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Innovative Approaches for Structural Health Monitoring of Restored Elements of Stone Monuments

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IAMON Workshop "Reinforced interfaces between structural members in ancient monuments"
July 10, 2024, Athens, Greece

At a glance ...

1. **Structural Health Monitoring**
2. **Sensing techniques**
    - ***2.1 Acoustic Emissions***
    - ***2.2 Pressure Stimulated Currents***
3. **Analysis of sensing data in the Natural Time Domain**
4. **Experimental validation**
    - ***4.1 Elementary experiments***
    - ***4.2 Structural tests***
5. **Concluding…**

Motive

The pioneering technique **(1-4)** (introduced by scientific teams working since the early eighties for the conservation of the Athenian Acropolis monuments) is based on the combined use of ***titanium elements*** and ***proper cement-based pastes***.

This technique creates ***complexes of three-materials*** (marble-paste-metal), with ***two hidden interfaces*** (marble-to-paste, and paste-to-metal), locations where damage mechanisms are usually activated.

Modeling the response of restored elements demands data from these loci. Such data can be only obtained ***with the aid of novel Structural Health Monitoring (SHM) techniques*** and innovative ***data analysis tools***.

A restored epistyle of the Parthenon Temple on the Acropolis of Athens

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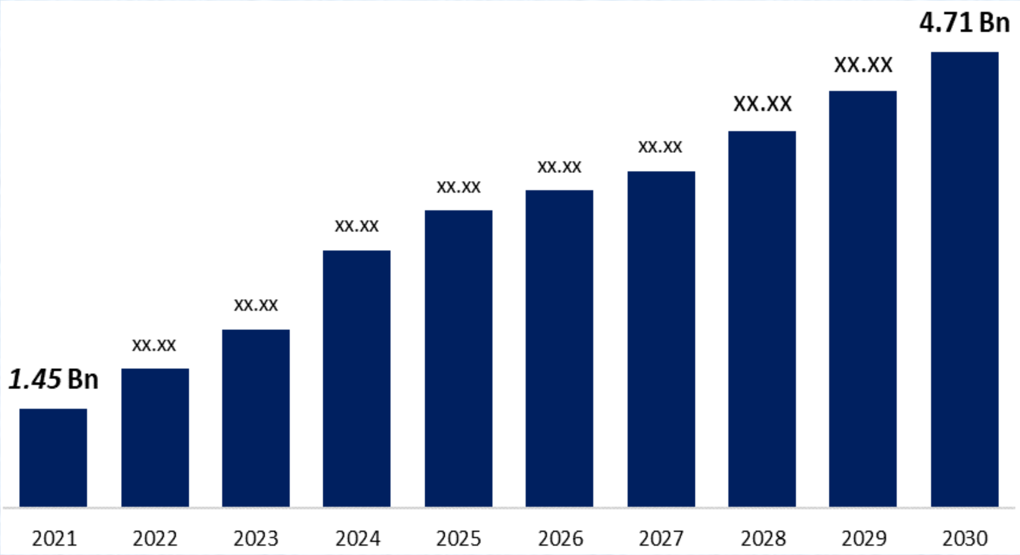
1. Skoulikidis Th. Deterioration des materiaux de construction et notamment des marbres par la corrosion de l' acier incorpore. Cas de l'Acropole. 1st Int. Symp. on the Deterioration of Building Stones, La Rochelle: Les Imprimeries Reunies de Chambery,1972
2. Angelides S. Replacement of steel connectors by titanium alloy, The Acropolis: Problems-studies-measures to be taken. In: Proc 2nd Int. Symp. on the Deterioration of Building Stones, Athens: National Technical University of Athens, 1976, 351–352
3. Korres M, Bouras Ch. Study for the Parthenon's restoration. Athens: Ministry of Culture, Committee for the Conservation of the Acropolis Monuments, 1983
4. Zambas C. Structural repairs to the monuments of the Acropolis-The Parthenon. Proceedings of the Institution of Civil Engineers, Civil Engineering, 1992, 92(4): 166–176.

About Structural Health Monitoring (SHM)

SHM is "*the process of acquiring and analyzing data using on-board sensors in order to continuously assess the damage level within a structure*" (1).

Damage denotes undesirable "…" (1). *changes to the material and/or the geometric properties of engineering systems, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance.*



Global Structural Health Monitoring Market [1]

SHM allows early detection of damages due to deterioration of materials, optimizes decisions over maintenance, repair, and reconstruction of the structure (2) and ***permits, hopefully, prediction and (prevention) of upcoming catastrophic events***.

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1. Farrar C.R., K. Worden. An introduction to structural health monitoring. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365.1851 (2007): 303-315.
2. Tonelli D. et al. (2020). Structural health monitoring based on acoustic emissions: Validation on a prestressed concrete bridge tested to failure. Sensors, 20(24), 7272.

Detection of pre-failure indicators

Predict upcoming catastrophic events governs the efforts of scientists in a wide range of disciplines. *As an example, predicting upcoming earthquakes is the "Holy Grail" for scientists working in Seismology*.

In spite of the intensive research we are rather far from the end target, at least for in-field practical application.

In the laboratory level, which is "sterilized" from "noises", things are easier and the results are promising: Theoretical approaches providing "***pre-failure indicators***" are already available (although they provide -for the moment being- data of qualitative rather than of quantitative nature).

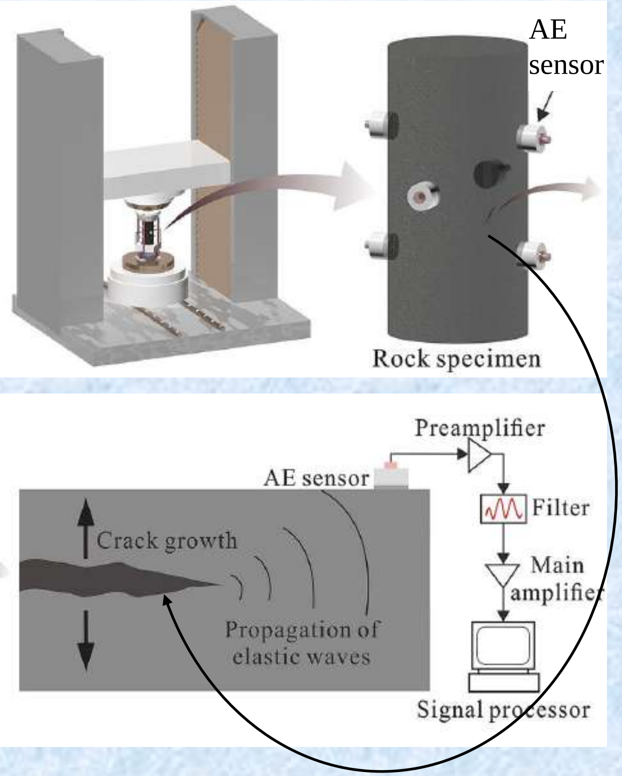
The scope of this study is to comparatively consider innovative approaches towards this direction, based on Natural Time Analysis.

The Damsel of the Sanct Grael (Dante Gabriel Rossetti, 1828-1882)

SHM techniques:

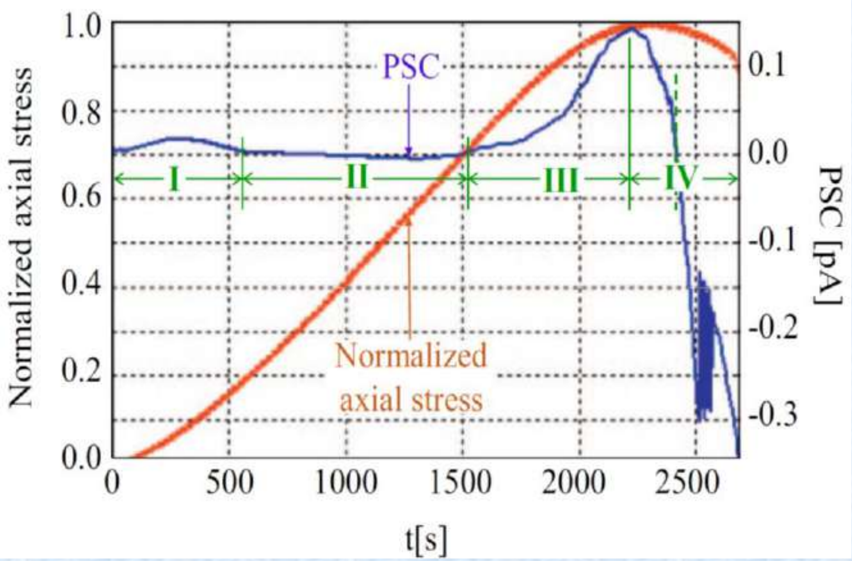
Acoustic Emissions (AE) vs. Pressure Stimulated Currents (PSC)

AE: It is based on the ***detection of elastic waves due to internal damages and the respective stress re-distribution caused*** (1).



