ANYAGVIZSGÁLÓK LAPJA Elektronikus folyóirat
MINŐSÉGBIZTOSÍTÁS * ÁLLAPOTELLENŐRZÉS 2013/3-4

MÁRVÁNY DERÉKSZÖGŰ CSATLAKOZÁSOK MECHANIKAI VISELKEDÉSÉNEK VIZSGÁLATA INNOVATÍV KÍSÉRLETI TECHNIKÁKKAL

THE MECHANICAL RESPONSE OF MARBLE EPISTYLES STUDIED WITH THE AID OF INNOVATIVE EXPERIMENTAL TECHNIQUES

KOURKOULIS[1,] S. K., PASIOU[1] E. D., I. STAVRAKAS[2] ,. HLOUPIS[2] G, TRIANTIS[2] D.*

Kulcsszavak: *márvány, csatlakozások, tradicionális és innovatív kísérleti technikák*
Keywords: *marble, epistyles, traditional and innovative techniques*

ABSTRACT

An experimental protocol is presented aiming at the description of the mechanical behaviour and fracture of interconnected epistyles under shear loading. The originality of the study lies in the fact that a novel measuring/sensing system was improvised consisting of both traditional and innovative techniques, permitting (among others) pumping of data from the interior of the specimens rather than from its surface exclusively. It was concluded that both premature and final fractures follow precursor signals detected by both the Pressure Stimulated Currents and the Acoustic Emissions recorded by the constituent elements of the measuring/sensing system used.

ÖSSZEFOGLALÁS

Egy olyan kísérleti elrendezést mutatnak be, melynek segítségével vizsgálták a nyíró terhelésnek alávetett sarok csatlakozások mechanikai és törési viselkedését. A vizsgálatok újszerűsége abban áll, hogy egyidejűleg alkalmazták a tradicionális és innovatív technikákat, megvalósítva azt, hogy nemcsak a felületről, hanem az anyag belsejéből nyertek adatokat. Megállapították, mind a törést megelőző, mind pedig a végső törési folyamatot mind a nyomás okozta áram, mind pedig az az akusztikus emisszió jelei rögzíthetők voltak a használt mérő/érzékelő elemekkel.

1. INTRODUCTION

Most of ancient Greek temples are stone monuments with dry joints. The Parthenon Temple on the Acropolis of Athens, built using marble blocks joined to each other by means of iron connectors, is a typical example. Its epistyles are interconnected by either “I”-shaped connectors (in case of blocks within the same layer) or “dowels” (in case of blocks of sequential layers), as it is shown schematically in Fig.1. The connectors were placed in grooves (mortises) sculptured in the marble volume. As a final step these grooves were filled with molten lead [1]. In order to describe the all-over mechanical behaviour of such structures one should gain clear insight of the response of these joints to various combinations of mechanical loads.

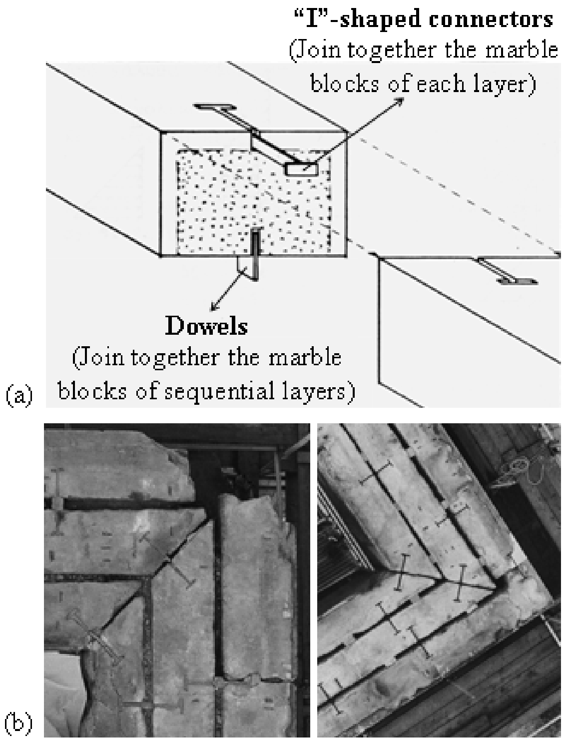


Figure 1: (a) Schematic representation of typical connections of marble blocks. (b) Epistyles of the Parthenon Temple before and after their restoration.

The Parthenon Temple is under restoration/conservation since the early eighties according to the latest achievements of all scientific branches involved [2]. For the restoration of its epistyles' interconnection the approach adopted by the scientific team responsible for the project (after very lengthy and laborious study [3-5]) is based on the substitution of damaged ancient iron connectors by (geometrical similar) titanium ones [6, 7] while instead of molten lead a suitable mortar is qualified [8-10].

