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Recent advances in structural health monitoring of restored elements of marble monuments

S.K. Kourkoulis*

Laboratory for Testing and Materials, Department of Mechanics, School of Applied Methematical and Physical Sciences, National Technical University of Athens, Theocaris Building, Zografou Campus, 157 73 Athens, Greece

Abstract

The motive of this study is the need of scientific teams working for restoration projects of masterpieces of classical Greek antiquity to accurately describe the mechanical response of complexes made of building stones and reinforcing metallic elements. The study was presented during a special session, devoted to the memory of late Professor Pericles S. Theocaris, organized in the frame of the '*1st International Conference of the Greek Society of Experimental Mechanics of Materials*', It is part of a wider project, the aim of which is, among others, to assess the efficiency of structural health monitoring tools in predicting upcoming failure. It is proven that the time evolution of the outcomes of both the 'Acoustic Emissions' and the 'Pressure Stimulated Currents' techniques exhibit characteristic changes that could be considered as warnings that the system studied enters to its 'critical stage'.

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Keywords: Marble; cultural heritage; stuctural health monitoring; acoustic emissions; pressure stimulated currents

1. Introduction

The experimental study of the mechanical response of restored structural members of monuments made of natural building stones (marble, porous stones, shell stones etc.) is quite difficult for a variety of reasons (like, for example, the size effect dictating the preparation of specimens of quite large dimensions, the co-existence of incompatible, from the mechanical point of view, materials, the existence of hidden interfaces, the anisotropy and inhomogeneity of the

* Tel.: +30 210 7721263; fax: +30 210 7721301.
E-mail address: stakkour@central.ntua.gr
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materials, the presence of discontinuities like cracks, etc.). As a result, there is a scarce of experimental data in the relative international literature and this scarcity makes it very difficult for numerical models (that could offer a way out from the deadlock) to be properly calibrated and validated. In this context (and taking into account that analytic solutions concerning the distribution of stresses within restored structural elements is beyond any expectation), scientists working for the restoration/conservation of ancient stone monuments are forced to use increased safety factors during the design of the interventions. However, using increased safety factors (for example for the cross section of reinforcing elements) is not always desirable (or even permissible) because it leads to increased damage of the authentic structural members, in direct contradiction to the principles of the "Venice Charter" for the restoration of monuments.

It is now evident, that unavoidable uncertainties enter in the design of interventions rendering the continuous Structural Health Monitoring (SHM) of restored elements of ancient monuments a pressing demand (especially in case of Masterpieces of Cultural Heritage), in order to monitor even the slightest changes of their response, which may be the onset of catastrophic material failure. SHM systems and techniques, already in use today (both in the laboratory and, also, in field applications), include, for example, detection of Acoustic Emission (AE) events, the quantification of electric resistance changes of embedded fibers with carbon nanotubes, application of optical fibers, global positioning systems etc. Although such systems are long ago used for practical applications there are still quite a few limitations. For example, the data recorded are of qualitative rather than quantitative nature while a direct correlation with quantities measured using traditional sensing tools is not as yet available. Moreover, for the case of SHM of monuments, the application of these techniques is difficult. Indeed experienced personnel is required, the installation of the sensors for long-term sensing/monitoring is expensive while for some of these techniques application of the respective sensors demands interventions which are not permitted for aesthetic/archaeological reasons.

In this direction, the present study aims, to comparatively assess the efficiency of widely used sensing techniques and also to evaluate the potentialities of a novel sensing tool, known as Pressure Stimulated Currents (PSC) (Stavrakas et al. (2004)). The main advantages of the latter can be very shortly summarized to the relatively small size of the sensors required, the simple complementary set-up and, finally, the low application cost. Special attention is paid to the ultimate loading levels, in an effort to check whether it is possible to timely predict the entrance of the element monitored to its "critical stage", namely to predict states of impending failure. This study, implemented in collaboration with the Laboratory of Electronic Devices and Materials of the University of West Attica, is in fact the continuation of a project that was started around 1978 by late Professor Pericles S. Theocaris. In its early steps, the aim of the project was to experimentally assess the mechanical response of the Parthenon Temple after the completion of a pioneering restoration project. In this context, an accurate copy of the restored temple was constructed, made of a photo-elastic material (Fig.1). Various loading scenarios were simulated and very interesting conclusions were drawn, especially concerning the critical role of the tensile stresses that would be developed at the upper part of the columns of the Temple in case of seismic loading (Theocaris and Coroneos (1979)).

