Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 2651-2658

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

HEALTH MONITORING OF A MONUMENT AT ACROPOLIS USING AN EXPERT ACQUISITION SYSTEM AND WIRED OPTICAL SENSORS

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Keywords: Health Monitoring, Optical Sensors, Monumental Structure.

Abstract. *Maintenance and preservation of monuments requires a balance between structural safety needs and respect to their architectural and historical value. Structural health monitoring (SHM) is a rapidly evolving methodology that has been increasingly implemented to maintain this balance.*

This paper presents the development and the implementation of a state – of – the - art methodology using an expert acquisition system (EAS) and wired optical sensors to monitor evolving deformations during a period of twenty – one months on a monumental structure "Propylaea" of the Acropolis in Athens. The aim of the on-going SHM program is to monitor deformations and increase the structural knowledge of the behavior of the ancient monument in order to take any precautionary measures and avoid excessive deformations.

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5595.18527

1 INTRODUCTION

Built at the western side of the Acropolis hill, Propylaea constitutes the monumental entrance building to the temple of Athena. In the known-to-us form, Propylaea comprises of a main building flanked by two wings, the northwest and the southwest corner, respectively. Northwest of the Propylaea, the Gallery building founded on an irregular, rocky background stands out as a two-sided building structure, consisting of the foundation made of limestone and upper-structure made of marble. The basement beneath the modern nearly constructed flooring of the Gallery is empty with observable conservation works, and the members of tufa-monument are substantial parts of the foundation of the Propylaea during Classical Times. Over time the structural shell of the Gallery has suffered many critical damages either from the natural environmental actions (earthquakes, passive earth pressure, corrosion of materials, etc.) or by human intervention (siege-weapons, bombing, manufacturing defects, etc.). Visible wide-cracks around the walls illustrate an active trend or a potential slip progression of the northwest corner of the structure to the north side of the hill. The specific location and construction state, require constant monitoring [1,2].

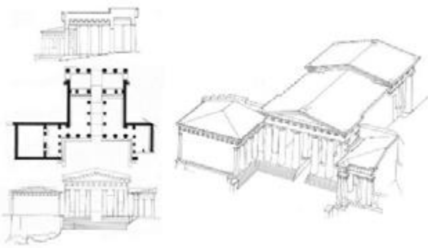


Figure 1: Propylaea drawings.

Figure 2: Western Side (1850).

Figure 3: Western side (Today)

2 OBSERVED AND MONITORED RESPONSE OF THE PROPYLAEA GALLERY

Of prominent importance are the observed deformations of the still standing structural elements of the Acropolis Propylaea. The in-plane and out-of-plane deformations are more intense on the north-western side of the Propylaea Gallery.

The north wall of the Propylaea Gallery presents an almost generalized settlement of 3cm as well as slight horizontal deformation extruding towards the outer plane in some areas and towards the inner plane in others. Towards the western edge the wall exhibits an intensive rotational behavior attributed to the deformational elongation of the western wall. As a consequence, the vertical joints have widened especially towards the inner surface.

The western wall of the Propylaea Gallery presents a generalized settlement, increasing from the edges (3cm) towards the middle (7cm at the outer section) and general displacement, flexure and divergence towards the outer plane. The deformation of the western wall presents a complex combination of individual mechanisms, consisting of mechanisms that trigger both longitudinal and lateral differential settlements, as well as an outer flexure mechanism that causes the wall elongation (wedge-shaped widening of vertical joints in plan view).

The analysis of the deformational behavior of the Propylaea Gallery aims at correlating the vertical and horizontal structural deformations and settlements with the real causes of these evolving phenomena. The identification and quantification of the aforementioned parameters up to this day have resulted in an evolving condition of bi-axial structural behavior directly linked to the on-going differential compression of the walls' structural bearing elements of the walls and the foundation rock subsidence, or partially connected to a preceding (not evolving) condition of lateral instability because of lateral upper-structure pressures.