[1] National Technical University of Athens, Dept. of Mechanics, Laboratory of Testing and Materials, Theocaris Bld, Zografou Campus, 157 73, Athens, Greece.
[2] Technological Educational Institution of Athens, Laboratory of Electrical Characterization of Materials and Electronic Devices, 122 10, Athens, Greece.
[*] Corresponding author

ANYAGVIZSGÁLÓK LAPJA Elektronikus folyóirat
MINŐSÉGBIZTOSÍTÁS * ÁLLAPOTELLENŐRZÉS 2013/3-4

The study of the mechanical response of the marble-mortar-titanium complex is very complicated since in case of excessive loading failure is expected to start from the interior of the complex, in the immediate vicinity of the corners of the grooves accommodating the metallic element. Pumping experimentally data from these regions is a very difficult laboratory task. It is however imperative to be accomplished, in order to explore the mechanisms leading to premature fracture of the marble body rather than of the metallic reinforcing element (as it is dictated by the “Venice Charter” [11]). Unfortunately traditional experimental techniques (like strain gauges) or even some modern ones (like the Digital Image Correlation - DIC) provide data pumped from the outer surface of the specimens although internal fracture mechanisms, are activated well before any visible phenomena appear on the surface. It is thus necessary to devise novel experimental systems which provide data directly from the interior of the specimens. Such systems are mainly based on detection of elastic waves (acoustic emissions), the electrical resistance variation [12] of the specimen etc. The main limitation is that their data are rather quantitative while a direct correlation with the respective data of traditional techniques is not as yet available.

In this context a combined experimental arrangement is described in the present study providing data from both the interior and the surface of a marble-cement-titanium complex, for comparison and calibration reasons. The insight gained demonstrated clearly that the innovative experimental techniques used permit the detection of precursor signals designating the onset of processes leading to catastrophic fractures while at the same time the combined use of traditional techniques permits quantification and calibration of the data gathered.

2 Materials, specimens and the experimental set-up

2.1 Materials and specimens

For the needs of the experimental protocol specimens were constructed simulating epistyles of ancient stone monuments mutually connected with a metallic “I-shaped” connector and suitable mortar. They were made of Dionysos marble due to the close similarity of its properties [13, 14] with the respective ones of the authentic material of the Temple i.e. Pentelic marble [15, 16]. The specimens were prepared by experienced technicians of the Parthenon work-site. After the two marble blocks (one of dimensions 25x26x20 cm^3 and a second one of dimensions 25x33x20 cm^3) were prepared a groove of depth equal to 7 cm was sculptured in both blocks, as it shown in Fig.2a. The titanium connector was placed in the groove which was then filled with liquid mortar (Fig.2b). The mortar consisted of one part of white cement and three parts of silica sand. Before tested the specimens were cured for at least 28 days.

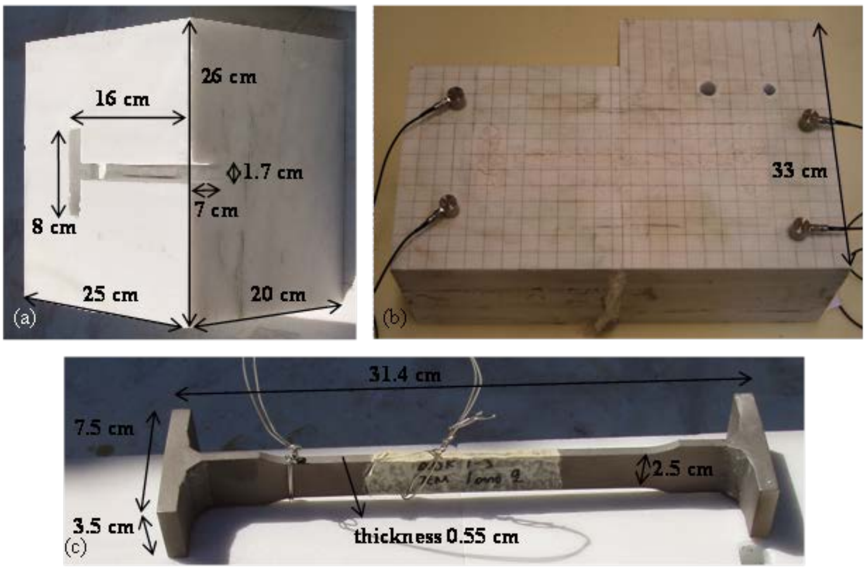


Figure 2: (a) The geometric characteristics of the fixed epistyle and the half groove.
(b) A typical specimen after its construction.
(c) A typical “I”-shaped metallic connector.