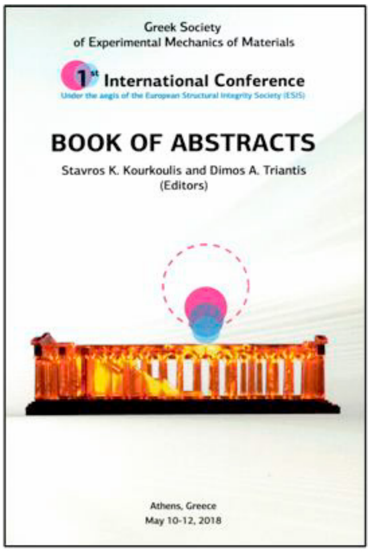


Fig. 1. The copy of the Parthenon Temple, prepared by P.S. Theocaris in his study for the assessment of the mechanical response of the Parthenon Temple after the completion of a restoration project proposed at that era. The study was implemented by means of photo-elasticity (upper photo). The specific photo was used as the main theme of the cover page of the book of abstracts of the "1st International Conference of the Greek Society of Experimental Mechanics of Materials" (right photo).

2. The experimental protocols: Elementary and structural tests

In order to achieve the goals of the present study, advantage is taken of the results of two ongoing experimental protocols. The first one deals with elementary tests, i.e. direct tension loading of standardized Double Edged Notched (DEN) specimens made of Dionysos marble. The specific marble variety was chosen since it is widely used for the construction of copies of destroyed structural elements of the monuments of the Acropolis of Athens. The mechanical properties of Dionysos marble are well documented in literature (Kourkoulis et al. (1999); Exadaktylos et al. (2001)). They strongly depend on the size of the specimens used for their determination, a phenomenon known as "size effect", characterizing the mechanical behaviour of most natural building stones (Kourkoulis and Ganniari-Papageorgiou (2010)). Especially for Dionysos marble the phenomenon is extremely pronounced. Moreover, Dionysos marble is characterized by bimodularity and anisotropy. More specifically, it is an orthotropic material, however, in most practical applications it is usually considered as transversely isotropic (Kourkoulis et al. (1999)).

The experiments are implemented using an INSTRON servo-hydraulic loading frame (capacity 250 kN) under displacement-control mode, at a very low rate, ensuring quasi-brittle conditions (Fig.1). During the tests a series of quantities were recorded including purely mechanical ones (load, displacement, notch mouth opening displacement) in combination with quantities related to the acoustic- (Acoustic Emissions, AE) and to the electric activity (Pressure Stimulated Currents, PSC). Both traditional (electrical strain gauges, LVDTs and clip-gauges) and innovative (acoustic sensors, electrodes, digital image correlation cameras, ultra high speed camera) sensing systems were used in a combined manner, in order to obtain the maximum possible volume of data from each experiment.

