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Procedia Structural Integrity 2 (2016) 2865–2872

Structural Integrity Procedia

www.elsevier.com/locate/procedia

21st European Conference on Fracture, ECF21, 20-24 June 2016, Catania, Italy

Pull-out of threaded reinforcing bars from marble blocks

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Abstract

Rejoining fragmented marble structural members of the Acropolis of Athens monuments is achieved by inserting threaded titanium bars into holes pre-drilled in the body of the members. Then the holes are filled with liquid cementitious material. This study aims to investigate the extraction of the bars from the marble volume (pull-out) in an effort to enlighten the mechanisms activated before and during the phenomenon. The study is implemented experimentally. The main problem hard to overcome was the fact that the weak link of the marble-cement-titanium complex, which is the marble-cement interface, is inaccessible for traditional sensing techniques. In this context innovative techniques were employed (Acoustic Emission and Pressure Stimulated Currents), which can detect failure and damages at the interior of the complex. Traditional sensing techniques were used in parallel mainly for calibration / validation reasons. The specimens, prepared by experienced personnel of the Parthenon's worksite, were prisms made of Dionysos marble. Threaded titanium bars were inserted into through holes filled with a liquid cement paste. The quantities recorded during the tests were the load, the displacement, the bar's axial strain and relative slip with respect to the marble, the electrical signals emitted and the acoustic emissions produced. Conclusions are drawn concerning correlations between the above quantities. The data gathered were then used to validate numerical models which will be used for parametric analyses.

Keywords: marble; stone monuments; pull-out; restoration; contact interfaces; acoustic emission; pressure stimulated currents

1. Introduction

The structural restoration of stone monuments is a complicated task that demands the co-operation of specialists from various scientific disciplines such as archeologists, architects, structural engineers, chemical engineers and survey engineers. The final decision made is usually a compromise between many and contradictory points of view. The basic problem in case of marble monuments is the restoration of their monolithic character which is sometimes

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10.1016/j.prostr.2016.06.358

badly damaged. In order for the structural integrity of such monuments to be properly restored, a pioneer technique was developed, some decades ago, by scientists working for the restoration of the Acropolis of Athens. According to this technique the fractured marble elements are connected by inserting titanium bars into pre-drilled holes. The adhesion between marble and bars is achieved by a proper white cement paste (Korres et al., 1989). The Acropolis' restoration project is based on the principles of Venice Charter, the worldwide accepted framework, which dictates the principles of any intervention: reversibility (if needed, the monument could be brought to its state prior to the intervention), minimization of the interventions to the extent that guarantees protection of the authentic material from further damage (for this reason the number of titanium bars required by the connection's design, should be the smallest possible) and finally compatibility between the materials used for the restoration and the authentic ones.

The basic building material of the Acropolis monuments is a kind of fine white marble quarried from mount Pentelicon. Since the specific quarries are nowadays inaccessible, Dionysos marble was chosen as the most suitable substitute material because its physical and mechanical properties are very close to those of the authentic marble (Kourkoulis et al., 1999). On the other hand, titanium is a relatively light metal of exceptionally high corrosion resistance (Penelis, 1996). For this reason it was selected as the most suitable reinforcement material. Finally, the filling paste used (binder and water without any aggregate) must absorb vibrations and minor deformations (in order to protect the structural member) since it comes into direct contact with the marble. The paste's quality should assure coherence and durability over time while its strength must not exceed that of the damaged marble since in case of overload it should be the restoration material that fails rather than the authentic stone (Aggelakopoulou, 2013).

The present work is part of a wider research project in progress, the aim of which is to quantify the parameters influencing the pull-out phenomenon, i.e. the gradual or abrupt slip of the reinforcing bars, without prior failure of neither the bar nor the marble. More specifically this study is devoted to the investigation of the progressive failure of the interfaces between the constituent elements of the marble-cement paste-titanium complex, by using sensing techniques which permit pumping data from the interior of the specimens. In this direction the Acoustic Emission (AE) and the Pressure Stimulated Currents (PSC) techniques were used, a choice based, among others, on the fact that the signals recorded using the above techniques are considered as pre-failure indicators (Triantis et al., 2008).

2. Experimental procedure

The specimens were made of Dionysos marble blocks (Fig.1). A central through hole (of diameter equal to 14 mm), was drilled on the blocks and was filled with liquid cementitious material. A threaded titanium bar, of outer diameter equal to d_{rod}=11.0 mm, was driven in the hole as it is shown in Figs.1(a-d). Three classes of blocks were tested denoted as Type A, B and C in Fig.1e. The anchoring length of the bar is 7.5 cm, i.e. equal to half of the height of Type C specimens (Fig.1f). The experiments were implemented after a 28-days curing period.