3 MONITORING SCOPE

The main purpose of structural health monitoring is the effective evaluation of the limestone foundation of the Propylaea Gallery's structural behavior during aging, natural phenomena such as earthquakes, extreme weather conditions, materials deficiencies, structural inconsistencies, etc.

The structural monitoring of the substructure provides a continuous provision of data, the exploitation of which facilitates the identification of the innate causes and their active deformational tendency. Use of the implemented optical technology can serve as a valuable tool and instrumentation.

The monitoring criteria can be categorized as short-term and long-term.

The short-term criteria are implemented in order to:

(i) Detect the evolution of unforeseeable and abnormal events.

(ii) Evaluate the response of the structure under seismic or other accidental loads.

(iii) Eliminating doubts concerning the existing cracks.

(iv) Accurate determination of temperature impact on the bearing structure.

Long-term criteria are used in order to:

(i) Forecast of structural changes associated with the fixation conditions between the thinner underlying rock mass (north-west section of the Acropolis Rock) and the structural foundation system.

(ii) Quantify measurable deformational parameters correlated with the structural response of the bearing system.

(iii) Assess the vulnerability of the bearing structure and categorization of potential risks.

(iv) Identify frequency and repetitiveness of adverse phenomena.

(v) Determine the seasonal temperature impact on the bearing structure.

(vi) Assess the structural behavior in terms of deformation.

The installation was implemented according to the monitoring scope and based on both the short and the long term criteria. The final monitoring scenario took into account the following parameters:

1. Most critical zones of the masonry bearing structure, based on the acknowledged pathologies and the geometry of the structure.
2. The deformational behavior of the structure in both directions (Vertical & Horizontal) and the correlation between them.
3. The assumption that the structure is based directly on an uncertain, in terms of stability, ground surface, consisting of different layers of soil and bare rock mass.

Under this framework, four innovative sensors (2.0 m length), based on optical fiber technology, were installed at the northern and western side of the Propylaea Gallery substructure both at the inner and outer surface [3]. The nomenclature, the geometry of the instrumentation and the final locations of the sensors, are all presented in Table 1. Figures 4 and 5 indicate the schematic location of sensors OS1 – OS4 as well as a corresponding photograph. The selection of the locations where the sensors were installed was based on two criteria: (i) the observed deformation on the walls and (ii) the anchorage requirements. The OS1 and OS2 are anchored on masonry, while the other two sensors are attached to concrete.

Sensor	Installation Date	Location
OS_1	02/06/2015	Out / West / Vertical
OS_2	02/06/2015	Out / West / Horizontal
OS_3	28/05/2015	In / West / Horizontal
OS_4	28/05/2015	In / North / Horizontal

Table 1: Instrumentation.

Figure 4: OS_1 & OS_2 Sensors locations / West side.