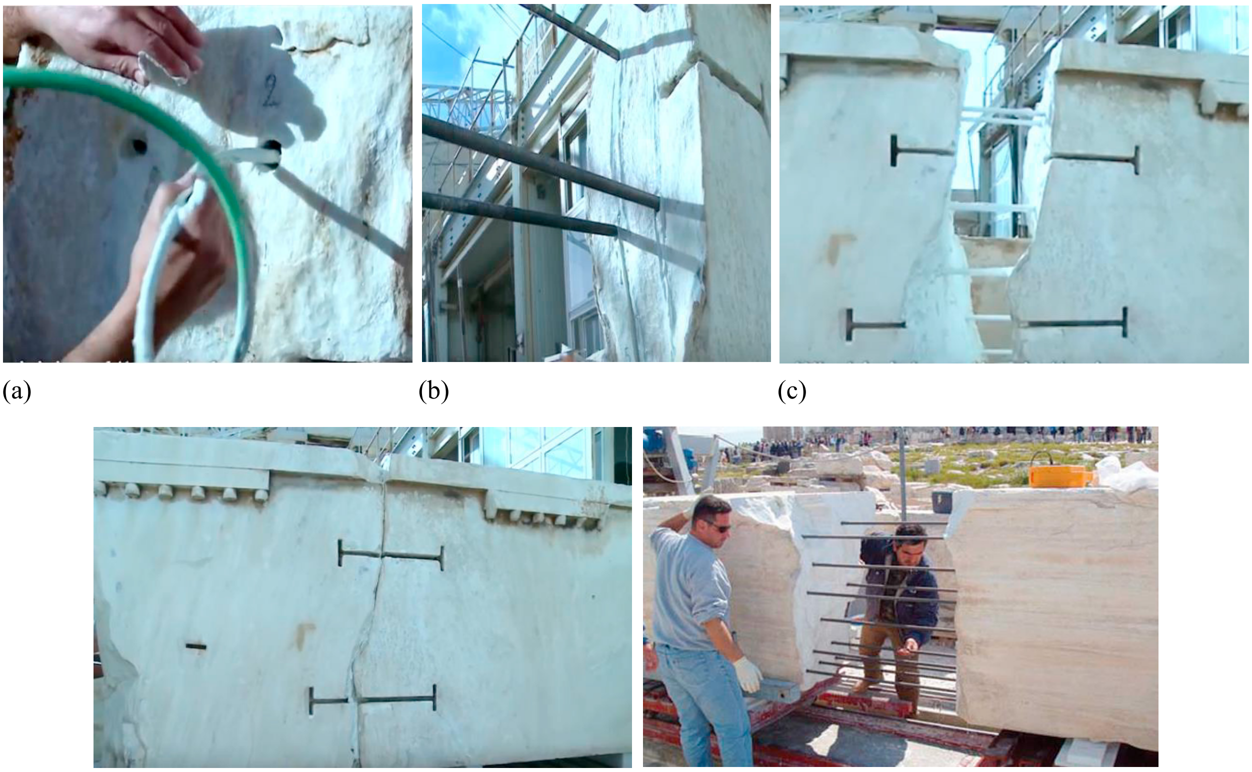
The idea behind this protocol, for which the damage mechanisms (mode-I cracking) and the most severe damage accumulation locations (crowns of the notches) are a-priori known, is to comparatively consider the data provided by the AE- and the PSC-techniques in the direction of assessing their capability to properly "follow" the damage mechanisms activated and, also, to provide indicators warning about upcoming failure (pre-failure indicators). A detailed description of the experimental set-up can be found in a recent article by Kourkoulis et al. (2018).

The second protocol considered includes structural tests, i.e., experiments with non-standardized specimens which simulate actual structural members. More specifically, copies of a characteristic restored epistyle of the Parthenon temple (under a scale of 1:3 in order to eliminate the potential role of the pronounced "size effect") are tested. The specimens consist of two parts, simulating the two major fragments of the actual epistyle, restored by three pairs of threaded titanium bars, according to the pioneering technique developed by the scientific team working for the ongoing conservation/restoration project of the Athenian Acropolis monuments (Zambas (1992)). According to this technique, fragmented epistyles are joined together by drilling holes (the number and diameter of which is dictated by the load

Fig. 2. A typical DEN specimen before the loading procedure (left photo) and the same specimen after fracture (right photo). It is worth noticing that the crack path is not normal to the loading axis, obviously due to the orientation of the material layers (Kourkoulis et al. (2018)).

that is expected to be transferred by the epistyle after it is placed in its original position) on the body of each fragment (Fig.3a). The wholes of one of the two fragments are then filled with a suitable liquid cementitious material and the treaded titanium bars are driven in the filled holes (Figs.3(a,b)). After a curing period of about thirty days the holes of the second fragment are, also, filled with liquid cementitious material, the faces of the two fragments are covered with the same liquid paste and the two fragments are driven against each other (Fig.3(c,d)). The complex is then left to cure for another thirty days. The technique has been widely and successfully applied, independently of the size of the epistyle, by properly adjusting the position of the reinforcing bars, their diameter and their number (Fig.3e).