Since elastic waves propagate throughout the structure, ***it is possible to remotely detect damages*** in not areas accessible areas (1).

PSC: It is based on the **detection of electric signals**, emitted while specific materials are loaded. They are related ***to the stress level*** and are generated at ***the transient interval between linear and non-linear response, related to the onset of irreversible deformations*** (2).



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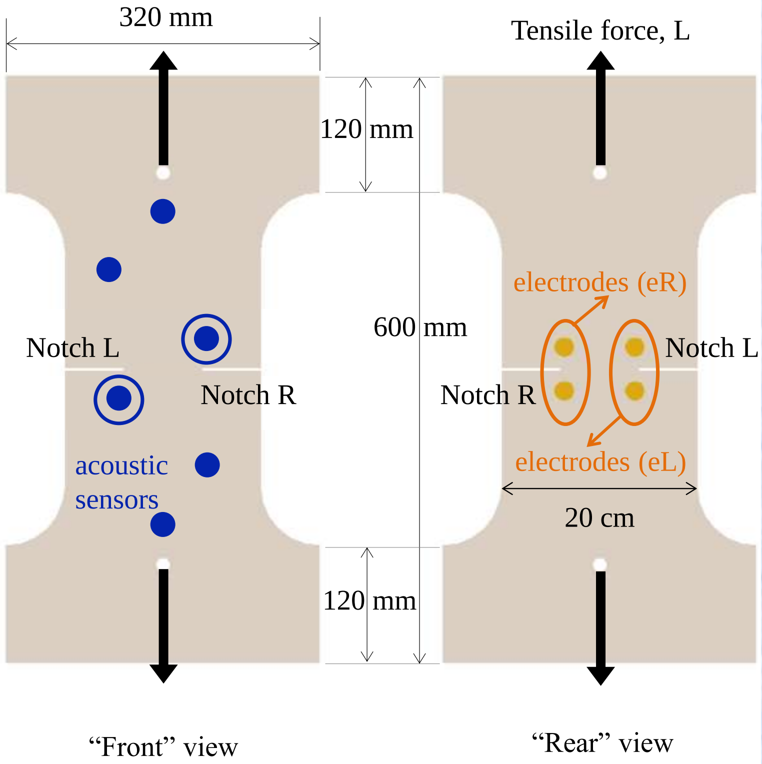
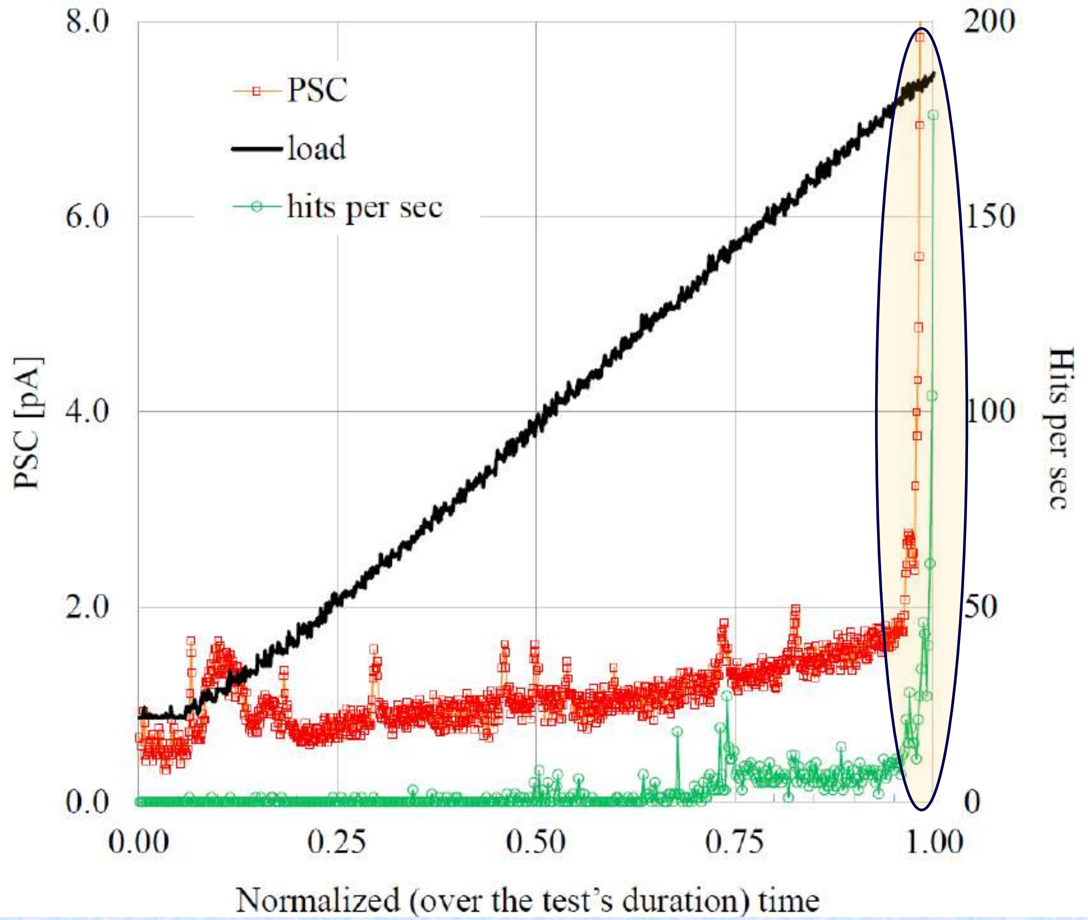
1. Meo M. Acoustic emission sensors for assessing and monitoring civil infrastructures. In Sensor Technologies for Civil Infrastructures; Woodhead Publishing: Cambridge, UK, 2014; Volume 1, pp. 159–178.
2. Triantis, D., Pasiou, E. D., Stavrakas, I., & Kourkoulis, S. K. (2022). Hidden affinities between electric and acoustic activities in brittle materials at near-fracture load levels. Rock Mechanics and Rock Engineering, 1-18.

PSC versus AE



Schematic representation of the experimental set-up for the DENT tests.



The acoustic activity in juxtaposition to the load induced and the PSC for a DENT specimen made from Dionysos marble.

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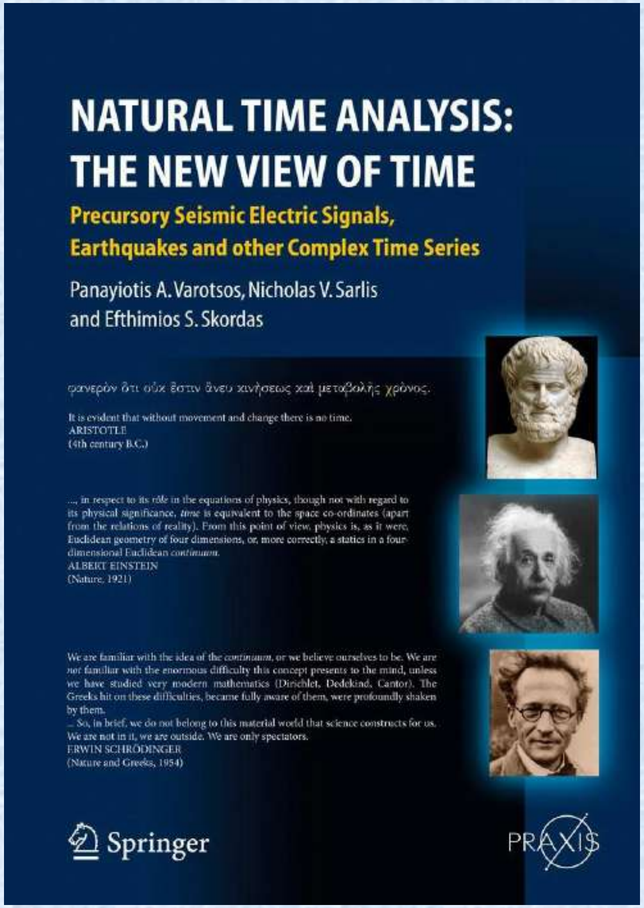
1. Triantis D. and Kourkoulis S.K., An alternative approach for representing the data provided by the acoustic emission technique, Rock Mechanics and Rock Engineering, 51, 2433-2438, 2018.