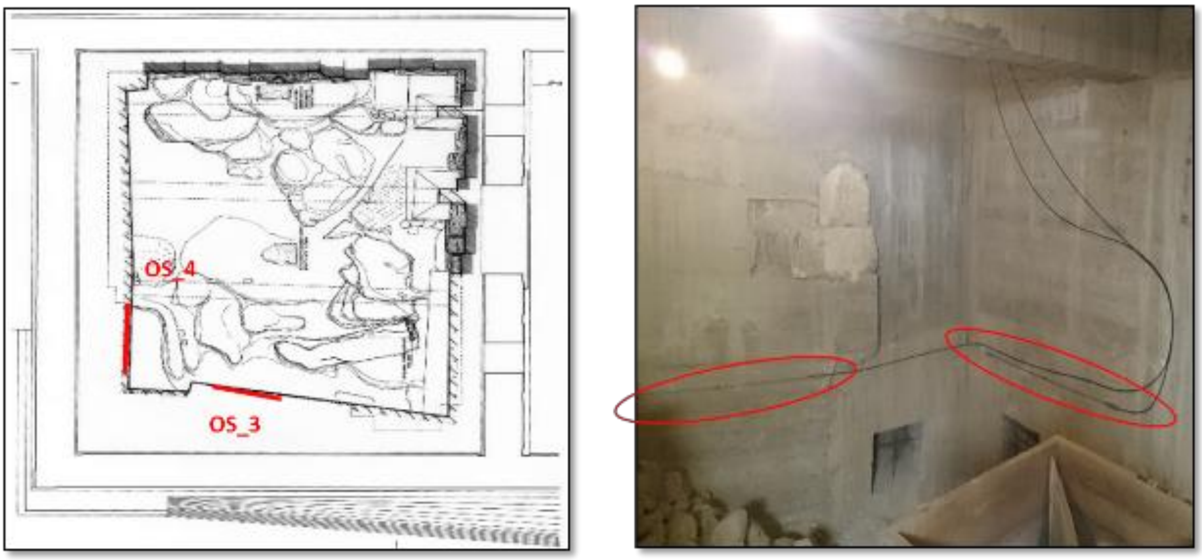
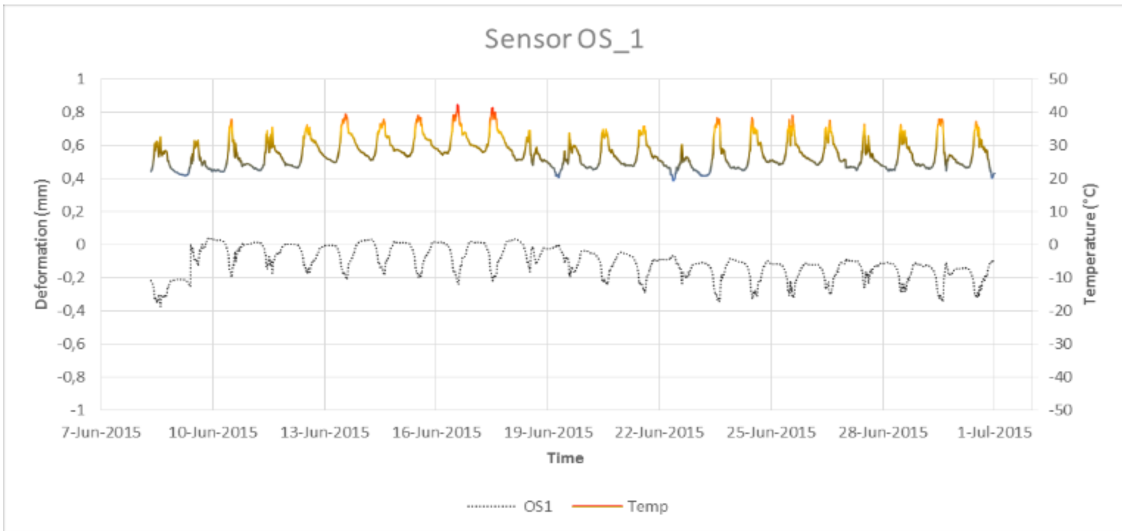
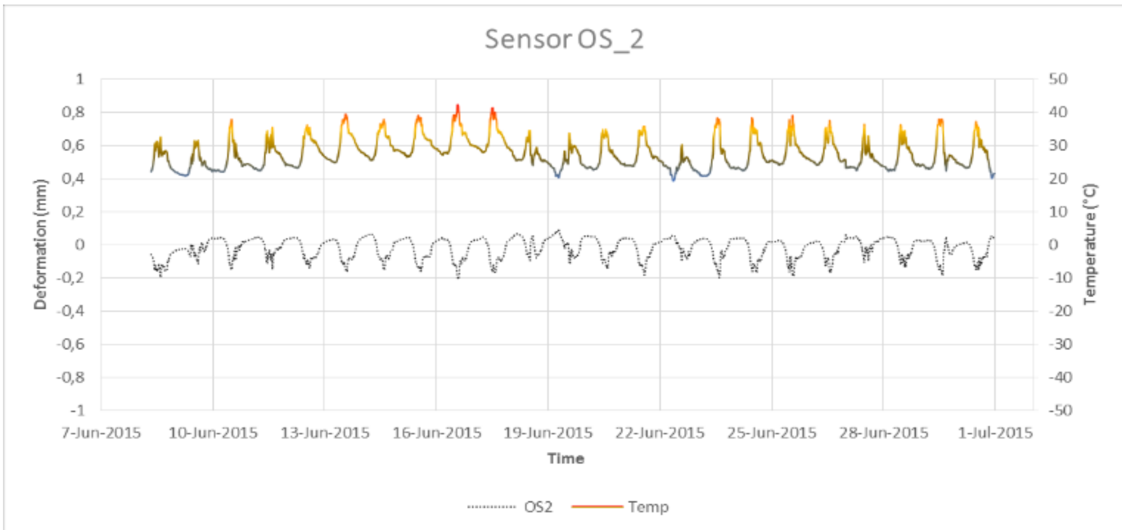