The marble block was then properly constrained by a rigid metallic plate with a hole in its center. The plate used for the type A specimens is shown in Fig.2a while that for types B and C is shown in Fig.2b. The plates were supported by 4 stiff threaded steel bars (Fig.2). The titanium bar was gripped by the frame's upper jaw. All tests were quasi-static, implemented under displacement-control mode conditions at a rate equal to 0.2 mm/min. The load was applied monotonically up to the removal of the bar. For the measurement of the axial strain along the titanium bar an Instron-Dynamic Extensometer of gauge length equal to 12.5 mm was used (Fig.2c). The relative sliding of the bar with respect to the marble block was measured by a calibrated LVDT (Linear Variable Differential Transformer) in touch with the bar's lowest end (Figs.3a,b). Furthermore, the whole system's deformation and the bar's pure movement were measured by 3 LVDTs placed at the bottom of the rigid plate (Figs.3c,d).

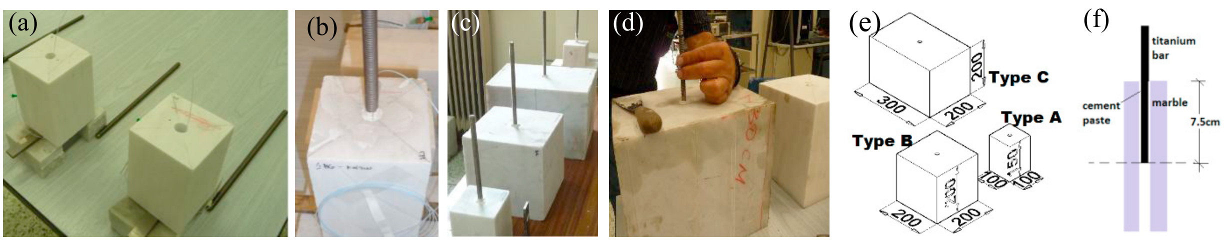

Fig. 1. (a) marble blocks; (b), (c) final specimen's view; (d) specimens' preparation; (e) marbles' dimensions in mm; (f) anchoring length.

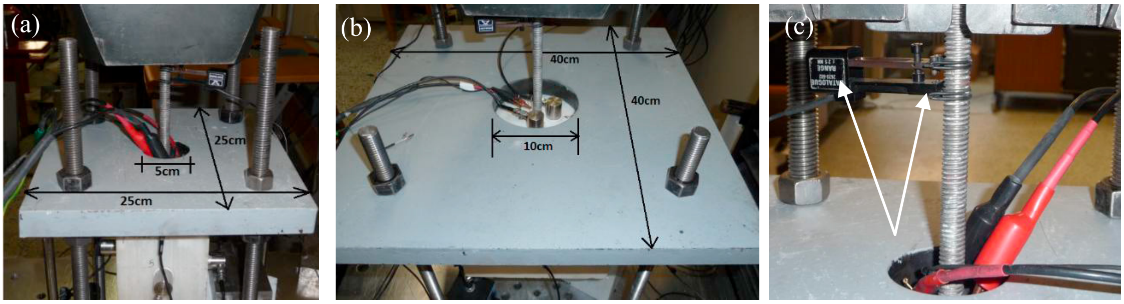

Fig. 2. (a) rigid metallic plate for marble type A; (b) rigid metallic plate for marble type B and C; (c) the dynamic extensometer used in tests.

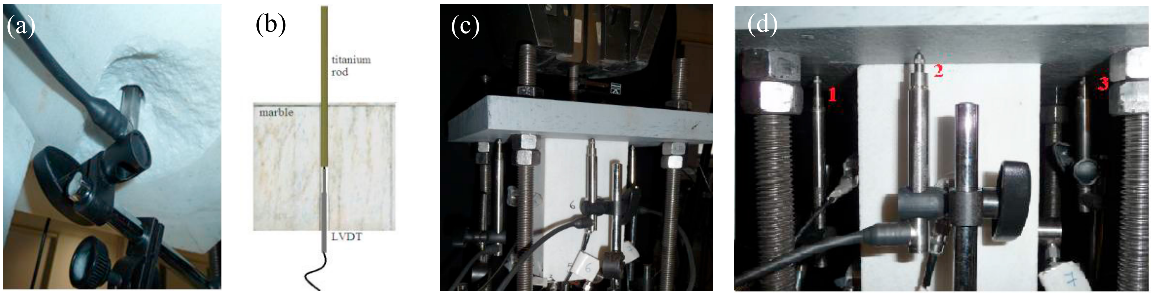

Fig. 3. (a); (b) LVDT in touch with the bar's lowest end; (c); (d) LVDTs on the rigid metallic plate.