Natural Time (NT) and Natural Time Analysis (NTA)



NATURAL TIME ANALYSIS:
THE NEW VIEW OF TIME
Precursory Seismic Electric Signals, Earthquakes and other Complex Time Series
Panayiotis A. Varotsos, Nicholas V. Sarlis
and Efthimios S. Skordas

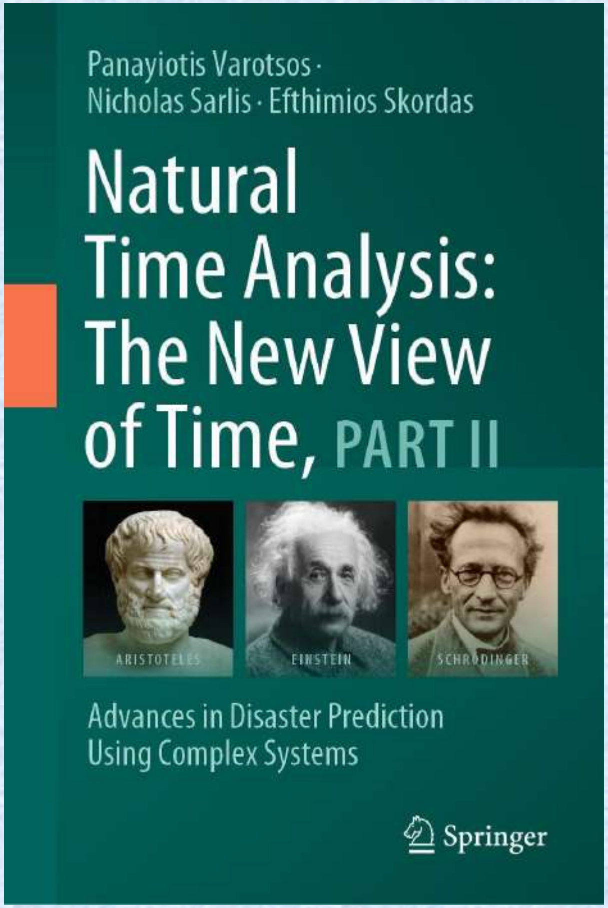
φανερὸν ὅτι οὐκ ἔστιν ἄνευ κινήσεως καὶ μεταβολῆς χρόνος.

It is evident that without movement and change there is no time.
ARISTOTLE
(4th century B.C.)

..., in respect to its rôle in the equations of physics, though not with regard to its physical significance, *time* is equivalent to the space co-ordinates (apart from the relations of reality). From this point of view, physics is, as it were, Euclidean geometry of four dimensions, or, more correctly, a statics in a four-dimensional Euclidean *continuum*.
ALBERT EINSTEIN
(Nature, 1921)

We are familiar with the idea of the *continuum*, or we believe ourselves to be. We are *not* familiar with the enormous difficulty this concept presents to the mind, unless we have studied very modern mathematics (Dirichlet, Dedekind, Cantor). The Greeks hit on these difficulties, became fully aware of them, were profoundly shaken by them.
... So, in brief, we do not belong to this material world that science constructs for us. We are not in it, we are outside. We are only spectators.
ERWIN SCHRÖDINGER
(Nature and Greeks, 1954)

Springer
PRAXIS



Panayiotis Varotsos ·
Nicholas Sarlis · Efthimios Skordas
Natural Time Analysis: The New View of Time, PART II
ARISTOTELES EINSTEIN SCHRÖDINGER
Advances in Disaster Prediction Using Complex Systems
Springer

The covers of the books that introduced the concept of Natural Time (1).

NTA preserves only the order of events (1) together with their energy, since ***attention is focused on the changes induced to the complex system due to the external loading*** (the latter is not part of the complex system).

NT provides a novel approach for the analysis of timeseries of events, in the direction of predicting upcoming catastrophic events.

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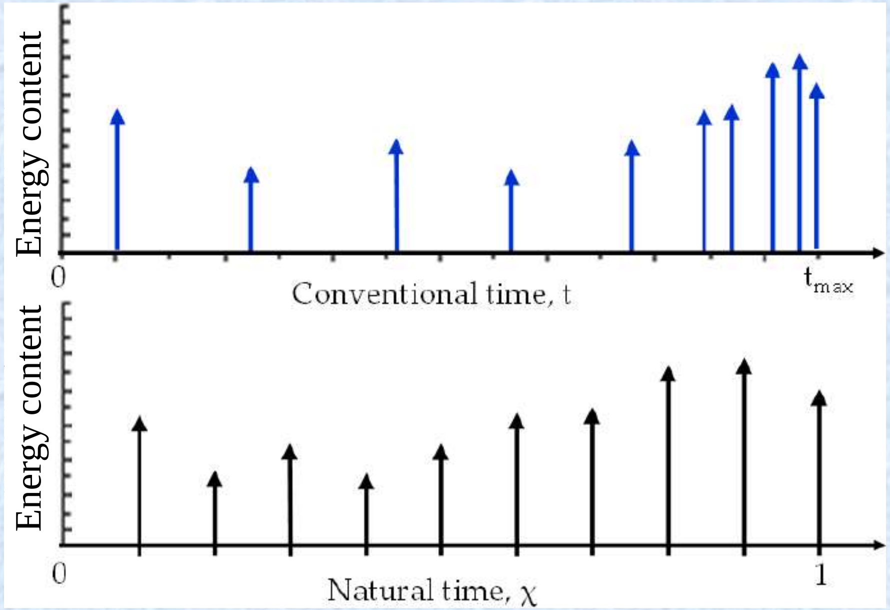
1. Varotsos, P., Sarlis, N. V., & Skordas, E. S. (2011). Natural time analysis: the new view of time: precursory seismic electric signals, earthquakes and other complex time series. Springer Science & Business Media.

Natural Time Analysis (NTA)

Along these lines, the Natural Time χ (from the Greek word "χρόνος" meaning "time") is introduced ***by assigning to the kth event (of a time series comprising N events) the quantity $\chi_k = k/N$ and pairing it to the energy E_k that was emitted during the specific kth event***.



Schematic interpretation of a time series in the conventional- (up) and the Natural-Time domain (down) [1].

The ***normalized energy p_k*** is then defined as:

$$p_k = \frac{E_k}{\sum_{n=1}^{N} E_n}$$

Since p_k are positive and sum up to unity they are treated as probabilities. In the frame of probability theory, information about the distribution of p_k is obtained from the behavior of the ***characteristic function Φ(ω) or equivalently of Π(ω) [2]:***

$$\Phi(\omega) \equiv \sum_{k=1}^{N} p_k e^{i\omega\chi_k} \qquad \Pi(\omega) = \left|\Phi(\omega)\right|^2$$

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1. Kourkoulis S.K., Pasiou E.D., Loukidis A., Stavrakas I. and Triantis D. (2022). Comparative assessment of criticality indices extracted from acoustic and electrical signals detected in marble specimens. Infrastructures, 7(2), 15.
2. Feller, An Introduction to Probability Theory and Its Applications, Vol. II, Wiley, New York, 1971.

