zone 1 and less severe that Zone 2. In Figure 7 the exact area where each Zone is extended is presented.

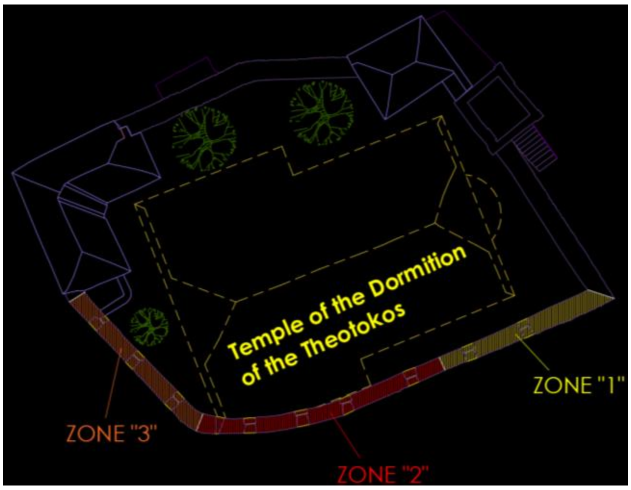


Figure 7: Zones 1, 2 and 3 of the fortification walls.

3.2 On-site and laboratory testing

Several on-site tests at different locations of the structure and laboratory testing were carried out in order to assess the mechanical characteristics of the stone masonry of the temple and the fortification walls. For the stones, rebound hammer tests were performed and for the mortar, rebound hammer tests and laboratory composition testing were performed. Also, with the aid of an endoscope used at selected areas of the structure, the composition of the masonry walls along their thickness was examined in each case.

3.3 Mechanical properties of masonry

The mechanical properties of the load bearing masonry were defined by taking into account the results of the investigation presented in section 3.2 of this work, as well as proposed values and equations from relevant standards and literature [4, 9].

3.4 Geotechnical survey

The geotechnical survey focused on the characteristics and the structural behavior of the rocky outcrop and its goal is to provide the required data in order to assess the stability of its slopes and propose the appropriate stabilization measures.

The volcanic rock is generally coherent, however there are many discontinuities, especially at its southern side, that, combined with the effect of corrosive factors, can lead to the detachment and fall of parts of the rock, while cavities at the base of the rock already exist.

4 ASSESSMENT OF EXISTING STRUCTURES AT THEIR CURRENT STATE

4.1 Assessment data

In order to assess the existing structures at their current state, analyses were performed according to the provisions of [1]. The corresponding values for the parameters as per [1] for the structures are the following: (i) design ground acceleration on type A ground is $a_{gR} = 0.24g$ for the seismic zone at the site, (ii) importance factor is $\gamma_I = 1.20$ for importance class III, (iii) soil factor is $S = 1.0$ for ground type A and (iv) since the structures are placed at the top of a rocky outcrop, a topographic amplification factor $S_T = 1.20$ has been considered.

4.2 Modeling and assessment of the temple

The load bearing walls of the temple have been modeled using shell elements, while the columns and the tie rods have been modeled using linear elements. The 3D structural model of the temple is presented in Figure 8.

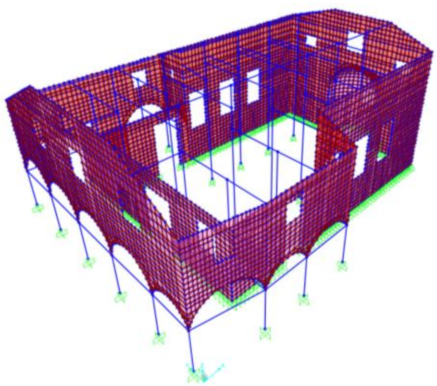


Figure 8: 3D structural model of the temple.

In order to assess the existing structure, the lateral force method of analysis was applied. The assessment of the piers has been performed for limit state of *Significant Damage (SD)*.

According to the results of the analysis, there is a significant number of piers that fail for earthquake loading. Thus, it is necessary to apply strengthening measures to the load bearing masonry of the structure.