Figure 5: OS_3 & OS_4 Sensors locations / Plan view.

4 EVALUATION OF THE MEASURED DATA

After the installation of the monitoring system, a first observation phase was required in order to evaluate the normal behavior of the structure under operational loads (1 month period). The purpose of such measurements was the definition of the main engineering parameters and characteristics which constitute the basis for future interpretation of the monitoring results. Moreover, it was essential to evaluate the temperature effect on the measurements and determine its impact on the structure.





Figures 6-7: 1st Observation Phase (1st month – June 2015) / Axial deformation in function of Temperature.

As far as the initial observation data is concerned, it is clear that all sensors fully follow the temperature changes with an inverse behavior both on a daily and a seasonal basis. The daily deformational variations of the structure because of temperature effects are strictly related to the thermal, coefficient of each material (OS_1 & OS_2: Masonry / OS_3 & OS_4: Concrete). The interpretation of measurements during the first observation stage indicate that the influence of the temperature is elastic on all sensors, as the deformation returns to its initial state after one complete temperature daily cycle.

Proceeding to the evaluation of the collected data, by completing a twenty-one (21) month period of structural health monitoring, there is a clear and comprehensive view of the overall response of the Propylaea Gallery north-western side wall under static loads in both directions (horizontal and vertical). As far as the vertical direction of the western side is concerned, an evolution of an irreversible deformational state with a clear compressive behavior is displayed (900μm, Fig.8). The sharp evolution of compressive deformations during the 2015 winter season is correlated with the sudden and extreme changes in weather conditions (strong storms, autumn 2015) which seem to have affected the Gallery support conditions. The phenomenon continues with less intensity for the rest of the monitoring period, whilst maintain the inelastic deformation of the system that never returns to its initial deformational state. Table 2 and Figures 9 -12 present the data collected during the three monitoring periods of the vertical and the biaxial deformations.

The compressive behavior in the vertical direction of the northwest corner of the Gallery leads to certain redistribution of permanent loads towards its side, which is associated with the overall movement mechanisms of the Propylaea structural system and should be evaluated in a context of a broader systematic monitoring process in order to give useful and significant conclusions. Possible unstable behavior of structure and rock-mass fixation conditions, related to the seasonal temperature cycles and environmental conditions, can prove the activation of the existing visible cracks both in the eastern and western side of the Gallery, although the original cause of these cracks might be completely different.

In the horizontal direction of the north-western side of the structure, a total residual compressive deformation in the range of 100 - 200mm has been recorded. The participation of the horizontal direction in the estimated structural deformational mechanism is significantly diminished, in comparison to the vertical one. Besides, all sensors tend to return to their initial state by completing deformational cycles entirely related to seasonal temperature variations.

A finite element analysis model (Fig.12) was conducted as a rough approximation to simulate the Gallery's structure in relation to a slightly unstable subsoil-foundation system, which is subject to differential settlements because of possible soil deterioration [4,5]. The model indicates an ongoing distribution of internal stresses, as measured by the optical sensors, enhancing the belief that the long-term exposure to extreme weather conditions leads to a critically short (but still measurable) attenuation of support conditions on the north-western side of the Propylaea Gallery.