3. Experimental techniques

3.1. Acoustic Emission

Fracture is combined with release of stored elastic strain energy, which is consumed for the generation of new cracks and the emission of elastic waves. The elastic waves propagate inside the material and they can be detected by AE sensors attached on the structure's surface (Grosse and Ohtsu, 2008). In the present series of experiments, 7 sensors were used for the type A specimens (Fig.4), 6 for the type B ones (Fig.5) and 8 for those of type C (Fig.6). The sensors were mounted as close as possible to the area where the acoustic signals are expected to be produced, according to the experience gathered during a series of preliminary experiments. The whole system was calibrated adopting the PLB (Pencil Lead Breaking) method: Breaking lead produces a signal of very short duration, which is quite similar to the signal produced by a natural Acoustic Emission source such as a crack. Moreover, the amplitude of lead break source is well within the range of typical crack sources (Tatro, 1971).

3.2. Pressure Stimulated Currents

The PSC technique is based on the detection of very weak electrical signals produced during the formation and growth of micro cracks inside rock-like materials (Triantis et al., 2006). For these signals to be recorded, two electrical

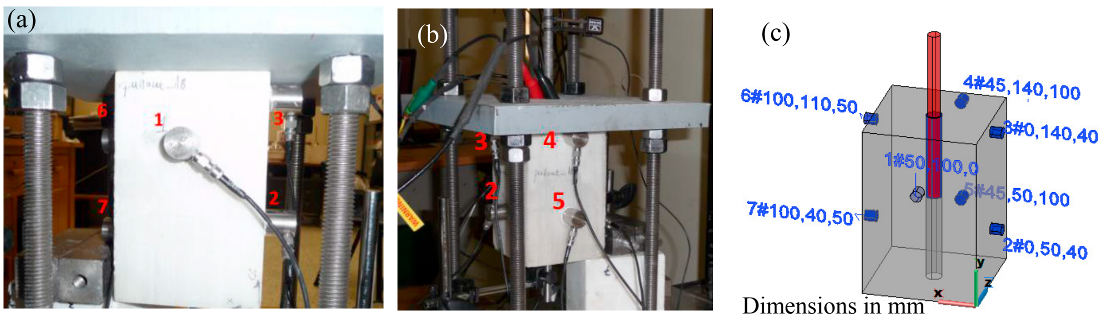

Fig. 4. (a); (b) positions of the Acoustic Emission sensors (marble type A); (c) sensors' coordinates.

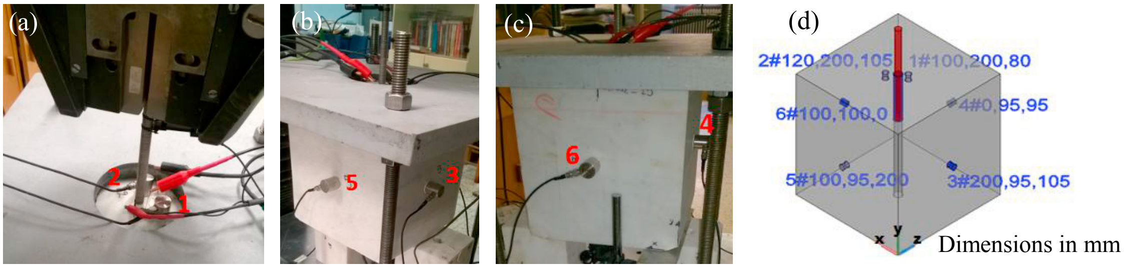

Fig. 5. (a); (b); (c) positions of the Acoustic Emission sensors (marble type B); (d) sensors' coordinates.

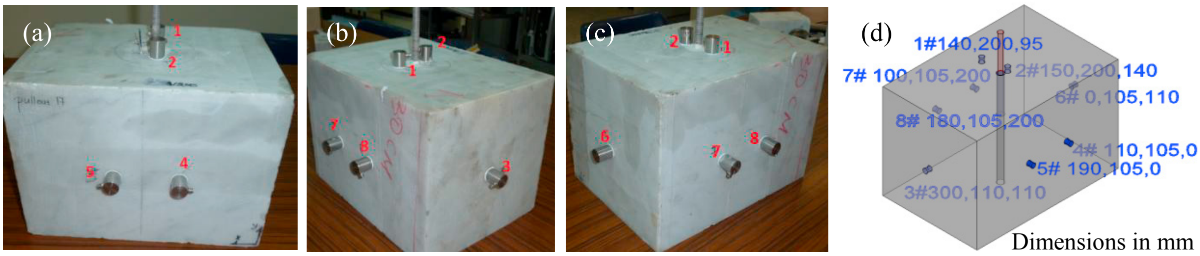

Fig. 6. (a); (b); (c) positions of the Acoustic Emission sensors (marble type C); (d) sensors' coordinates.