4.3 Modeling and assessment of the fortification walls

4.3.1. Kinematic analysis

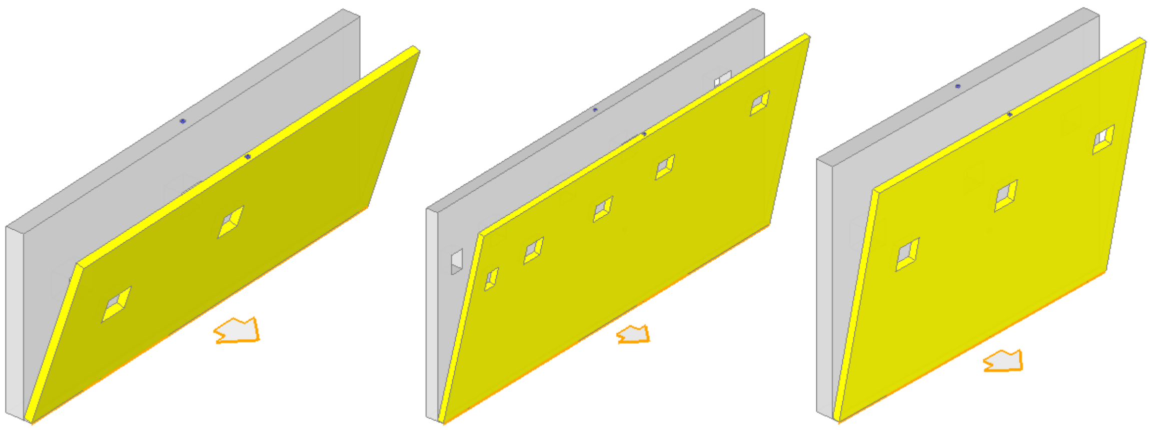
The damage that has been observed at many different areas of the fortification walls indicates that there is a high risk of development of partial out-of-plane mechanisms that could cause the collapse of several parts of the walls in the future. Thus, kinematic analysis was applied in order to assess the behavior of the fortification walls.

Based on the observations at the assessed structure, one possible partial out-of-plane mechanism has been considered: the detachment and overturning of the external layer of the stone masonry. This mechanism is presented in the following.

4.3.2. Assessment with kinematic analysis

Initially, from on-site investigation, all the parts of the fortification walls that are in risk of collapse because of possible partial out-of-plane mechanisms of failure were identified. Then, a different structural model for each assessed area of the structure was created. If the acceleration that causes the partial out-of-plane mechanism is lower than the control ground acceleration, then strengthening measures are required in order to avoid partial failure. For the limit state of *Significant Damage (SD)* the control ground acceleration is divided by the behavior factor of the mechanism which is $q_{LM} = 2.00$ [4].

For the assessment of the fortification walls three different structural models were created, one for each zone, as presented previously. For the modelling of each part of the load bearing walls, macro elements were used. The three models are presented in Figures 9 – 11.



Figures 9, 10 and 11: Kinematic analysis structural models of Zones 1, 2 and 3, respectively, of the fortification walls. Detachment and overturning of the external layer of stone masonry.

For Zone 1 the collapse multiplier of the mechanism is $a_0 = 0.045g$. The ground acceleration that causes failure of the mechanism is $PGA_{SD} = 0.076g$. The safety factor is $\lambda = 0.220 < 1.0$. For Zone 2 the safety factor is $\lambda = 0.145 < 1.0$. For Zone 3 the safety factor is $\lambda = 0.145 < 1.0$. It should be noted that a partial out-of-plane mechanism fails if its safety factor is lower than 1 ($\lambda < 1.0$).

As a result, for all cases the structure fails for the considered mechanism and proper strengthening interventions should be applied.

4.4 Modeling and assessment of the rocky outcrop

For the assessment of the rocky outcrop three different kinds of analysis were performed: (1) tectonic discontinuities analysis, (2) rock slope stability analysis and (3) rockfall analysis.

By applying the tectonic discontinuities analysis, the system of the internal discontinuities of the rock is determined and, thus, it is possible to calculate the volume of the rock parts that could be detached and fail. By applying the rock slope stability analysis, the required force in order to stabilize each precarious rock part is calculated. By applying the rockfall analysis, based on data obtained by the imprint of the slopes of the rock and by visual observations, the positions with the highest risk of detachment of rock parts were determined. Then, from the rockfall analysis, the rock fall trajectory, as well as, its total kinetic energy and bounce height were determined.