The geometry and dimensions of the specimens, as well as the position and the anchoring length of the reinforcing bars are shown in Fig.4. It can be seen that the specimens were composed by joining together two asymmetric marble blocks. The fracture surface was inclined with respect to the longitudinal axis of the restored epistyle by an angle equal to 70^o (in an attempt to enrich the data concerning the role of the specific parameter provided earlier by Kourkoulis et al. (2012). Ten-point bending was imposed with the aid of an extremely stiff AMSLER servo-hydraulic loading frame (Capacity 6 MN) and a specially designed system of seven "I"-shaped beams. The specific loading scheme is in accordance to the suggestions of older studies by Kourkoulis et al. (2010), concerning the optimum laboratory simulation of the actual loading conditions of the epistyles (after they are placed in their original position), which is in fact loading by the "dead weight" of the superimposed structural elements. The tests were, again, implemented under displacement-control mode at a rate ensuring quasi-static loading conditions. The same combination of traditional and innovative sensing systems, described in the previous experimental protocol, was used. The only difference was that now an Optic Fiber was placed along one of the two reinforcing bars of the lowest pair in an attempt to measure directly the axial strain developed along the bar, although the results were not very encouraging. A detailed description of the overall experimental set-up can be found in a recent paper by Kourkoulis and Dakanali (2017).



(a) (b) (c)

(d) (e)

Fig. 3. (a) Filling the drilled holes with liquid cementitious paste; (b) Driving threaded titanium bars in the holes of the one of the two fragments; (c) The two fragments are driven against each other; (d) The restored epistyle (of the Parthenon Temple) before polaced in its original position; (e) Restoring a huge epistyle of the Propylaea of the Acropolis of Athens.

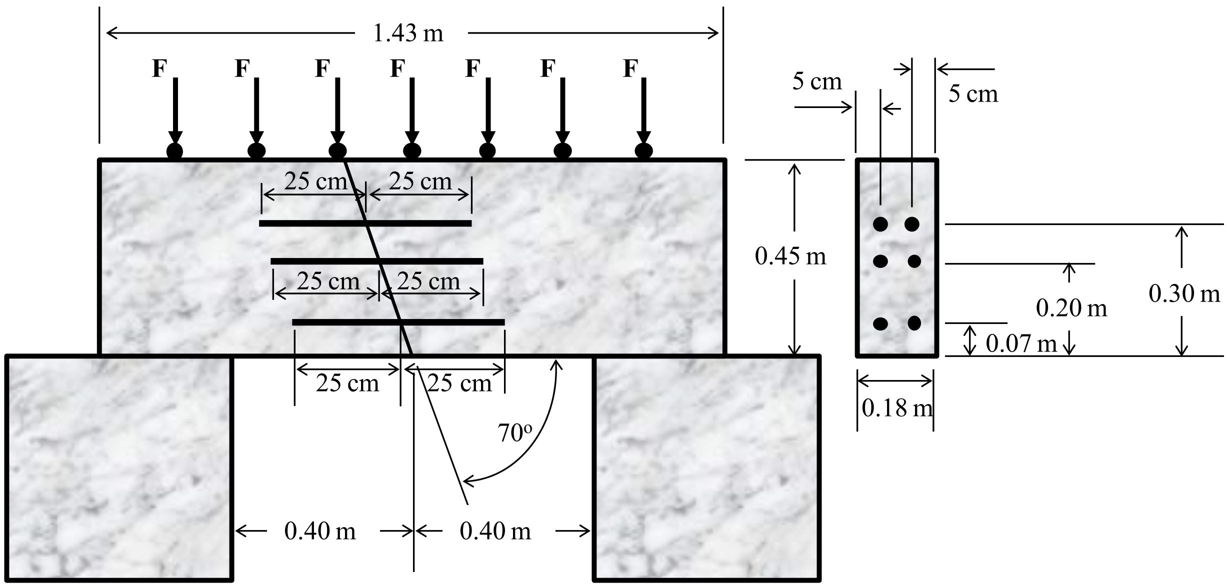


Fig. 4. The geometry and the dimensions of the specimen for the structural tests

3. Experimental results

3.1. Elementary tests

Typical results from the first protocol (i.e., DEN tension tests) are presented in Fig.5a, in which the time evolution of the load imposed is plotted in juxtaposition to that of the PSC. As it is expected for a brittle material, like Dionysos marble (Kourkoulis et al. (1999)), the load is almost linearly depending on time, which is equivalent to linear dependence on elongation, given that the tests were implemented under displacement control mode. In other words, no kind of pre-failure warning signs can be detected in the specific (load-time) space. On the other hand, the time evolution of the PSC is by no means linear. For about two thirds of the test's duration (i.e., up to point B in Fig.5a) the electric activity is negligible and the PSC is more or less constant equal to zero, excluding some local abrupt disturbances.