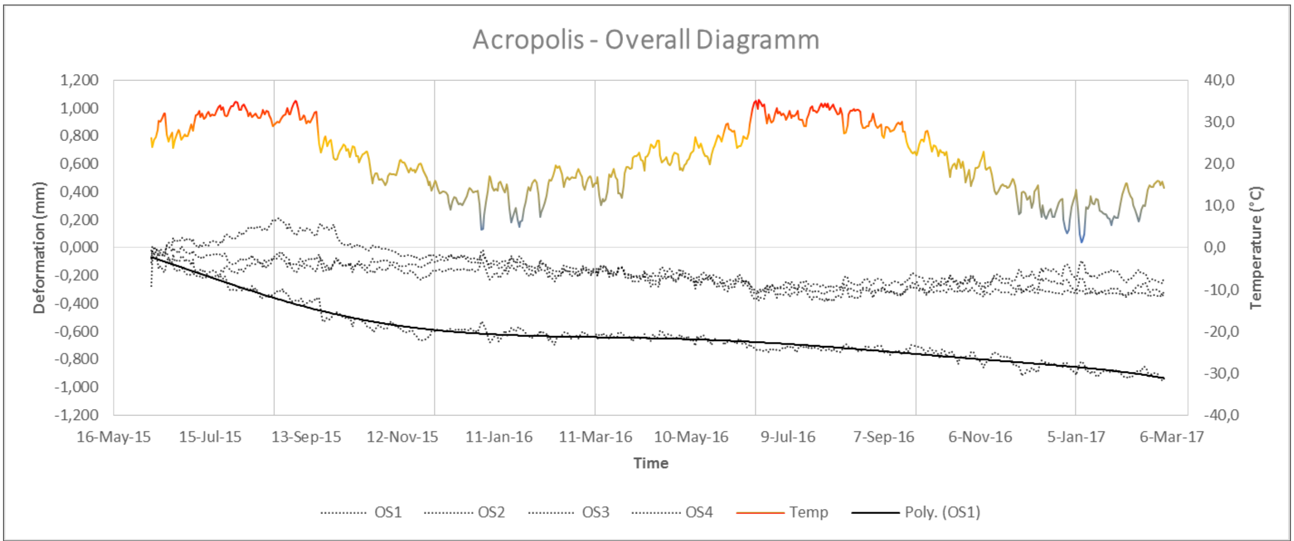
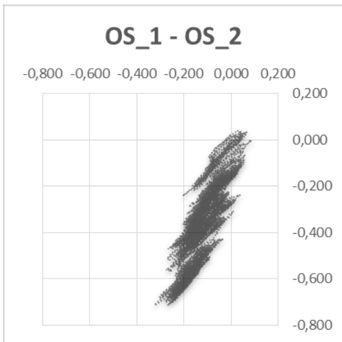


Figure 8: Overall Diagram of all sensors / Deformation in function of Temperature.

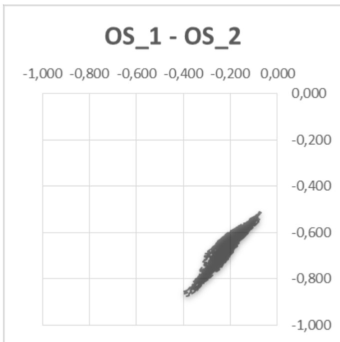
The overall diagram presents the time-history of the structure's western-side deformational behavior in both directions, vertical and horizontal, as detected by the external sensors in the western side OS_1 and OS_2 respectively. The dynamic evolution of compressive deformation in the vertical direction, in comparison to the lower participation of the horizontal one is depicted in the estimated overall deformational mechanism of the structural system and fully demonstrated in the records of the optical sensors.

	1st Monitoring period	2nd Monitoring period	3rd Monitoring period
Percentage of total vertical deformation	70%	15%	15%

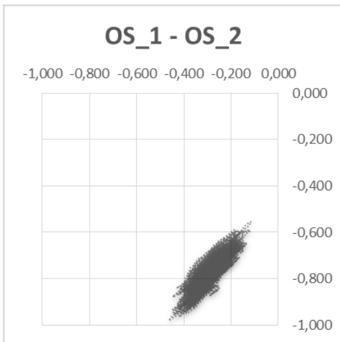
Table 1: Instrumentation.