2.2 The experimental set-up and procedure

Given that the behaviour of connections under direct tension has been already studied [9, 10], the present protocol was focused to their behaviour under pure shear. Indeed in-situ observation of the Parthenon epistyles indicates that a number of them have failed by shear forces as it can be seen in Fig.3. The implementation of shear loading, which is by itself an experimental challenge, was achieved by a properly designed system of gripping and immobilizing devices, limiting to the minimum possible, any parasitic effects. These effects include bending and/or torsional moments which appear inevitably due to the inherent geometric asymmetries of the specimens (recall that the grooves and therefore the position of the connectors are not symmetric with respect to any plane of material symmetry of the complex, Figs.1,2). More specifically, the left epistyle was rigidly clamped on the loading frame by means of a rigid metallic plate, two "Γ" shaped rigid metallic elements and six (three in front of the specimen and three behind the specimen) extremely stiff threaded metallic bars. The loading platen was fixed on the other marble block with the aid of two "Π"-shaped metallic elements. A typical specimen placed on the frame's table is shown in Fig.4.

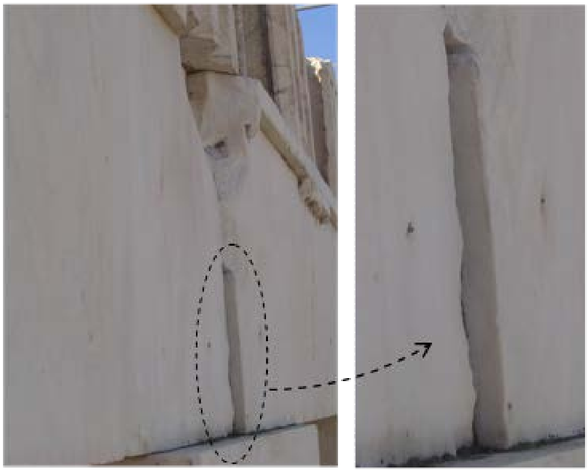


Figure 3: Transverse relative translation of two marble epistyles of the Parthenon Temple.

For the measurement of displacements and also for the detection of various signals from the interior of the specimens a novel complex system was improvised consisting of:

(a) A set-up permitting detection and measure of weak electrical current emissions (known as Pressure Stimulated Currents - PSC) [12]. For the application of the PSC technique a pair of electrodes was attached on the front surface of the specimens close to the area where marble's fracture is expected. The electrical current was measured with the aid of a Keithley 6517A electrometer resolving currents as low as 0.1 fA.
(b) A commercial 8-channel Acoustic Emission (AE) system (Physical Acoustics) permitting fig
(c) 3-D localization of acoustic events.
(d) A novel 3-D Digital Image Correlation (DIC) system by Limess.
(e) Two clip-gauge extensometers measuring the relative displacement of the two blocks of the specimens.
(f) Four traditional dial gauges measuring parasitic displacements and rotations.

The force was exerted using a stiff 250 kN INSTRON servo-hydraulic loading frame and it was measured with the aid of a 50 kN load cell, calibrated by means of a certified load ring. The experiments were carried under displacement control mode at a rate equal to 0.2 mm/sec.