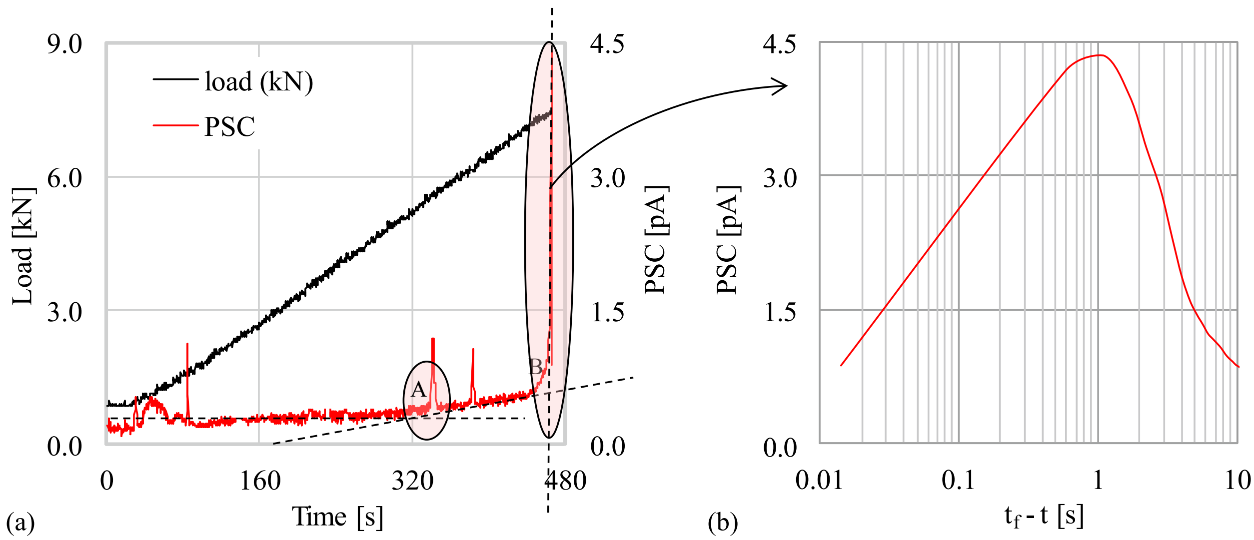


Fig. 5. (a) The load imposed on a typical DEN specimen under tension in juxtaposition to the PSC; (b) The electric activity in terms of the PSC during the last ten seconds of the experiment against the (t_f-t) parameter in a semi-logarithmic plot.

Then the PSC starts increasing smoothly according to an almost linear manner. A little before fracture it exhibits a dramatic increase (point B in Fig.5a) and then it drops quite abruptly, just before the fragmentation of the specimen.

According to the respective literature (Stavrakas et al. (2004)), the increase of the PSC designates an increased rate of micro-cracking within the specimen. Moreover, a sudden increase of the PSC accompanied by an abrupt drop is a clear indication that the system (specimen) has entered in its "critical stage" and fracture is impending (Triantis et al. (2012)). Motivated by this argumentation, it was decided to reconsider the time evolution of the PSC using an "inverse" time arrow. In other words, the time evolution of the PSC is considered against the (t_f-t) parameter, where t_f represents the time instant of fracture (Fig.5b). The plot is realized in a semi-logarithmic system, in an attempt to enlighten what happens during the very last loading steps, taking into account that internal events of any type (mode-I and mode-II micro-cracking, coalescence of micro-cracks, generation of macro-cracks etc.) are very densely packed in time while fracture is approaching. As it is seen from Fig.5b, almost 10 seconds before fracture the value of PSC starts increasing quite abruptly providing an excellent pre-failure warning. About 1 second before fracture its value decreases, tending to zero, indicating that a fatal macro-crack started propagating interrupting the electric paths.