contacts were attached on the specimens. The first one was embedded in the cement paste before its curing and the second was inserted in a hole of depth equal to 1 cm predrilled on the marble relatively close to the reinforcing bar (Fig.7a,b), in an effort to record the electrical signals produced on the marble-cement paste interface.

The generation of PSC is attributed to several sources as it is for example the materials' piezoelectric properties, movement of dislocations and fracto-emission. Specifically for marble, which is a quartz-free rock, the piezoelectric effect is not considered as a potential physical mechanism for the generation of the electric signals recorded. A model, applicable for marble, was proposed by Slifkin (1993). It was further developed by Vallianatos and Tzanis (1998) who explained electric signal emissions due to dislocation and other defect movements that cause local polarization. The specific model is widely adopted and it is known as the Moving Charged Dislocations (MCD) model.

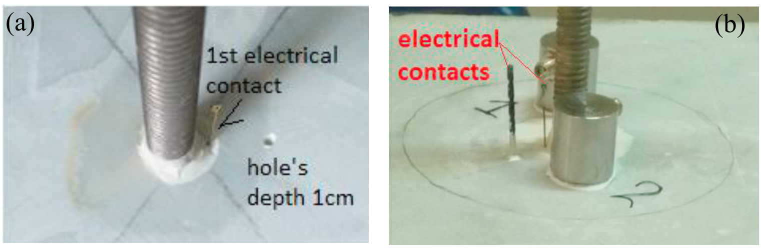

Fig. 7. (a); (b) electrical contacts.

4. Experimental results

4.1. Data from traditional sensing systems

Typical raw data concerning the load-time variation are presented in Fig.8a. The curves are characterized by an almost linear initial segment which covers the range up to almost half of the maximum load attained. A strongly non-linear segment, of continuously decreasing slope, follows up to the maximum load and then the curves become descending as the join loses its structural integrity. Concerning the variation of the load versus the axial strain developed along the bar some characteristic curves are shown in Fig.8b. As it was expected, they resemble closely the standardized behavior of the stress-strain curve of typical ductile metallic materials: A perfectly linear elastic segment is followed by an almost linear strain-hardening portion of very small positive slope. When the join loses its

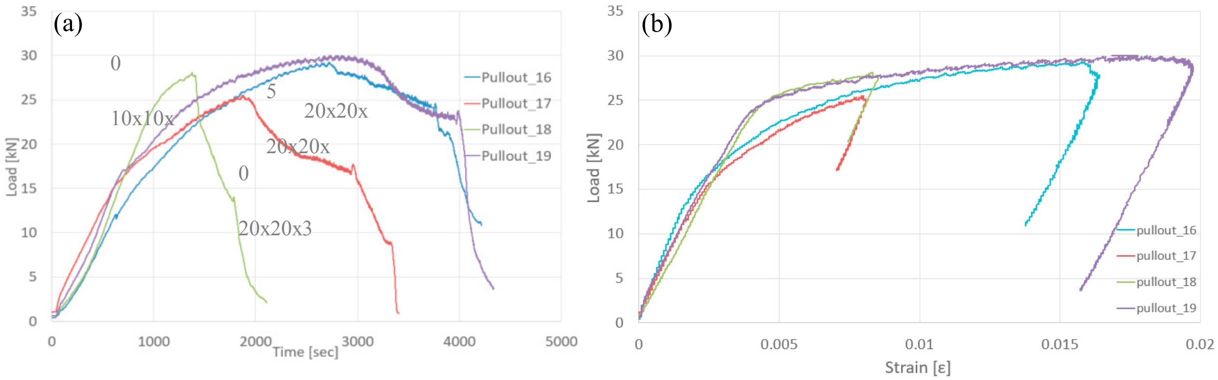

Fig. 8. (a) time variation of load; (b) Variation of load versus bar's strain.