Natural Time Analysis (NTA)

The Taylor expansion of $\Pi(\omega)$ as $\omega \to 0$ results in: $\boldsymbol{\Pi(\omega) = 1 - \kappa_1\omega^2 + \ldots}$, giving rise to ***the variance κ_1 of Natural Time :***

$$\kappa_1 = \left\langle \chi^2 \right\rangle - \left\langle \chi \right\rangle^2 = \sum_{k=1}^{N} \chi_k^2 p_k - \left(\sum_{k=1}^{N} \chi_k p_k \right)^2$$

where brackets $\langle \ldots \rangle \left(\equiv \sum_{k=1}^{N} \ldots p_k \right)$ denote ***averages with respect to the distribution of the normalized energies***.

In the frame of the NTA, another useful quantity is the entropy S in Natural Time, which is given by the expression[1]:

$$S = \langle \chi \ln \chi \rangle - \langle \chi \rangle \ln \langle \chi \rangle \quad \text{or} \quad S = \sum_{k=1}^{N} \frac{k}{N} \ln\left(\frac{k}{N} \right) p_k - \left(\sum_{l=1}^{N} \frac{l}{N} p_l \right) \ln\left[\sum_{m=1}^{N} \frac{m}{N} p_m \right]$$

This is a **dynamic entropy** (different from statistical entropies like that of Shannon) and exhibits positivity, concavity, and experimental stability (1). ***When the complex system is stable, E_k are independent and identically distributed random variables. Then $p_k \to 1/N$ (which is called 'uniform' distribution) and S reaches the characteristic value*** (1):

$$S_u \equiv \frac{\ln 2}{2} - \frac{1}{4} \approx 0.0966$$

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1. P. Varotsos, N. Sarlis, E.S. Skordas, M.S. Lazaridou, Entropy in the natural time domain, Phys. Rev. E 70(1) (2004) 011106.

Natural Time Analysis (NTA)

Upon reversing the time arrow and ***hence applying the time reversal operator T*** to p_k, i.e.,

$$\mathrm{T}p_k = p_{N-k+1},$$

the entropy upon time reversal S_- is obtained as:

$$S_- = \sum_{k=1}^{N} \frac{N-k+1}{N} \ln\left(\frac{N-k+1}{N}\right) p_k - \left(\sum_{l=1}^{N} \frac{N-l+1}{N} p_l\right) \ln\left[\sum_{m=1}^{N} \frac{N-m+1}{N} p_m\right]$$

In contrast to S, κ_1 is unaltered under time reversal (power spectrum of any time series).

It is experimentally verified in a variety of cases, upon analyzing the seismicity in the area prone to suffer the strong earthquake, that the following two conditions (1,2):

$$\boldsymbol{\kappa_1 = 0.070} \quad \textit{and} \quad \boldsymbol{S \lesssim S_u \ \text{and}\ S_- \lesssim S_u}$$

are simultaneously fulfilled when the system enters the critical stage.

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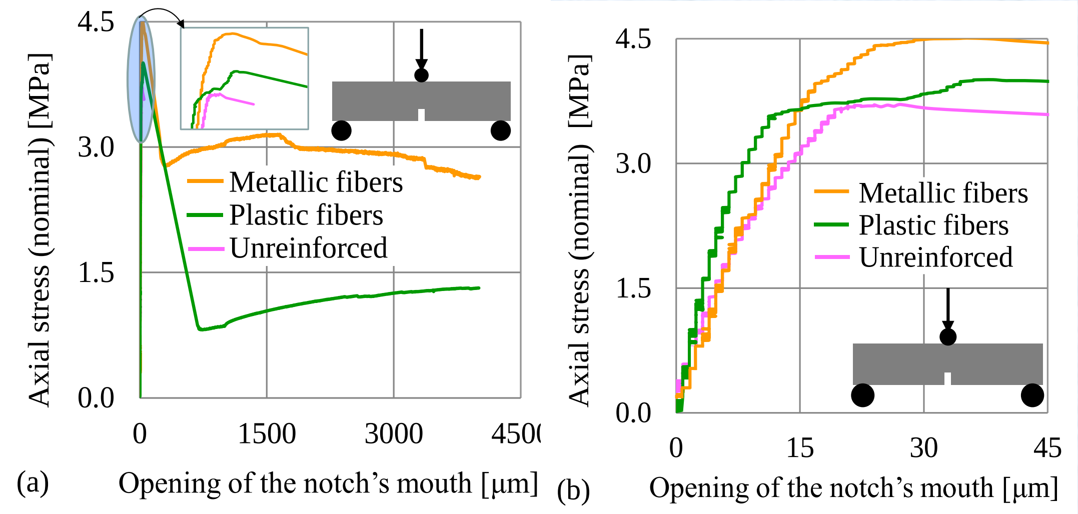
1. S. Uyeda, M. Kamogawa, H. Tanaka, Analysis of electrical activity and seismicity in the natural time domain for the volcanic-seismic swarm activity in 2000 in the Izu Island region, Japan, J. Geophys. Res.-Sol. Ea. 114(B2) (2009) B02310.
2. E.L. Flores- Márquez, A. Ramírez-Rojas, J. Perez-Oregon, N.V. Sarlis, E.S. Skordas, P.A. Varotsos, Natural time analysis of seismicity within the Mexican Flat Slab before the M7.1 earthquake on 19 September 2017, Entropy 22(7) (2020) 730.

Elementary experimental protocols: Plain concrete beams under 3PB

Three-point bending (3PB) tests with notched prismatic beams of square cross-section made of concrete either plain or reinforced with short plastic or metallic fibers (1).



(a) The "nominal axial bending stress" versus the opening of the mouth of the notch for typical specimens of the three categories tested; (b) Detailed view of the very early loading steps.

The experimental set-up (upper) and a closer view of the lower face of a typical specimen (lower)

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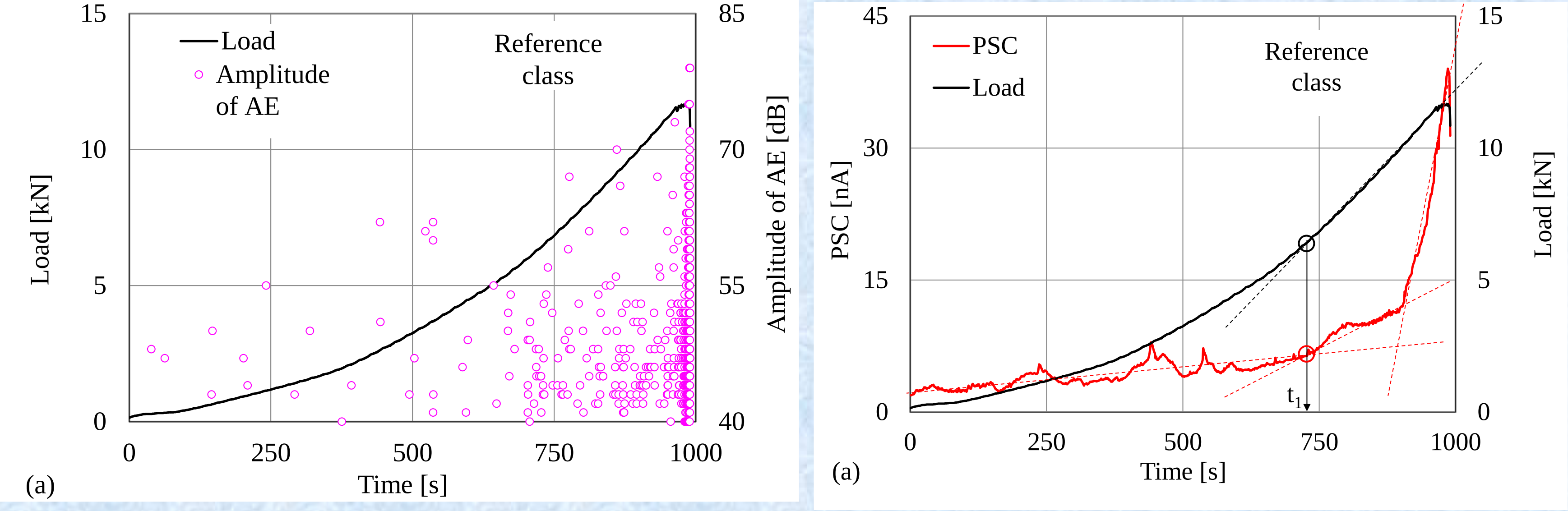
1. Kourkoulis S.K., Loukidis A., Pasiou E.D., Stavrakas I., Triantis D., Response of fiber reinforced concrete while entering into the critical stage: An attempt to detect pre-failure indicators in terms of Non-Extensive Statistical Mechanics, Theoretical and Applied Fracture Mechanics, 123:103690, 1-16, 2023.