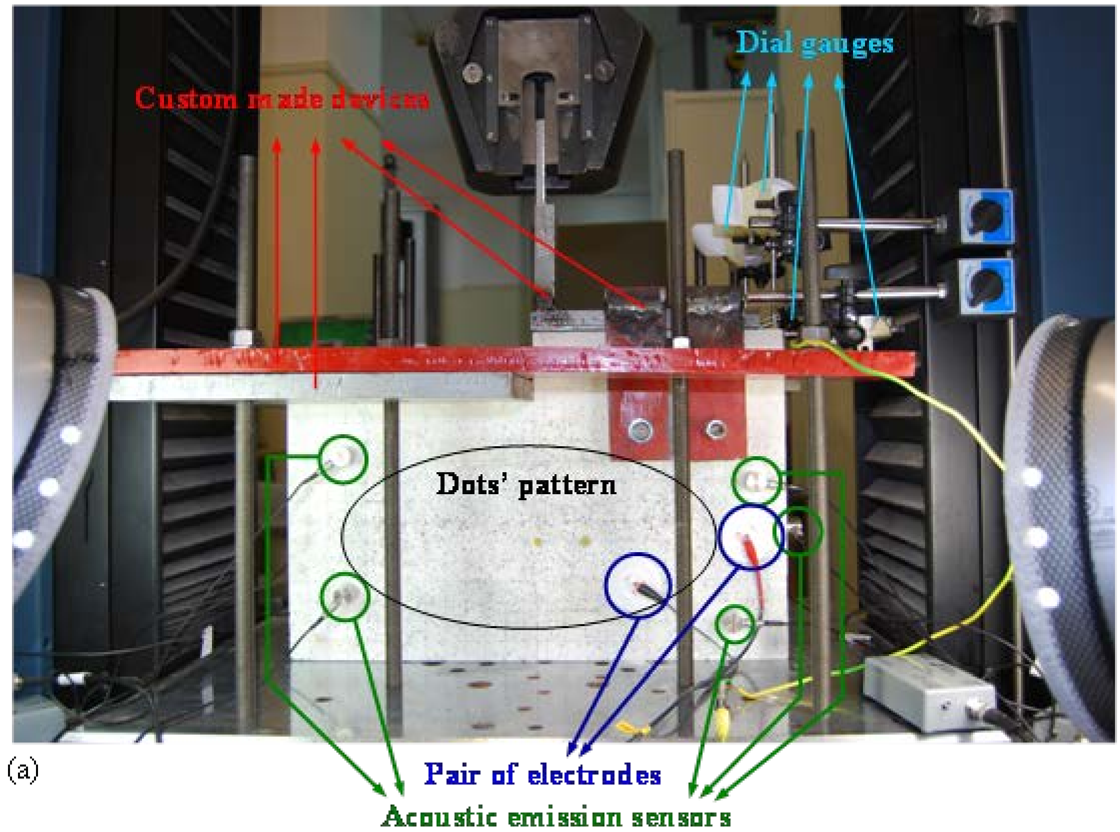
The constituent elements of this system can be seen in Fig.4.

3 Experimental results

The force induced by the loading frame on a typical specimen is plotted as a function of time in Fig.5. It is seen that after a small non-linear portion of very small slope (due to inevitable bedding errors) the force becomes an almost linear function of time until a limit equal to about 11.0 kN where a sudden load-drop is observed. From this point on the force becomes again a monotonous function of time (or equivalently of the displacement, since the test is under constant displacement control mode), almost linear until a level equal to about 20 kN. Then the force - displacement relation becomes strongly non-linear with gradually decreasing slope until a maximum force equal to 25.5 kN is reached. At this instant the moving marble block is fractured into two pieces as it is shown in Fig.6.

In Fig.5 the time variation of the pressure stimulated current (PSC) is also plotted in juxtaposition to that of the force. It is very interesting to note that a few seconds before the first abrupt load drop the PSC exhibits a significant decrease equal to about 40% of its current value. Then the value of PSC starts increasing according to a monotonous manner until the time instant at which the force-displacement curve starts changing its slope. From this instant on the time-dependence of PSC becomes wavy along an almost horizontal mid-line.

The two clip gauges capture also the results of the early damage mode detected either as load- or PSC-drop at a force level equal to 11.0 kN, as it shown in Figs.6b. In this figure the opening displacement recorded along the interfacial line of the two blocks (see Fig.4b), is plotted against time (or overall vertical displacement).



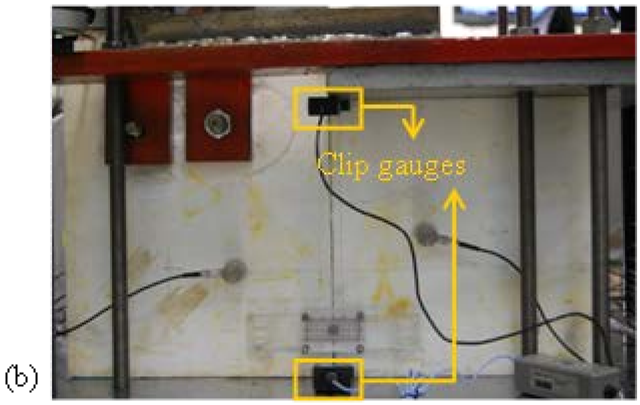


Figure 4: The experimental set-up.

(a) The dots' pattern for the DIC technique, the acoustic sensors and the electrodes for the PSC technique in the front surface of the specimen are clearly seen.

(b) The back surface of the specimen with the two clip gauges attached on it and two out of the eight acoustic sensors.