The data concerning the acoustic activity are plotted in Fig.6a. As a first step, the cumulative number of acoustic hits (CNAH) is plotted versus time in Fig.6a, in juxtaposition to the load imposed. Again, the time evolution of the CNAH is by no means linear, contrary to that of the load. Indeed, for about two thirds of the test's duration the specimen is either "silent", i.e., the acoustic activity is negligible (0<t<160 s), or the CNAH increases according to an almost imperceptible manner (160<t<320 s). Then, at a time instant equal to about two thirds of the test's duration (point A in Fig.6a) the acoustic activity is strongly amplified and the CNAH increases rapidly. Finally, a few seconds before fracture, the acoustic activity is amplified further becoming almost "explosive" (point B in Fig.6a).

The time evolution of the CNAH is in excellent qualitative agreement with that of the PSC described in previous paragraph (Fig.5a). It was thus decided to focus again attention on the acoustic activity (recorded by the sensor closer to the notch from which fracture started) during the last loading steps, in an attempt to gain insight about the damage mechanisms activated during this critical time interval. In this context, the average frequency, AF, of the acoustic hits is plotted against their rise time in Fig.6b. The specific way of representing the data provided by the acoustic sensors is considered that provides information about the nature of the source of the acoustic signals (Aggelis (2011)). More specifically, it is considered that signals of high AF and low rise time are due to "tensile" (mode-I) cracks while signals of low AF and high rise time are due to other cracking modes (mode-II or mixed-mode) or due to friction. For the experiment under consideration it is seen that during the time interval 1 s<t_f-t<10 s (corresponding to the very rapid increase of the PSC discussed in Fig.5b) the acoustic signals are packed close to the AF axis indicating mode-I micro-cracking. On the other hand during the very last second (corresponding to the rapid decrease of the PSC) signals with increased rise time are recorded. According to Kourkoulis et al. (2018) the specific behaviour indicates propagation of macro-cracks traversing the material layers of Dionysos marble generating shear phenomena.

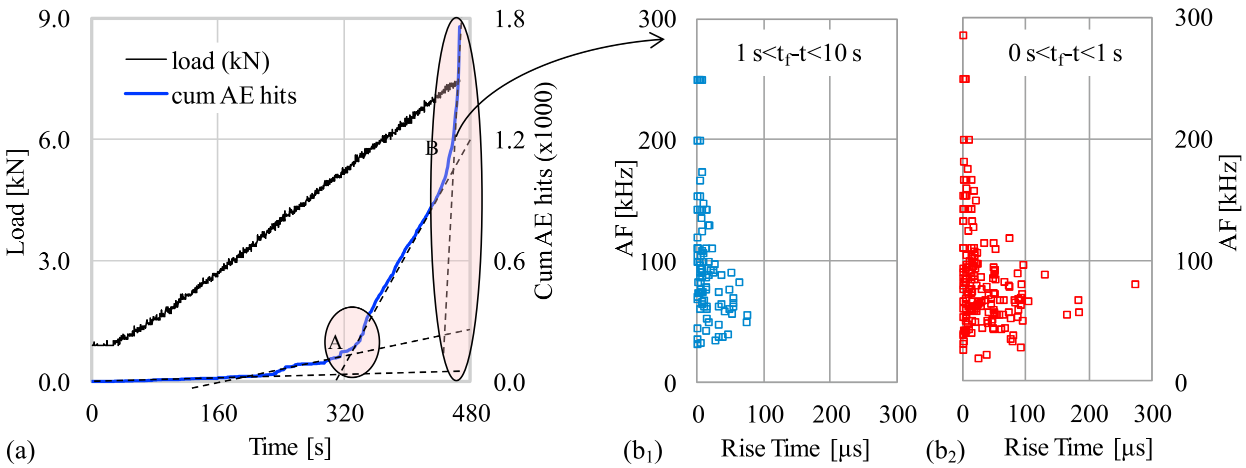


Fig. 6. (a) The load imposed on a typical DEN specimen under tension in juxtaposition to the cumulative number of acoustic hits; (b) The average frequency of the hits versus the respective rise time for 1 s<t_f-t<10 s (b1) and 0 s<t_f-t<1 s (b2).