The experimental protocol: Plain concrete beams

In a typical test with plain concrete N=643 hits were recorded. As it is expected for a brittle material, the fracture is abrupt and ***the vast majority of the acoustic hits is densely packed in the immediate vicinity of the fracture instant***.

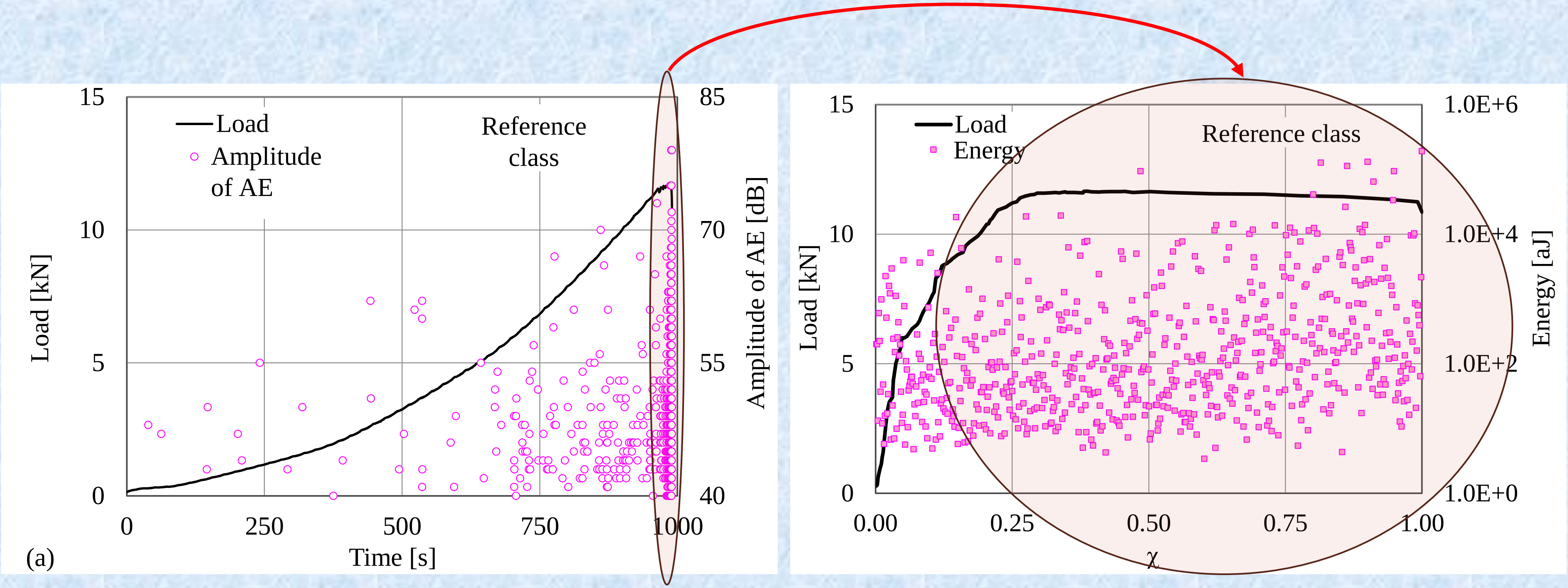
It is, thus, quite possible that ***interesting information remains hidden due to the extremely increased "accumulation" of data in a very narrow time "window".*** In this context, it appears challenging to "spread out" this densely packed information adopting the concept of Natural Time, χ.



The temporal evolution of the load applied in juxtaposition to that of the (a) amplitude of the Acoustic Emissions; and (b) to that of the electric activity.

The experimental protocol: Plain concrete beams

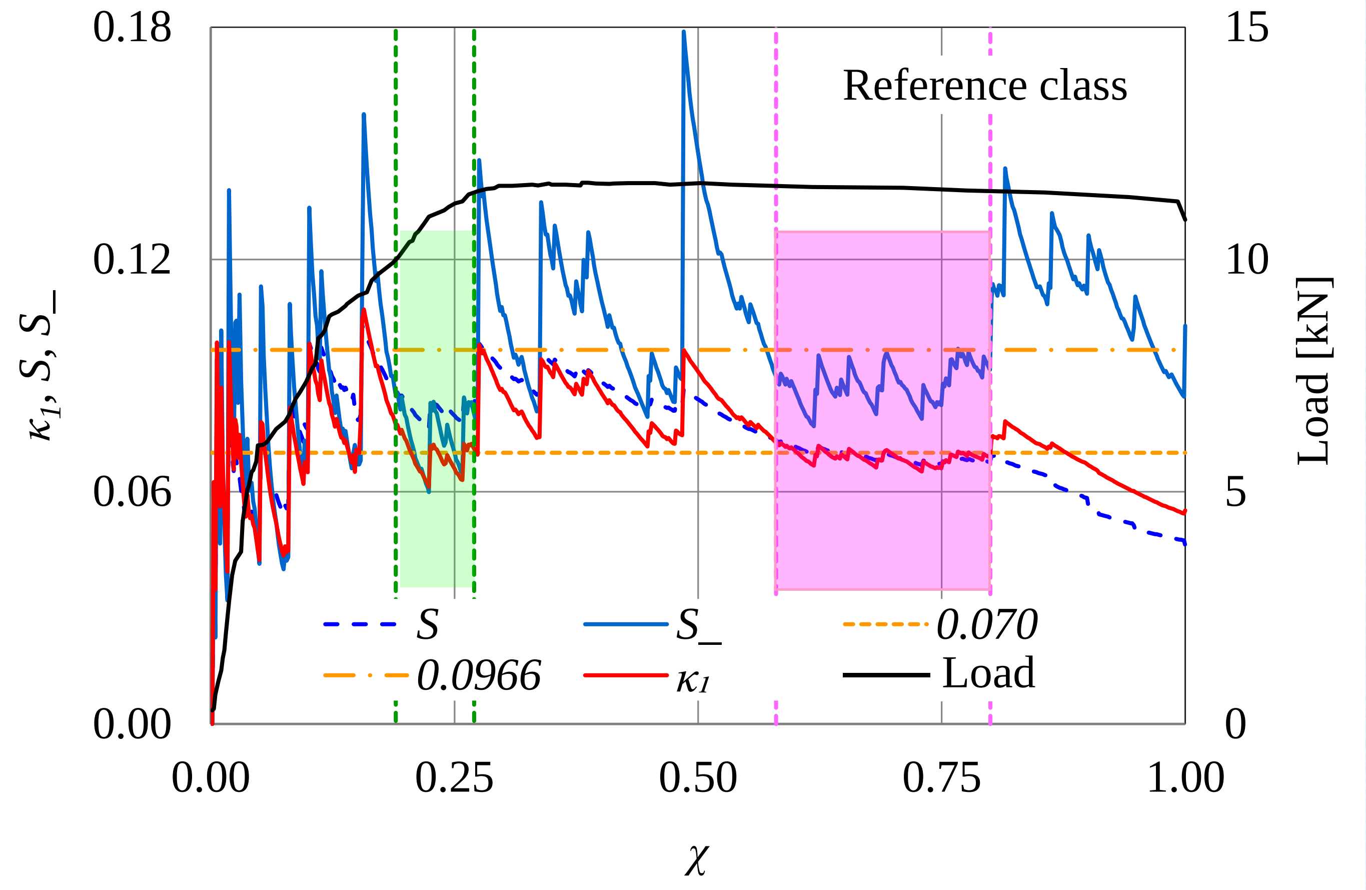
A first advantage of the use of the Natural Time concept is directly concluded: ***The acoustic hits are uniformly "spread out" over the whole range of the independent variable*** (in this case χ), permitting easier exploration of any information that could remain hidden due to the "suffocating" condensation of experimental data in the conventional time domain.