integrity (at the maximum load attained) the bar is gradually relieved and both the load and the strain start decreasing. In general, the maximum load attained in all tests exhibits relatively low scattering. Significant differences are only observed after the maximum load is attained. It is interesting to comparatively consider Figs.8a and 8b: The linear segment in Fig.8a, which represents the elastic response of the structural system as a whole is much shorter compared to that in Fig.8b, which represents the elastic response of the bar only. It is thus concluded that in case the marble-cement-titanium complex is considered as a system it enters non-linearity (and perhaps irreversibility) much earlier due to phenomena taking place along the system's interfaces. The above statement is further supported by Fig.9 in which the load-time curve is plotted in juxtaposition to the respective curve of the displacement of the titanium bar (as it was recorded by the LVDT which is in touch to the bars free end (Figs.3a,b) for two characteristic experiments. It is clearly seen that the bar's motion as a rigid body (corresponding to the third slope-change shown in both Figs.9a and 9b) starts well before the level of the maximum load attained finally.

Similar conclusions can be drawn from Fig.10 in which the variation of the displacement of the rigid restraining plate (blue curve) is plotted versus time, in juxtaposition to the respective graphs of the bar's displacement (red curve) and the bar's axial strain (green curve) also versus time. It is clearly indicated that, at the instant at which the bar starts sliding, the metallic restraining plate stops moving: Indeed the characteristic plateau of the blue curve appears at excellent temporal agreement with the third inclination change of the bar's displacement curve.

4.2. Data from the Acoustic Emission and PSC techniques

A thorough analysis of the data gathered from the AE sensors reveals that the acoustic emission recordings are in a kind of temporal correlation with the changes of the bar's displacement. This correlation can be seen in Fig.11, in

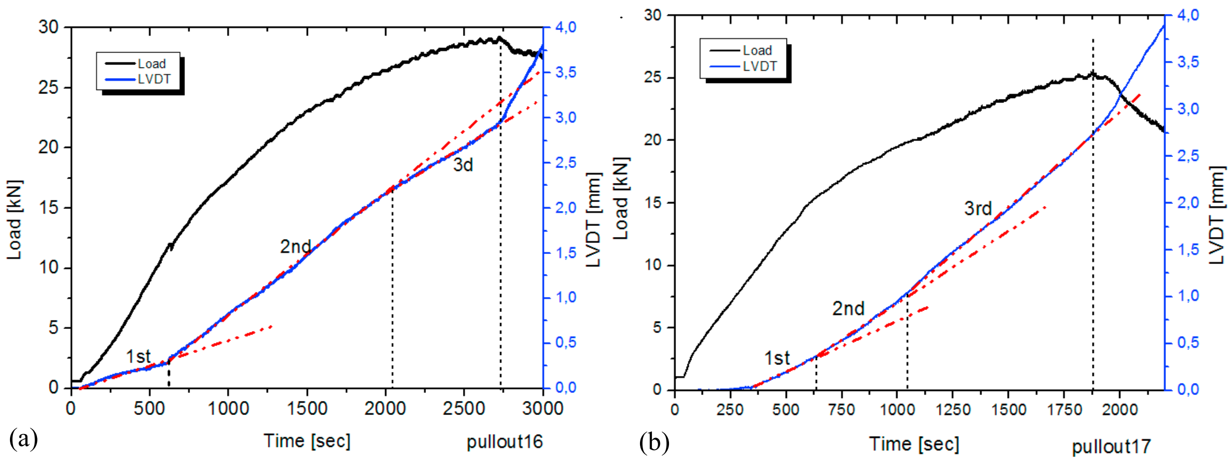

Fig. 9. (a); (b) time variation of load and the LVDT's indication.

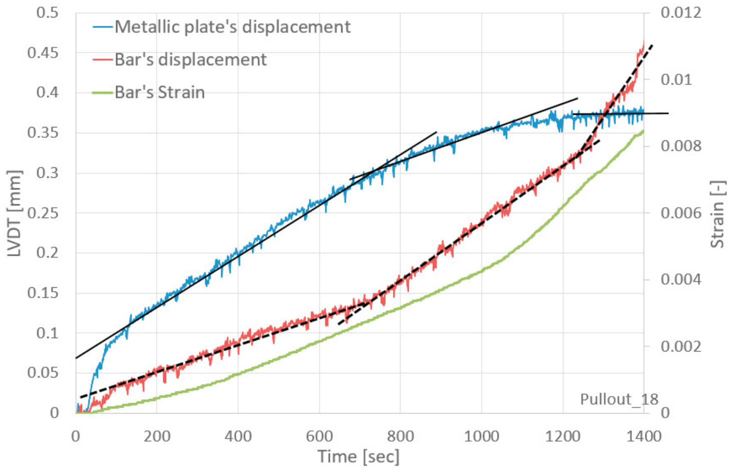

Fig. 10. Time variation of the rigid plate's displacement, the bar's displacement and the bar's axial strain.

which the time variation of the duration and energy of the AEs are plotted versus time in conjunction with the respective time variation of the data gathered from the LVDT in touch with the bar's lowest end (blue line). In the same figure the variation of the load versus time is plotted (green line). It is clear that the AEs before the bar's sliding are fewer and of lower energy and duration compared to the respective AEs of the 3rd after the sliding starts. Moreover the characteristic slope changes of the load-time curve are accompanied by increased AEs duration.