3.2. Structural tests

The mechanical response of the restored epistyle is presented in Fig.7a, in which the overall load imposed is plotted against the deflection of the central cross section. Ignoring an initial settling portion (0A), the plot is characterized by an almost linear response (ABC) for almost three quarters of the maximum load attained (although a slight slope change is observed at about 50% (point B) of the peak load). At a load level equal to about 330 kN (point C), approaching 90% of its peak value, a load was observed due to the fracture of the upper corner of the left fragment (encircled in the photo embedded in Fig.7b). Then the load recovered reaching its maximum value (point E), equal to about 375 kN, when the lower level of reinforcing bars fractured suddenly leading the structure to collapse.

An alternative representation of the epistyles' mechanical response is shown in Fig.7b, in which the overall load is plotted against the opening of the fault, as it was measured both at the lowest edge of the specimen (y=0.0 m) and also at the first level of reinforcing bars (y=0.07 m). The characteristic points A to E mentioned in Fig.7a are again clearly visible. The main difference is that linearity is now restricted up to a load level of about 275 kN (point B΄). Moreover, after the first load drop (point D) a plateau appears (DD΄ in Fig.7b). Taking into account that pull-out was totally suppressed it can be safely concluded that this plateau can be only attributed to plastic flow of the reinforcing bars. In general, the overall form of both plots of Fig.7b closely resembles that of tension tests of ductile metallic materials.

The data recorded with the aid of the PSC- and the AE-techniques techniques are shown in Fig.8. The time evolution of the PSC is plotted in Fig.8a, in juxtaposition to that of the load imposed. The duration of the test can be split in four distinct intervals, in full accordance to the respective load-deflection plot (Fig.7a). It is extremely important to note that at point B, where an imperceptible slope change of the load-time curve is observed, the PSC changes its rate of increase and after a while it decreases attaining a local minimum before the local fracture of the left fragment's corner (point C). Then PSC recovers, however after point D (the onset of the plateau shown in Fig.7b) it decreases, indicating that no more damage due to micro-cracking is accumulated, supporting the previous conclusion that the plateau is not related to damage of the marble volumes but rather it is due to plastic flow of the reinforcing bars.

The acoustic activity during the whole loading procedure is shown in Fig.8b, in which the duration and the energy of the acoustic hits recorded by the AE sensors are plotted versus time. The four intervals described in Fig.8a are again clearly distinguishable. As it is expected, the specimen is almost "silent" during the first time interval (corresponding to the specimen's settling phase). During the second time interval, the acoustic activity is almost constant, concerning both the energy and the duration of the signals. Then, during the third interval (preceding the local fracture of the left fragment) the acoustic activity is strongly amplified and signals of extremely high energy and increased duration are recorded. What is, however, quite remarkable, is that during the fourth interval (in fact during the plateau of Fig.7b) the acoustic activity is quite limited, indicating the absence of intense micro-cracking within the marble volume, in full accordance to the respective conclusion drawn with the aid of the PSC technique.