The evolution of the load applied in juxtaposition to the respective evolution of the energy content of the acoustic hits in terms of conventional time (left) and in terms of Natural Time (right).

The experimental protocol: Plain concrete beams

Based on the evolution of the three critical quantities (S, S_, κ_1), ***two regions of criticality (i.e., time intervals at which both conditions of NTA simultaneously satisfied) are detected***. The first one (green rectangle) is located in the $0.19 \leq \chi \leq 0.27$ region, while the second one (magenta rectangle) is located in the $0.58 \leq \chi \leq 0.80$ region.



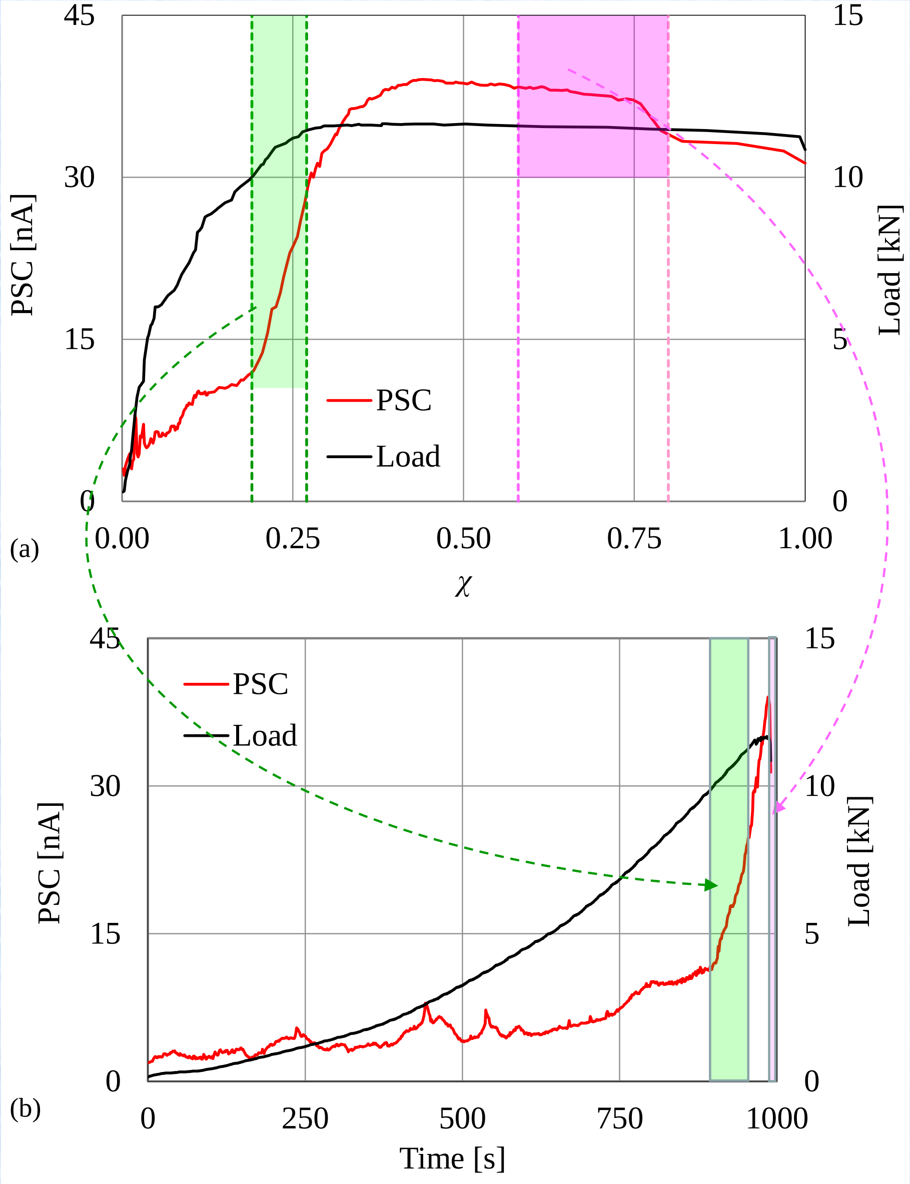
The evolution of the entropy S, the entropy upon time reversal S_, and the variance κ_1, in terms of the Natural Time, in juxtaposition to the respective evolution of the Load applied. The limits κ_1=0.070 and S_u=0.0966, signaling entrance of the system into a critical state are drawn as orange dotted lines.

The experimental protocol: Plain concrete beams

It is amazing now ***to observe the evolution of PSC in the two criticalityregions*** in the NT Domain (as detected by means of AEs).

In the first region (i.e., 0.19<χ<0.27) coloured again green, the PSC exhibits a quite abrupt increase of its value (in other words, the d(PSC)/dχ slope is maximized). In this region, the load increases from about 86% to about 98% of its peak value.

This rapid increase of the PSC indicates ***onset of coalescence of network of micro-cracks and initiation of the process for forming macroscopic cracks,*** designating entrance of the system into the stage of impending fracture.

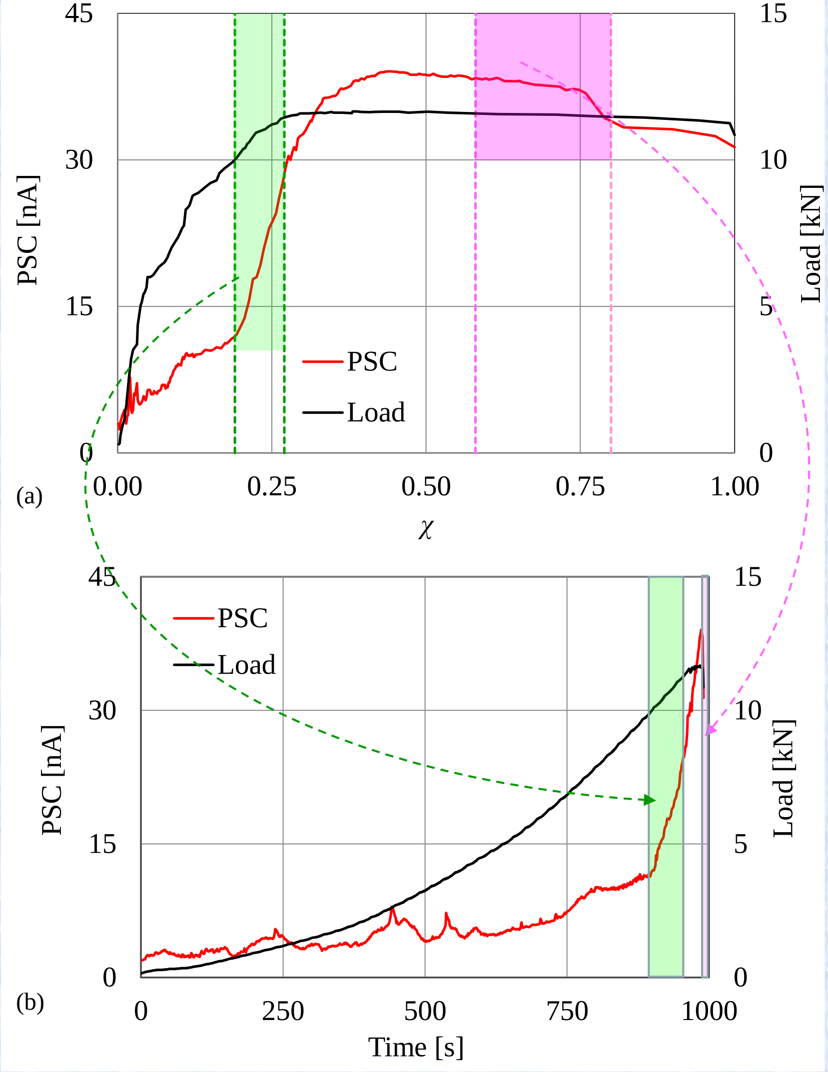


(a) The evolution of the PSC in the NT Domain, in juxtaposition to that of the load. (b) The regions of criticality in the conventional time domain.