It is here recalled that the duration of the AE signals is a significant characteristic of the acoustic source: Burst signals of low duration correspond basically to cracks and sources that have a spontaneous release of energy. On the other hand, continuous signals have high duration. A characteristic example of long duration signal is that that produced by friction (Grosse and Ohtsu, 2008). Taking then advantage of the as above observations it could be concluded that the accumulation of the signals after the 1900 sec, the time period that corresponds to the 3rd region of the LVDT's indications, could be well attributed to the friction between the sliding bar-paste and marble.

As a last step the variation of the bar's displacement and that of the cumulative energy of the AE versus the load induced is plotted in Fig.12 for two typical experiments. It is very interesting to observe that almost simultaneously to every slope change of the bar's displacement curve a significant increase of the energy of the AEs is recorded. Concerning the data gathered from the PSC technique an alternative method for their exploration was chosen here. Indeed, while the traditional method (Triantis et al., 2006; Kyriazopoulos et al., 2011) is based on the quantification of the electric activity in terms of the current's intensity, in this study it was decided to take advantage of the electric charge produced during a certain time interval (Triantis et al. 2008) the cumulative value of which is determined as:

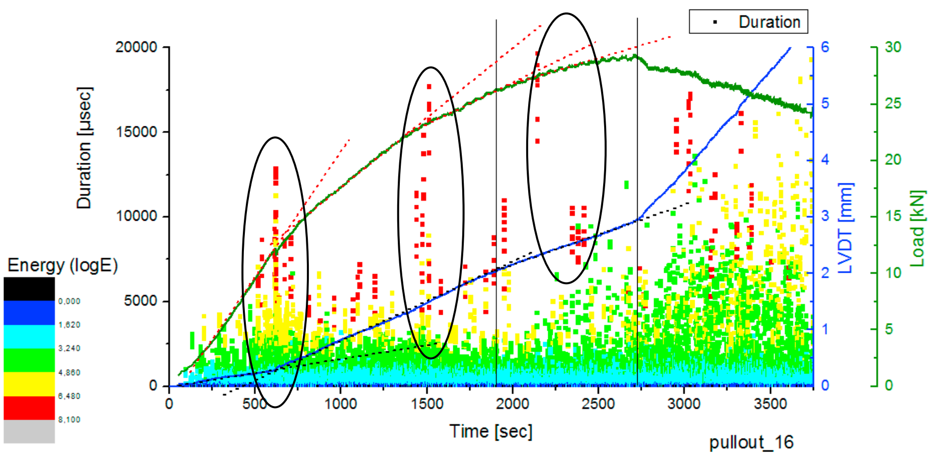

Fig. 11. Time variation of the AE recordings' duration, the LVDT (in touch with the bar's lowest end) indications and the load.