As a next step a 3D-location analysis of the acoustic events was performed. The first acoustic events appeared at the center of the specimen, in the vicinity of the epistyles' interface. As the force induced is increased the acoustic events in this

ANYAGVIZSGÁLÓK LAPJA Elektronikus folyóirat
MINŐSÉGBIZTOSÍTÁS * ÁLLAPOTELLENŐRZÉS 2013/3-4

area increase while additional events are also detected around the "heads" of the groove (Fig.7a). For an optimum representation of the acoustic events' location to be achieved, the specimen was divided in five parts as it is shown in Fig.7b. The cumulative number of events is plotted in Fig.7c, for each one of all five regions of Fig.7b, in juxtaposition to the respective variation of the force induced by the loading frame. To gain better insight of the cumulative number of events in the four regions surrounding the central one (which are shadowed by the number of events in the central portion of the specimen) they are plotted again in Fig.7d, without the respective variation at the central region. Well before the final fracture, the cumulative number of events at the lower part of the right epistyle starts exceeding the events at the other three parts. It is noticed that the number of events in all five regions becomes measurable only after the first load- (and PSC-) drop and then their number starts increasing abruptly until the final fracture of the moving block. It is very interesting to observe that as the fracture load level is approached the cumulative number of events at the lower part of the right epistyle (the area where the final catastrophic crack will appear) starts increasing at a higher rate exceeding significantly the events recorded at the other three parts. Moreover it is to be highlighted that the above change of the events accumulation rate at the region of final crack appearance is designated also by the slope-change of the load-displacement curve.

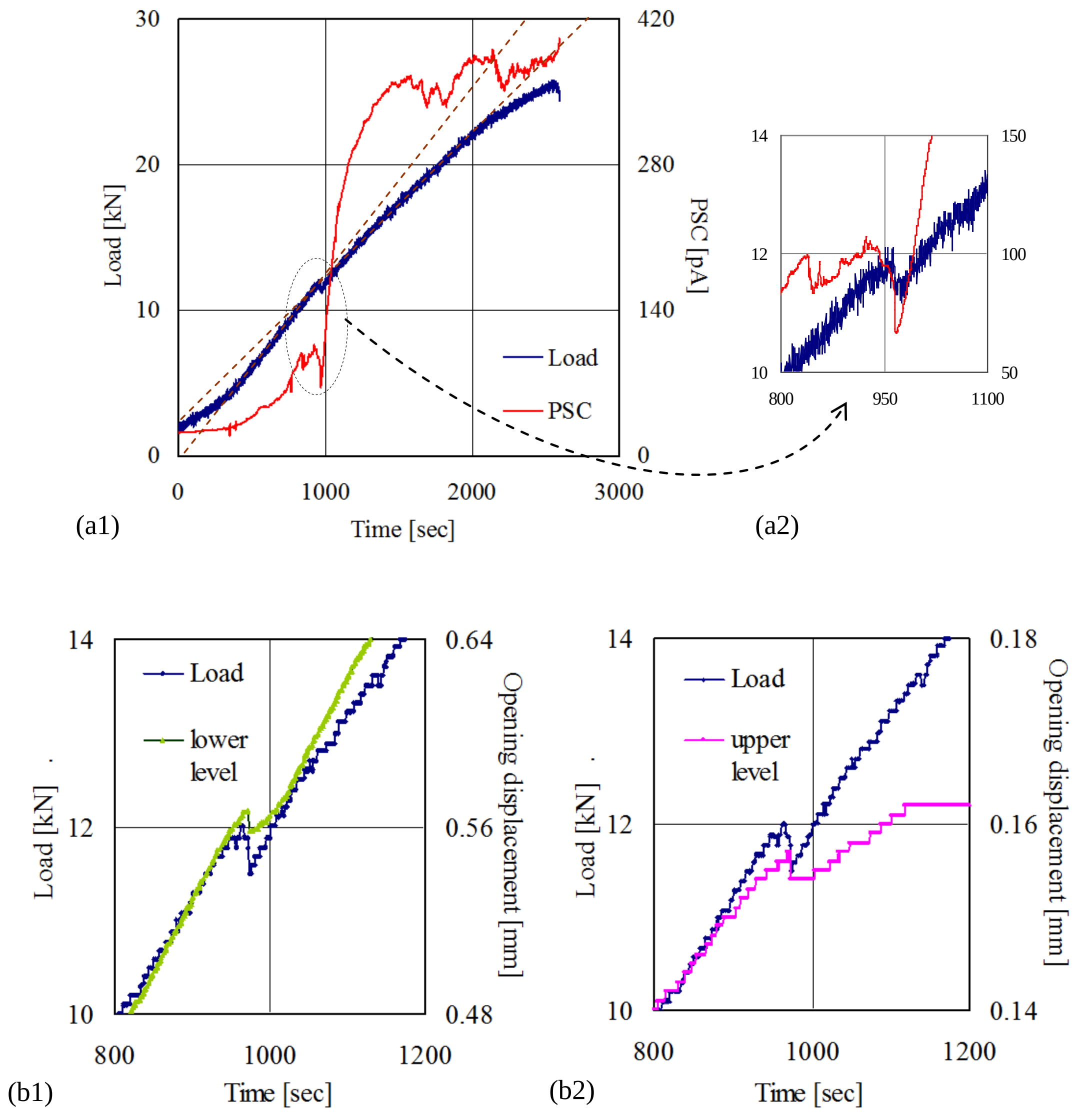


Figure 5: The variation of the load induced in juxtaposition to the electric current produced (a1). The load drop is accompanied by a simultaneous current drop (a2) and an instantaneous closing of the epistyles (b1,b2).