The experimental protocol: Plain concrete beams

In the second region (0.58<χ<0.80), the PSC decreases smoothly, ***as a result of reduction of the available electric paths***. This is due to the onset of propagation of the main macrocrack, gradually interrupting the network of electric paths. In this region, the load has already started decreasing, although very smoothly.

It is very interesting to observe the two criticality regions in case the evolution of the PSC and that of the load applied are plotted versus the conventional time, t. Both criticality regions come together in a very narrow window. Especially the second region is hardly distinguishable, ***indicating that critical information could remain unexploited***. Once again, the advantages of studying the acoustic and electric activities in the NT Domain are clearly highlighted.



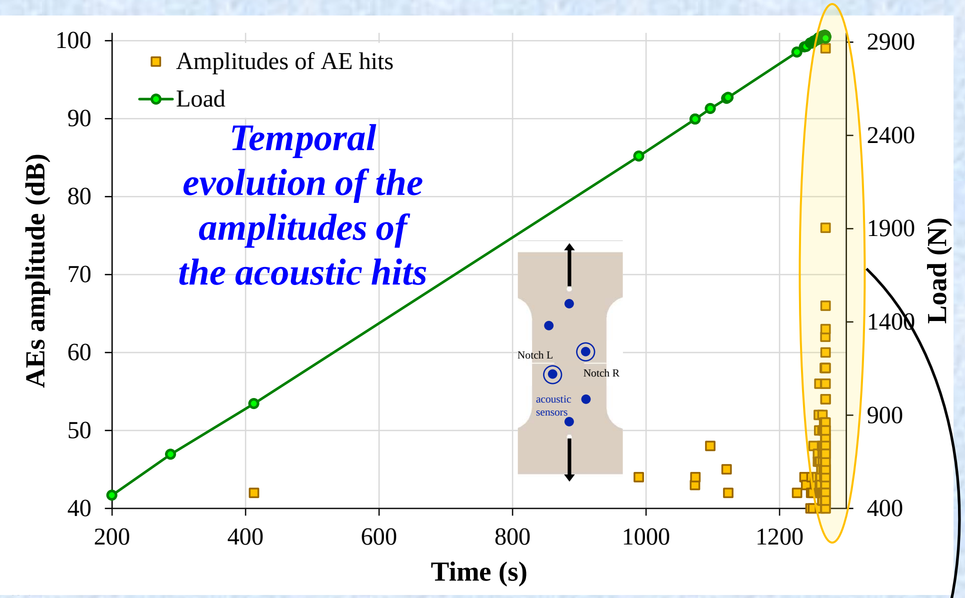
The PSC in the regions of criticality

Elementary experimental protocols: DENT marble specimens

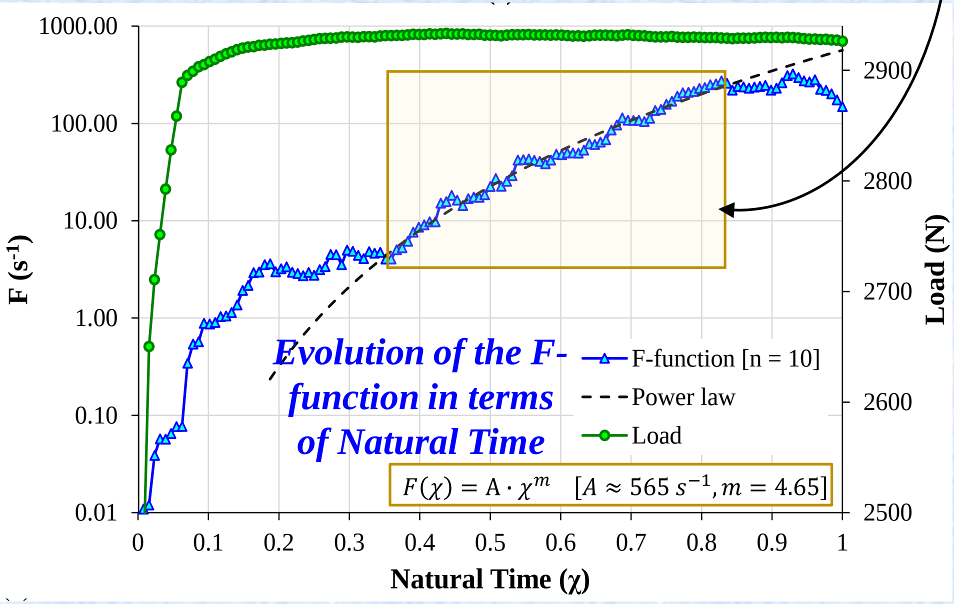
For the critical region (i.e., when catastrophic fracture is impending), the function F(χ) is governed by a power law of the form [1]:

$$F(\chi)=A\cdot\chi^{m}$$

where A is a constant [A=F(χ=1)] and m is an exponent ***related to how strongly the acoustic activity is intensified at the time instants just before macroscopic fracture***. It governs the system from χ=0.36 to χ=0.85. The respective load values are equal to 2931 N and 2928 N. The maximum load attained is 2933 N, i.e., ***the power law governs the system a little before and a little after the maximum force is attained***. In other words the power law is valid 2.4 s before fracture.



Temporal evolution of the amplitudes of the acoustic hits



Evolution of the F-function in terms of Natural Time

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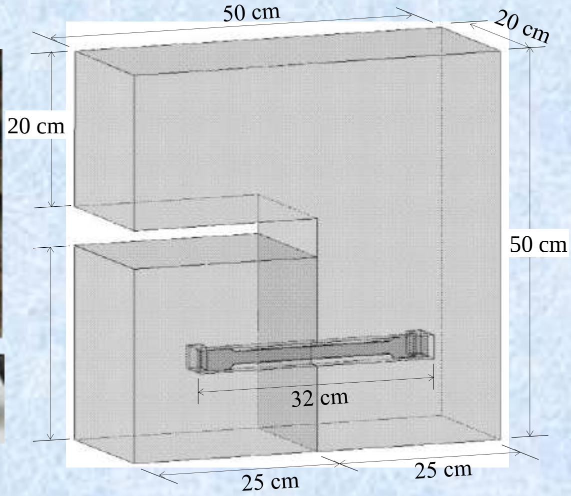
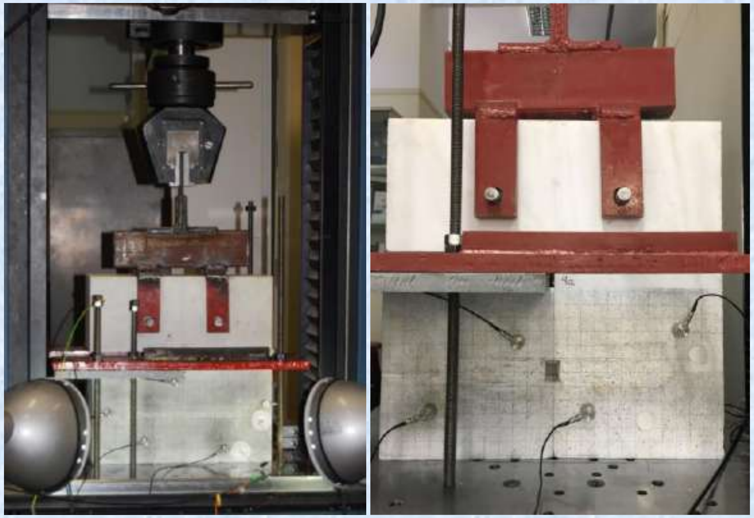
1. Kourkoulis S., Pasiou E., Dakanali I., Stavrakas I., Triantis D., Notched marble plates under tension: Detecting prefailure indicators and predicting entrance to the "critical stage", Fatigue and Fracture of Engineering Materials and Structures, 41, pp. 776-786, 2018.