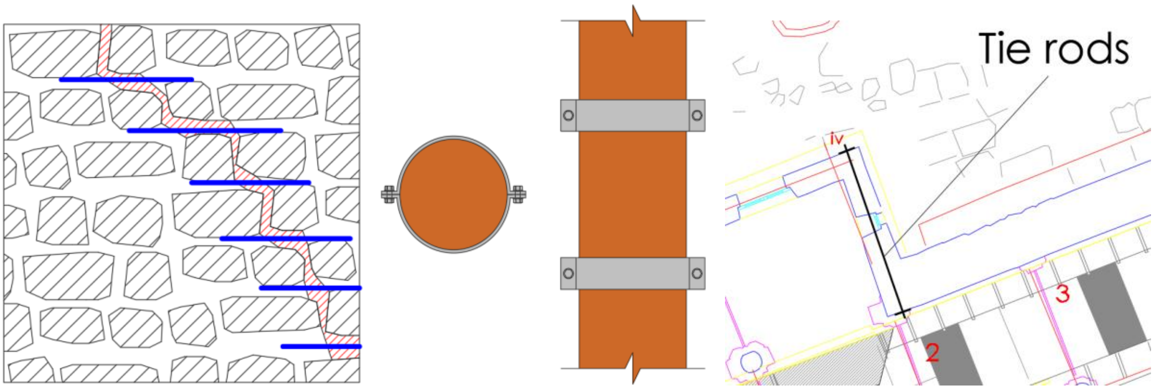
5 STRUCTURAL INTERVENTIONS

5.1 Temple structural interventions

The proposed structural intervention of the temple can be divided in two categories: (1) damage restoration and (2) strengthening measures.

5.1.1. Temple damage restoration

For the cracks of the stone masonry walls, jointing and stapling with a non-corrosive metal alloy horizontal bars will be applied (Figure 12). For the cracks of the wooden columns, external confinement with stainless steel plate elements will be applied (Figure 13). For the detachment between the main walls of the temple and those of the gallery, stainless steel tie rods will be applied. This way, the pier will also be strengthened in shear (Figure 14). For the corroded wooden elements of the masonry of the gallery and those of the cross vaults, replacement with new wooden elements will be applied. For the corroded iron tie rods, replacement by stainless steel tie rods will be applied. For the cracks of the stone elements at the base of the arches, they will be sealed with the application of mortar injections.



Figures 12, 13 and 14: Crack stapling with horizontal non-corrosive metal alloy bars. Wooden column external confinement with stainless-steel elements. Tie rods connecting the main wall with that of the gallery.

5.1.2. General temple strengthening measures

Given that a significant number of piers of the temple fail, as presented in section 4.2 of this work, general strengthening measures will be applied at the temple as a whole. These measures are:

- Jointing applied at all the load bearing masonry walls of the temple, except those at which it has already been applied at an earlier state.
- Homogenization of all the load bearing masonry walls of the temple.

The proposed structural interventions of the monument have been designed so that they comply with the modern understanding of conservation engineering. For example, both mortars, for jointing and for homogenization, will have to be compatible with the existing masonry. Also, their compressive strength will be equal to 10 MPa.

5.1.3. Assessment of the strengthened temple

In order to assess the strengthened temple, the improved mechanical properties were applied to the structural model and the assessment was performed again. According to the results of the analysis of the strengthened temple, there are four piers that still fail for earthquake loading. Thus, it is necessary to apply additional strengthening measures to the load bearing masonry of the structure.

5.1.4. Specific strengthening measures

As stated in the previous paragraph, four piers still fail after the application of the general strengthening measures. These piers are the ones that connect the perimeter walls of the temple to those of the gallery and the ones on either side of the apse. All of them fail in shear, thus, horizontal tie rods, distributed vertically, will be applied.

According to the results of the analysis of the strengthened temple with the general and the specific measures, no piers fail, thus the monument is sufficient.

5.2 Fortification walls structural interventions

5.2.1. Fortification walls strengthening measures

For the restoration of the walls the following structural interventions are applied:

- Jointing at all the surface of the masonry, except those at which it has already been applied at an earlier state.
- Homogenization of masonry, in order to fill the internal voids and warrant its behavior as a unified structural element.
- Improvement of the connection between the external and the internal layer of masonry by applying non-corrosive metal alloy bars perpendicular to the surface.

5.2.2. Assessment of the strengthened fortification walls

The three structural models of the fortification walls presented in Paragraph 4.3.2 are being reanalyzed after the application of the strengthening measures.

For Zone 1 the collapse multiplier of the mechanism is $\alpha_0 = 0.311$. The ground acceleration that causes failure of the mechanism is $PGA_{SD} = 0.524g$. The safety factor is $\lambda = 1.516$. For Zone 2 the safety factor is $\lambda = 1.047$. For Zone 3 the safety factor is $\lambda = 1.007$. As a result, for all cases the strengthened fortification walls are sufficient.

5.3 Rocky outcrop protection measures

The interventions applied at the rocky outcrop have the goal of stabilizing its slopes and the foundation of the temple and the fortification walls as well as protecting the residential area. The interventions are the following:

- Removal of precarious rock parts, except at the areas around the foundation of the temple and the fortification walls.
- Removal of planting and root systems from slope discontinuities.
- Filling of existing cavities with concrete and covering with stone masonry.
- Application of cement injections to seal existing cracks.