1st Monitoring period
(2/6/2015 – 30/11/2015)

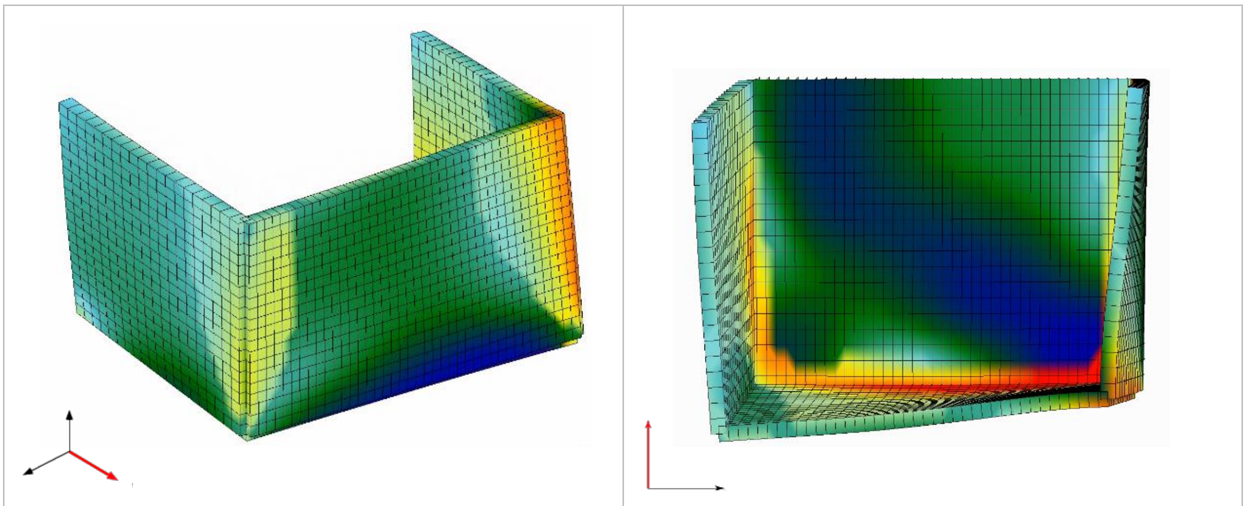


2nd Monitoring period
(1/12/2015 – 30/05/2016)



3rd Monitoring period
(1/6/2016 – 31/12/2016)

Figures 9-11: Biaxial deformational behavior over 3 monitoring periods.



(a)	(b)
Deformed state based on: (a) 3D view and (b) plan view	

Figure 12: Finite element analysis model.

Finally, it is important to mention that all conclusions regarding the deformational behavior of the structure, are solely attributable to static actions, as no dynamic event (earthquake, etc.) has been detected during the overall monitoring period. The monitoring of the dynamic response of the structural system under seismic stimulation is considered as necessary in order to fully assess the dynamic vulnerability of the bearing structure and assess its potential risks [6,7]. It should be pointed and that vibrational testing using modal parameters as a means to apply SHM on stiff masonry bodies, such as the "Propylaea", can be subject to critical difficulties [8]. Combination of other techniques, such as the one presented in this work appears to be a promising methodology for SHM of masonry structures.

5 CONCLUSIONS

The work presents the results of SHM investigation on a most prelevant historic structure. Use of the state – of – the – art fiber technology combined with an effective evaluation of the recorded data revealed the on – going deformation of the structure. Assessment of the results warrants avoidance of excessive damage and the implementation of precautionary measures.

The method is most suitable to monitor stiff monumental structures. It can also complement other instrumentation (e.g., deployment of accelerometers, GPS technology measurements) as well as FEM analysis in order to develop a reliable and effective SHM for flexible monumental structures.

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