ANYAGVIZSGÁLÓK LAPJA
MINŐSÉGBIZTOSÍTÁS * ÁLLAPOTELLENŐRZÉS
Elektronikus folyóirat
2013/3-4

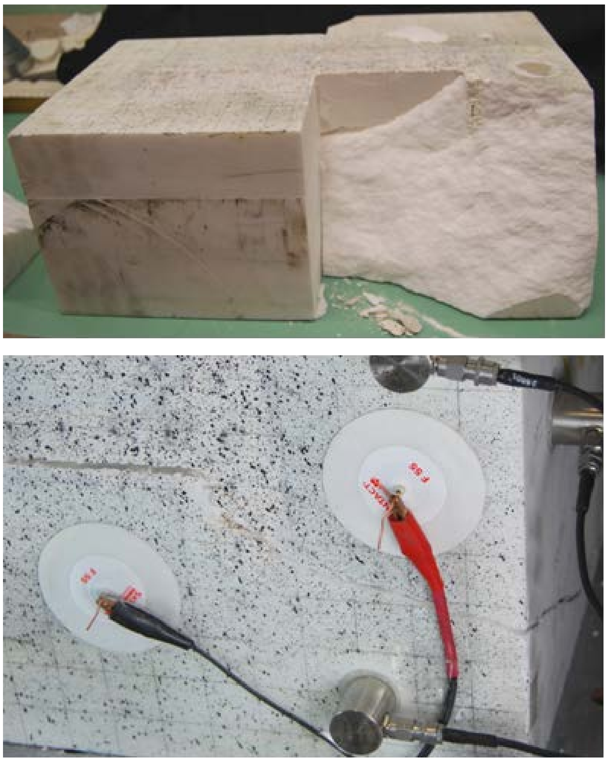


Figure 6: A typical conical fracture of the epistyle.

As far as it concerns the data gathered from the surface of the specimen using the DIC technique their main contribution was the detection and quantification of parasitic phenomena. In this direction the variation of the displacement field components along the x-axis (the axis of the connector) and y-axis were recorded as functions of time. It was definitely concluded that the right marble block (i.e. the one on which the load is applied) does not behave as a rigid body: Indeed as the load induced increases its right part experiences larger displacement along the y axis while its lower part experiences larger displacement along the x axis. The final distributions of these displacement components can be seen in Fig.8: The development of a parasitic bending moment in the xy-plane is obvious.

The DIC technique was proved very helpful also for the study of the mortar's behaviour around the marbles' interface. Focusing attention at the center of the specimen, two areas of mortar were isolated on both sides of the interface and their displacements along the x axis were plotted versus the force induced in Fig. 9. It is seen that initially (i.e. before the first load drop) the mortar behaves as a rigid body. From this point on it is evident that the mortar splits in two parts which start moving almost independently. The above observation supports the opinion that the first load drop is related to the failure of the mortar, in the region of the specimens' blocks interface.