- Application of passive anchoring bars for the stabilization of precarious rock parts and the strengthening of unstable areas of the slope.
- Application of protection steel mesh at the south, southwest and west side of the slope.

6 CONCLUSIONS

For the assessment of the historic Temple of the Dormition of the Theotokos and the perimetric fortification walls, as well as, the rocky outcrop on which they are founded, at the settlement of Petra on the island of Lesvos, a series of in-situ and laboratory tests were performed in order to estimate the mechanical characteristics of the load bearing stone masonry walls. Also, the geotechnical characteristics of the rock were measured with an extensive geotechnical investigation.

A series of structural analysis of the temple, kinematic analysis of different areas of the fortification walls and rock stability analysis of the rocky outcrop was performed in order to: (1) assess the load bearing capacity of the temple, (2) examine the possibility of failure of the fortification walls due to out-of-plane mechanisms, (3) examine the possibility of failure of rock parts of the rocky outcrop that could lead to damage or injuries at the residential area of the settlement and (4) specify the required strengthening measures for each case. The results are the following:

- With the proper strengthening, the structural behavior and seismic capacity of the masonry temple can be significantly improved, so that it complies even with the current provisions of [1] for new structures. Such strengthening measures could include: (i) jointing of the external layers, (ii) homogenization of the masonry, (iii) application of external confinement at existing columns and (iv) application of tie rods.
- Fortification stone masonry structures could be vulnerable to deterioration of the materials of their structural elements and earthquake loads causing partial out-of-plane mechanisms. Vulnerability worsens when such a structure is founded at the highest edge of a steep slope.
- Such fortification structures present a high possibility of failure because of partial out-of-plane mechanisms. Kinematic analysis can calculate the seismic hazard of a masonry structure for partial out-of-plane failure mechanisms.
- With the proper strengthening, partial out-of-plane mechanisms can be avoided. Such strengthening measures could include: (i) jointing of the external layers, (ii) homogenization of the masonry and (iii) spiral stainless-steel bars applied perpendicular to the external layer.
- Rock formations with a steep slope can be vulnerable to the detachment and fall of rock parts, that could cause damage at structures placed at lower altitudes and/or injuries of civilians.
- With the application of proper protection measures the detachment of rock parts can be avoided and the safety of the public can be assured. Such protection measures could include: (i) removal of precarious rock parts and planting, (ii) filling of existing cavities, (iii) application of cement injections, (iv) application of anchoring bars, (v) application of steel mesh and (vi) application of rockfall protection mesh.

REFERENCES

[1] CEN, *EN 1998-1:2004. Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings*, Comité Européen de Normalisation, Brussels, 2004.

[2] CEN, *EN 1996-1-1:2005. Eurocode 6: Design of masonry structures - Part 1-1: Common rules for reinforced and unreinforced masonry structures*, Comité Européen de Normalisation, Brussels, 2005.

[3] CEN, *EN 1998-3:2005. Eurocode 8: Design of structures for earthquake resistance - Part 3: Assessment and retrofitting of buildings*, Comité Européen de Normalisation, Brussels, 2005.

[4] CEN, *EN 1998-3:2005. Final draft EN1998-3 NEN SC8 PT3. Eurocode 8: Earthquake resistance design of structures*, Comité Européen de Normalisation, Brussels, 2017.

[5] Earthquake Planning and Protection Organisation, EPPO, *Code of interventions on masonry structures, Athens*, 2022. (In Greek)

[6] DR, *Valutazione e riduzione del rischio sismico del patrimonio culturale con riferimento alle norme techniche per le costruzioni di cui al D.M. 10/01/2018*, 26/02/2011.

[7] Spyrakos C.C., *Finite element modelling in engineering practice*, Pittsburg, PA, USA: Algor Publishing Division, 1995.

[8] Spyrakos C.C., *Engineering Structures. Bridging performance based seismic design with restricted interventions on cultural heritage structures*, **160**, 34-43, 2018.

[9] Spyrakos C.C., *Masonry structures: Assessment and interventions for seismic loads*, Athens, ERGONOMOS IKE, 2019. (In Greek)

[10] Spyrakos C.C., Raftoyiannis J., *Linear and nonlinear finite element analysis*, Pittsburg, PA, USA: Algor Publishing Division, 1997.

[11] Spyrakos C.C., Touliatos P., Patsilivas D., Pelekis G., Xampesis A., Maniatakis C.A., *Retrofitting of Heritage Structures – Design and evaluation of strengthening techniques. Seismic analysis and retrofit of a historic masonry building, In S. Syngellakis Editor*, 65-74, 2013.