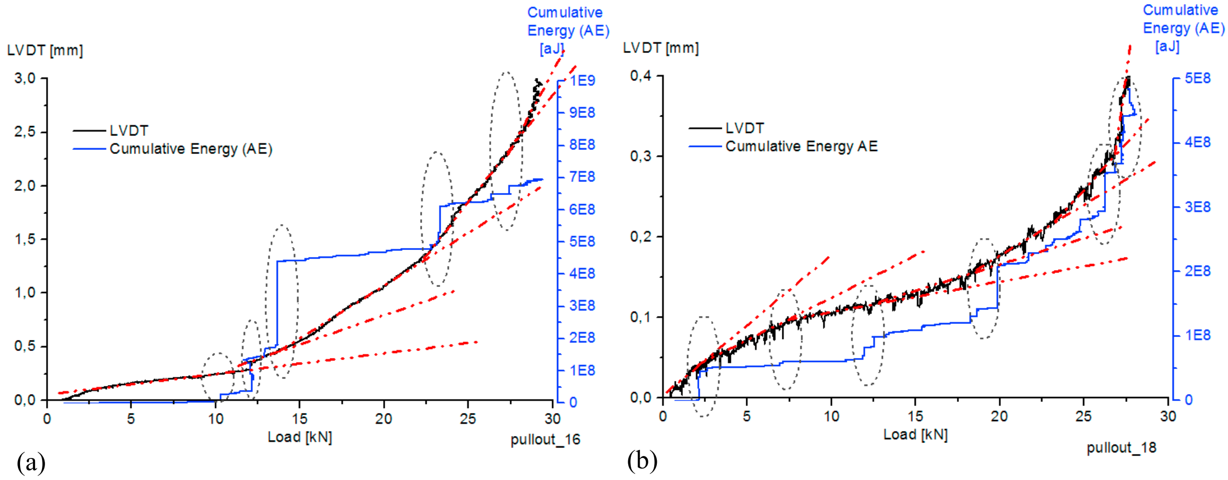

Fig. 12. The variation of the bar's displacement and cumulative energy of the AE versus the load for two experiments.

$$Q = \int_0^t I_{PSC}(t)dt \tag{1}$$

where $I_{PSC}(t)$ is the intensity of the electric current recorded by the two electric contacts described in Section 3.2. The variation of Q(t) is plotted in Fig.13 for two typical experiments in conjunction with the variation of the bar's dispacement as recorded by the LVDT in touch with the bar's lowest end. The quantitave similarity of the two curves is striking for both tests and the same is true for all the experiments of the present protocol.

5. Discussion and conclusions

The combined use of different sensing techniques during the present series of pull-out tests enlightened some critical aspects of the phenomenon while, in addition, some very interesting correlations between the data pumped by each technique were revealed. It was indicated that the behavior of the bar-cement-marble system deviates from linearity well before the maximum load is attained (Fig.8a). Taking into account that both the reinforcing bar and also the remaining elements of the set-up (marble, restricting plate, supporting bars) keeps performing linearly (Fig.8b) it can be concluded that the weak link of the system is one of the two interfaces. Taking into account the conclusions of an earlier study by Kourkoulis et al. (2008), where it was definitely proven that the cement-threaded bar interface does not fail during the whole loading procedure, it can be supported that the marble-cement interface is the one that fails leading the marble-cement-bar complex to inability to fulfill its structural role.

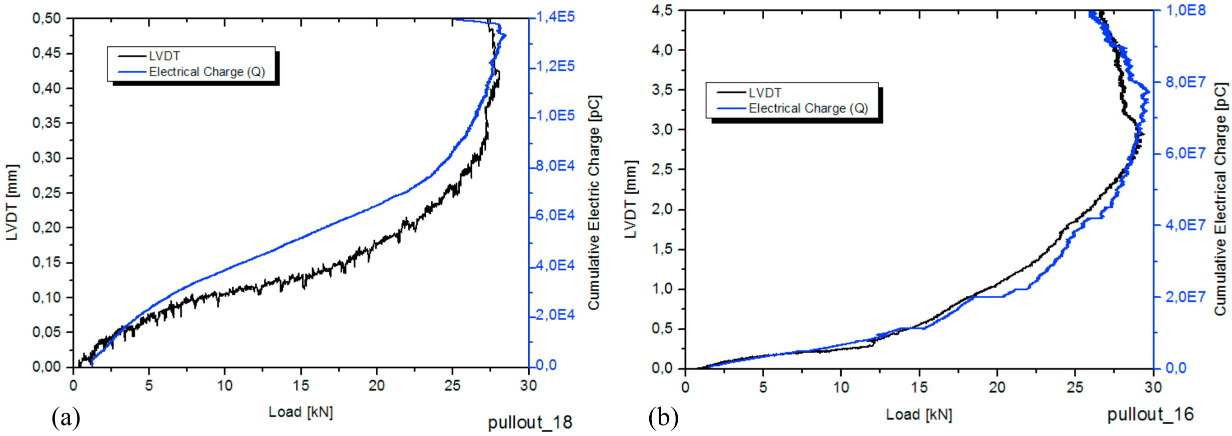

Fig. 13. The change of the bar's displacement and the cumulative electric charge versus the load for two characteristic experiments.