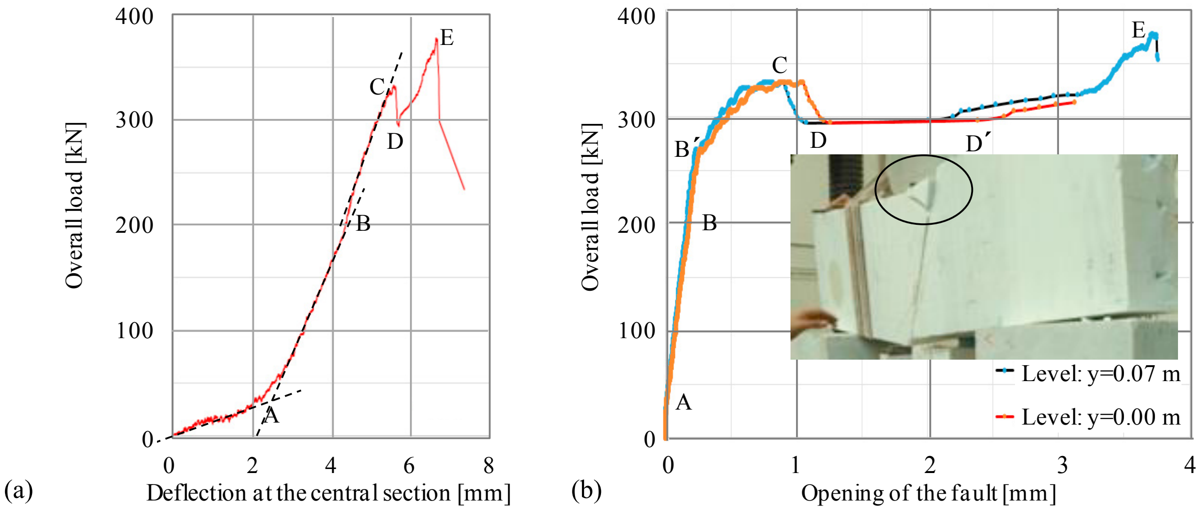


Fig. 7. The overall load imposed on the epistyle versus (a) the deflection of its mid-section and (b) the opening of the fault at two height levels.

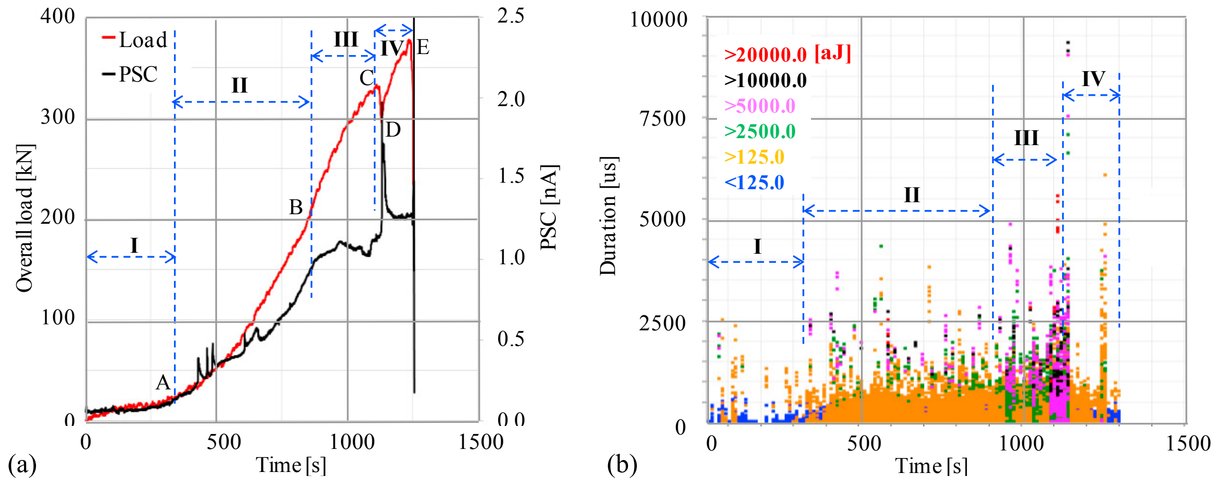


Fig. 8. (a) The PSC and the load applied versus time; (b) The duration and the energy of the acoustic signals versus time.

4. Discussion and conclusions

The response of elementary and structural mechanical systems was monitored using a sensing system combining traditional and innovative techniques. The novel ones (PSC, AE) were proven very effective and their outcomes were in excellent mutual agreement and, also, in good accordance with the respective data of the traditional techniques. Moreover, they were proven advantageous because they provided data from the interior of the specimens, which is of crucial importance in case of complexes with internal interfaces (as it is for example the case of restored epistyles).

Concerning the entrance of the system to its "critical stage" (impending fracture) it was proven that the PSC technique provides clearly distinguishable pre-failure indicators: Well before fracture, the electric current recorded exhibits characteristic changes attaining their peak several seconds before fracture. This behaviour was found in excellent agreement to the data of the AE technique (either analyzed on the basis of the cumulative number of acoustic hits or of the energy and the duration of the acoustic signals). It is thus safely concluded that the potentialities of the PSC technique as a Structural Health Monitoring system must be further explored, taking into account its advantages (low cost and small size of the sensors). The latter renders the PSC technique quite attractive for monitoring ancient stone or marble monuments for which the aesthetic aspect (dictating the use of small sensors) is crucial while, on the other hand, there is an increased need for sensors, especially in case of monuments with many restored structural elements.

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