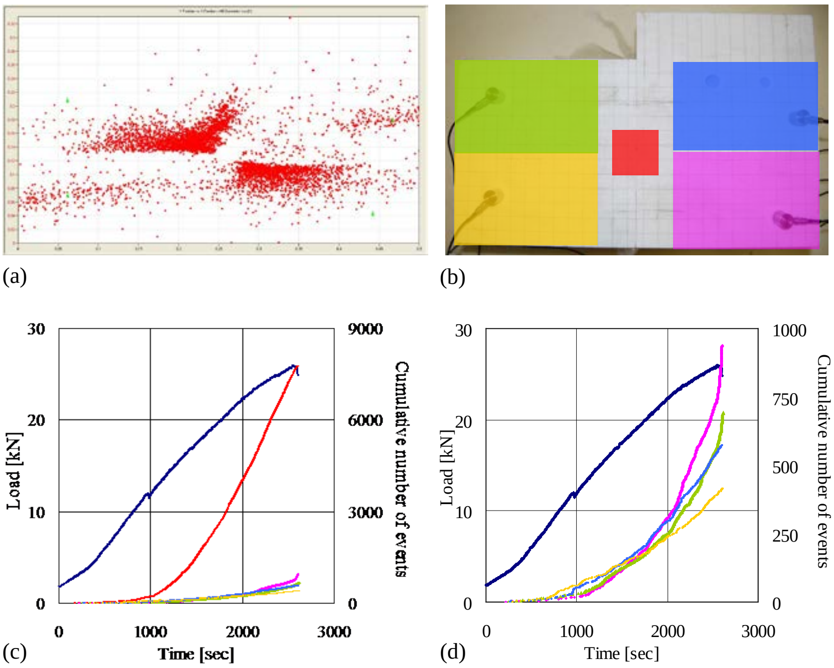
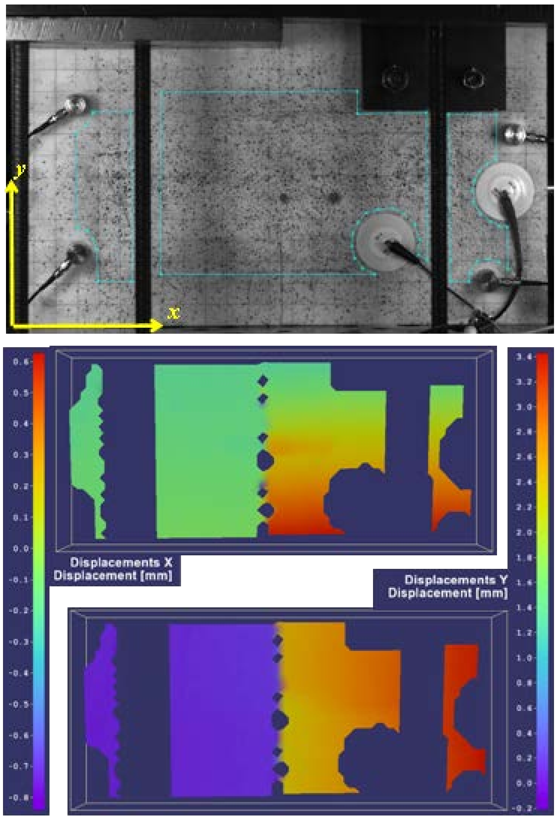


Figure 7: (a) The two dimensional distribution of the acoustic events.
(b) The five regions of the specimen in which the acoustic events were quantified.
(c) The cumulative number of acoustic events as detected in the five regions of the specimen and the load imposed vs. time.
(d) The cumulative number of acoustic events as detected in the four regions around the flanges of the

groove and the load imposed vs. time. It is clearly seen that the rate of the acoustic events produced in the region where the final fracture takes place becomes larger than the ones of the other three regions well before the crack appears.

(a)



(b)

Figure 8: (a) A typical photo as captured by the cameras of the DIC technique. (b) The distribution of the x- and y-component of the displacement field developed in the front surface of the specimen during the last photo captured before the epistyle's fracture.

4. Discussion and conclusions

Detailed analysis of all the data gathered from this combined "attack" indicates that not only the mortar's failure but also the fracture of the marble volume itself follows after clear warning signals recorded by both the PSC and AE sensors well before anything is macroscopically visible at the surface of the specimens.

Indeed the first failure of the specimen, i.e. the mortar's fracture accompanied by an early abrupt load, follows a significant current decrease while the acoustic events are localized in the immediate vicinity of the epistyles' interface. On the other hand the onset of the epistyles' final fracture follows also a clearly distinguishable PSC drop and an increase of the acoustic events in the specific area.

Concluding it could be safely stated that, although the laboratory reproduction of shear is itself a difficult experimental task (quite often shadowed by the presence of parasitic phenomena), the present protocol provided some rather interesting conclusions supporting the approach that the techniques used could be suggested as easy-to-use tools providing well in advance precursor signals about upcoming failures. Moreover the PSC technique due to its simplicity and the low cost of its application could be qualified as an irreplaceable tool for in-situ continuous spatially monitoring of the mechanical damage evolution.