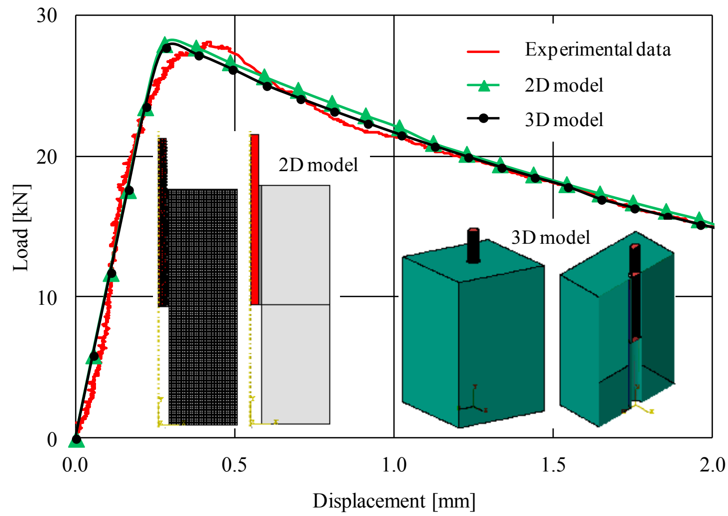

Fig. 14. The predictions of the two- and three-dimensional numerical models for the load-displacement curve against the experimental data.

Besides the conclusions concerning the structural integrity of the connection it was also proven that all three kinds of quantities considered (mechanical, acoustic and electrical ones) exhibit similar characteristics concerning their temporal variation. More specifically it was revealed that changes of slope of both the load and the absolute displacement of the bar appear to be directly related to the appearance of acoustic events of increased duration and energy. Moreover the cumulative electric charge appears to closely and systematically follow the variation of the bar's displacement. It is evident that these similarities should be further studied experimentally before definite conclusions are drawn. In any case the experience gathered from the present protocol constitute an encouraging basis and can be proven valuable in the direction of calibrating sensing techniques which can provide data from the interior of the specimens and from internal interfaces which are inaccessible by traditional sensing techniques.

The data gathered from the experimental protocol were then used for the assessment/validation of numerical models (with the aid of the Finite Element Method and the commercial software ABAQUS) which are planned to be used for a thorough analysis of the parameters influencing the structural integrity of the joint (mechanical properties of cement and its thickness, thread geometry, relative dimensions and anchoring length). Preliminary results (Fig. 14) are encouraging indicating that the pull-out phenomenon is equally well described by both 2D and 3D models.

References

Aggelakopoulou, E., 2013. Design and evaluation of restoration mortars for the Acropolis monuments, The Acropolis Restoration News, 13, 13-17.

Berthelot, J.M., Rhazi, J., 1990. Acoustic emission in carbon fibre composites, Composite Science and Technology, 37, 411-418

Grosse, C.U., Ohtsu, M., 2008. Acoustic Emission testing, Basics for research - Applications in Civil Engineering, Springer-Verlag Berlin Heidelberg.

Korres, M., Toganides, N., Zambas, C., Skoulikidis, Th., 1989. Study for the restoration of the Parthenon, Vol.2a, Athens: Ministry of Culture, Committee for the Preservation of the Acropolis Monuments (in Greek).

Kourkoulis, S.K., Exadaktylos, G.E., Vardoulakis, I., 1999. U-notched Dionysos Pentelicon marble in three point bending: The effect of non-linearity, anisotropy and microstructure, International Journal of Fracture 98, 369-392.

Kourkoulis, S.K., Papanicolopulos, S.-A., Marinelli, A., Vayas, I., 2008. Restoration of antique temples: Experimental investigations on the pull-out behaviour of anchors in marble, Bautechnik, 85(2), 109-119.

Penelis, G., 1996. Techniques and materials for structural restoration, Proc. 11th World Conference on Earthquake Engineering (11WCEE), International Association of Earthquake Engineering (IAEE), Tokyo.

Slifkin, L., 1993. Seismic electric signals from displacement of charged dislocations, Tectonophysics, 224, 149-152.

Tatro, C.A., 1971. Design criteria for Acoustic Emission, ASTM STP 505, American Society for Testing and Materials, Philadelphia, 84-99.

Triantis, D., Stavrakas,I., Anastasiadis, C., Kyriazopoulos, A., Vallianatos, F., 2006. An analysis of pressure stimulated currents (PSC) in marble samples under mechanical stress, Physics and Chemistry of the Earth, 31(4), 234-239

Kyriazopoulos, A., Anastasiades, C., Triantis, D., Brown, J.C., 2011. Non-destructive evaluation of cement-based materials from pressure stimulated electrical emission - Preliminary results, Construction and Building Materials, 25, 1980-1990.

Triantis, D., Anastasiadis, C., Stavrakas, I., 2008. The correlation of electrical charge with strain on stressed rock samples, Natural Hazards and Earth System Sciences. 8, 1243-1248.

Vallianatos, F., Tzanis, A., 1998. Electric current generation associated with the deformation rate of a solid: Pre-seismic and co-seismic signals, Physics and Chemistry of the Earth, 23, 933–938.