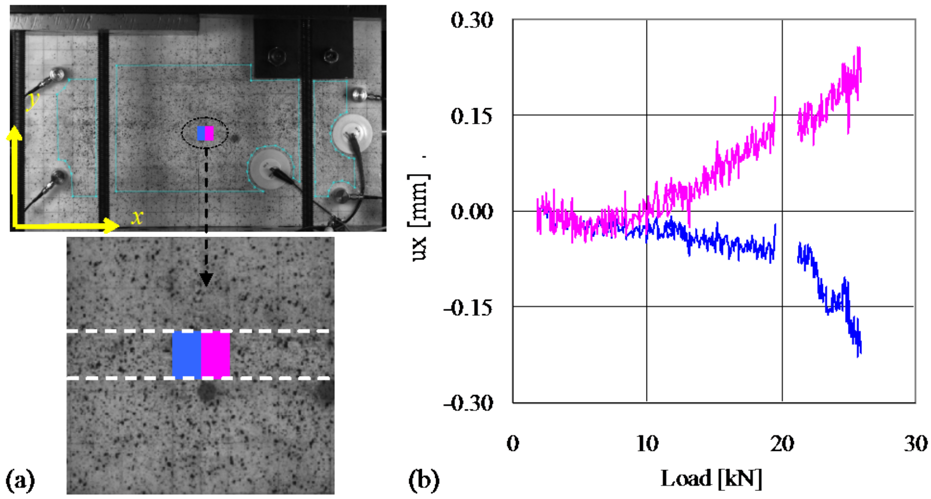


Figure 9: (a) The isolated mortar's areas used to study the state of the mortar. (b) The variation of the x-component of the displacement field developed in mortar on both sides of the epistyles' interface.

Acknowledgements

This research has been co-financed by the European Social Fund (ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework - Research Funding Program: Heracleitus II. Investing in knowledge society through the ESF. The kind assistance of Mr Nikos Toganidis (Former architect in-charge of the Parthenon's restoration worksite) and of Mrs Antigone Vrouva and Mr Ignatios Chiou (Civil Engineer and marble-craftsman, respectively, of the Parhenon restoration worksite) is kindly acknowledged.

References

1. Korres M., Bouras Ch. (1983). *Study for the Parthenon's restoration* (in Greek). Ministry of Culture, Committee for the Conservation of the Acropolis Monuments, Athens, Greece.
2. Egglezos D., Ioannidou M., Moullou D., Kalogeras I. (2013). Geotechnical issues of the Athenian Acropolis. In: Geotechnics and Heritage - Case Histories, E. Bilotta, A. Flora, S. Lirer, C. Viggiani (eds.), CRC Press, Chapter 2, 13–47.
3. Livadefs C.J. (1956). The structural iron of the Parthenon. Journal of the Iron and Steel Institute, 182:49-66.
4. Conofagos K., Papadimitriou G. (1981). The steel connectors of the Erechtheion were constructed with the same technique as the one used for "Damascus swords" in Middle Ages. Proceedings of the Academy of Athens, 56:173-190.
5. Varoufakis G.J. (1992). The iron clamps and dowels from the Parthenon and Erechthion. The Journal of the Historical Metallurgy Society, 26:1-18.
6. Skoulikidis Th. (1972). Deterioration des materiaux de construction et notamment des marbres par la corrosiond' acier incorpore. Cas de l' Acropole. In: Proceedings of the 1st International Symposium on the Deterioration of Building Stones, 11 - 16 September 1972, Centre de Recherches et d' Etudes Océanographiques, La Rochelle, France, Les Imprimeries Reunies de Chambery, 41-45.
7. Angelides S. (1976). Replacement of steel connectors by titanium alloy, The Acropolis. Problems-Studies-Measures to be taken. In: Proceedings of the 2nd International Symposium on the Deterioration of Building Stones, 27 September – 1 October 1976, Athens, Greece, National Technical University of Athens, 351-352.
8. Zambas C. (1992). Structural repairs to the monuments of the Acropolis - The Parthenon. In: Proceedings of the Institution of Civil Engineers, Civil Engineering, 92:166-176.
9. Zambas C. (1994). Study for the restoration of the Parthenon (in Greek), Vol.3b. Ministry of Culture, Committee for the Conservation of the Acropolis Monuments, Athens, Greece.
10. Zambas C., Bouras Ch. (2001). The works of the Committee for the Conservation of the Acropolis Monuments on the Athenian Acropolis. Archaeological Receipts Fund, Athens, Greece.
11. ICOMOS (1976). Venice Charter under review by ICOMOS, ICOMOS Newsletter, 8:.2.
12. Stavrakas I., Anastasiadis C., Triantis D., Vallianatos F. (2003). Natural Hazards and Earth System Sciences, 3: 243-247.
13. Exadaktylos G.E., Vardoulakis I., Kourkoulis S.K. (2001). Influence of Nonlinearity and Double Elasticity on Flexure of Rock Beams – II. Characterization of Dionysos Marble. International Journal of Solids and Structures 38: 4119-4145.
14. Kourkoulis S.K. (2012). Critical aspects of the mechanical behaviour and failure of Dionysos marble under direct tension. Journal of the Serbian Society for Computational Mechanics, 6: 199-215.
15. Tassogiannopoulos A.G. (1986). A contribution to the study of the properties of structural natural stones of Greece (in Greek). Ph.D. Dissertation, National Technical University of Athens, Greece.
16. Zambas C. (2004). Mechanical properties of Pentelik marble (in Greek). Ministry of Culture, Committee for the Preservation of Parthenon Publications, Athens, Greece.