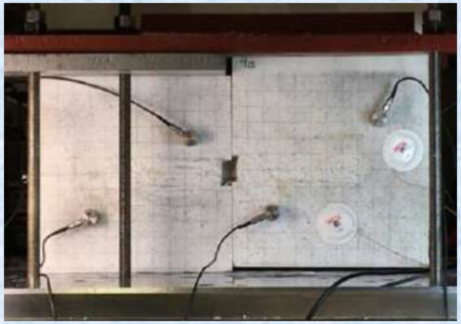
Structural tests: Shear loading of mutually interconnected marble epistyles

Interconnected marble blocks (a cubic and a “Γ”-shaped one), joined together by means of either “I”- or “Π”-shaped titanium connectors [1], were tested.

Eight AE sensors were used to detect and record AE data.







Typical specimen with “I”-shaped connector before and while loaded.

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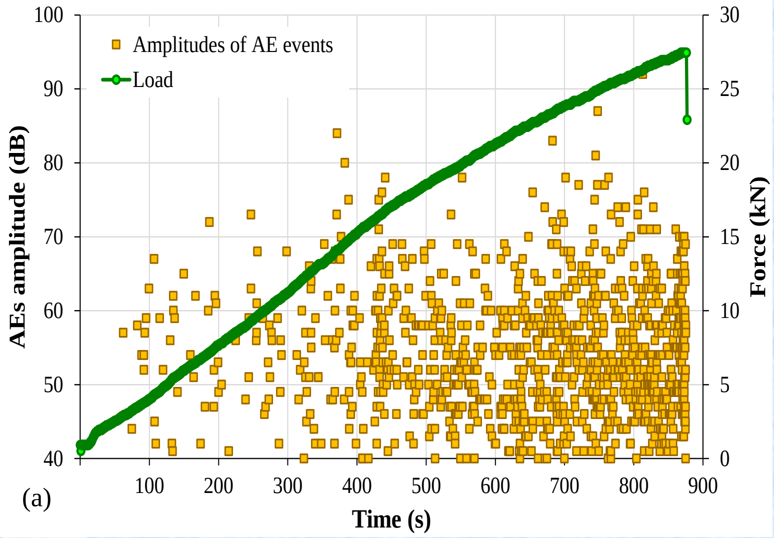
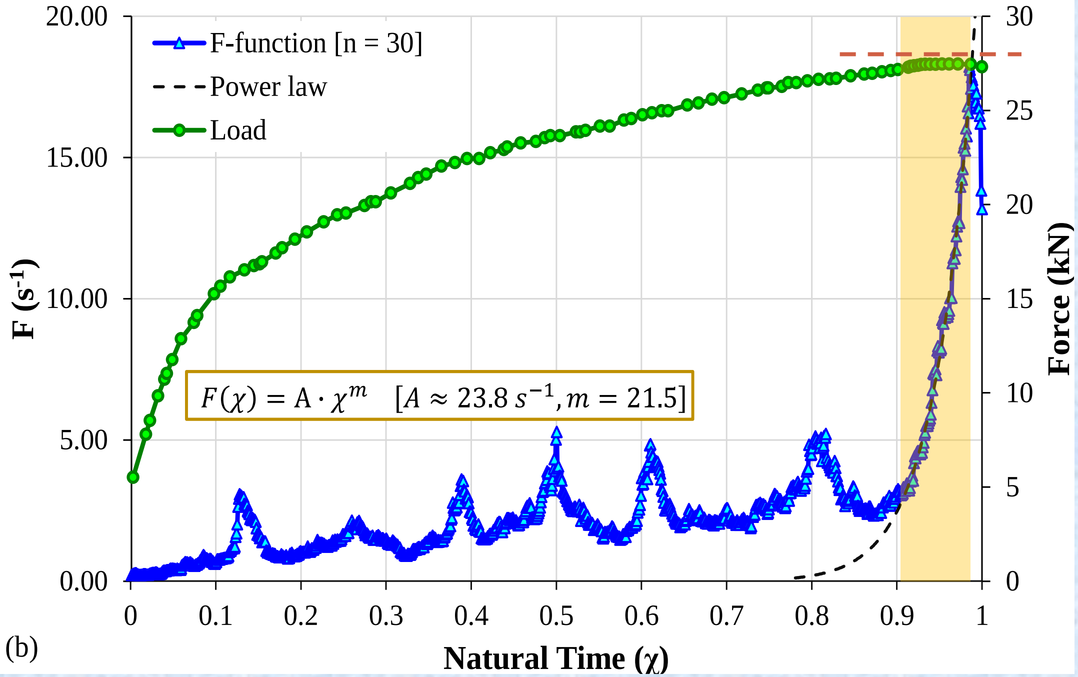
1. Kourkoulis S.K., Pasiou E.D., Stavrakas I. and Triantis D., Assessing structural integrity of non-homogeneous systems by means of Acoustic Emissions and Non-Extensive Statistical Mechanics, Fracture and Structural Integrity, 68, 440-457, 2024.

Shear of Mutually Interconnected Marble Blocks

Displacement-control loading mode was adopted (0.2 mm/min). For the test studied here, fracture (of the moving block) occurred when at the peak force of 27.5 kN. ***During the test N=1092 hits were recorded***.

The power law governs again the evolution of F(χ) function while the applied load approaches its maximum and catastrophic fracture is impending. Its validity lasts from χ=0.91 to χ=0.97. Fitting gives m=21.5 (quite high since ***a great number of acoustic events are produced in a short period***.





Load and acoustic activity in terms of conventional time (a) and, in terms of Natural Time

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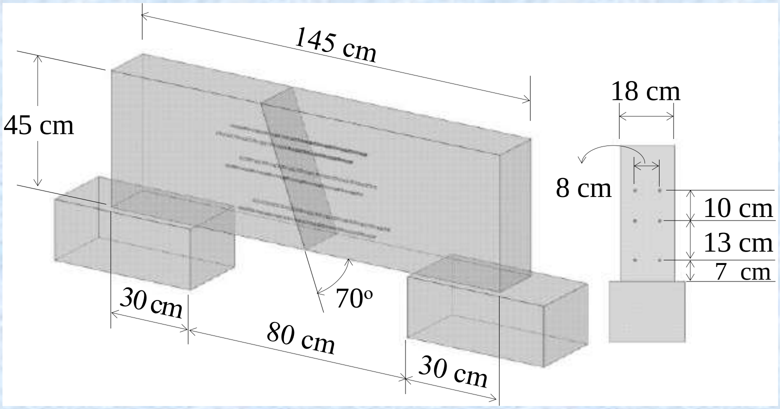
1. Pasiou, E.D.; Stavrakas, I.; Triantis, D.; Kourkoulis, S.K. Marble epistyles under shear: An experimental study of the role of “Relieving Space”. Frontiers of Structural and Civil Engineering 2019, 13, 767-786.

Bending of an asymmetrically fractured and restored epistyle



A copy of a typical epistyle of the Parthenon (scale of 1:3) was tested. It consisted of two asymmetric fragments, joined together by means of three pairs of bolted titanium bars of diameter 8 mm (threaded all along their length), which were driven in pre-drilled holes filled with liquid cement paste. The anchoring length was 25 cm on either side of the fracture plane (1).

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1. Kourkoulis S.K., Pasiou E.D., Stavrakas I. and Triantis D., Assessing structural integrity of non-homogeneous systems by means of Acoustic Emissions and Non-Extensive Statistical Mechanics, Fracture and Structural Integrity, 68, 440-457, 2024.

Bending of an asymmetrically fractured and restored epistyle

For the detection and recording of the acoustic activity 8 acoustic sensors (R15α, Mistras Group, Inc., New Jersey, USA) were used, properly attached at strategic points of the "epistyle" at either side of the interface of the two fragments.

The displacements developed during loading were monitored using a 3D-Digital Image Correlation (DIC) system (LIMESS, Messtechnik & Software GmbH, Germany), together with two clip-gauges (on either side of the fault).

For the detection and measuring of the PSC two pairs of electrodes were used (1).

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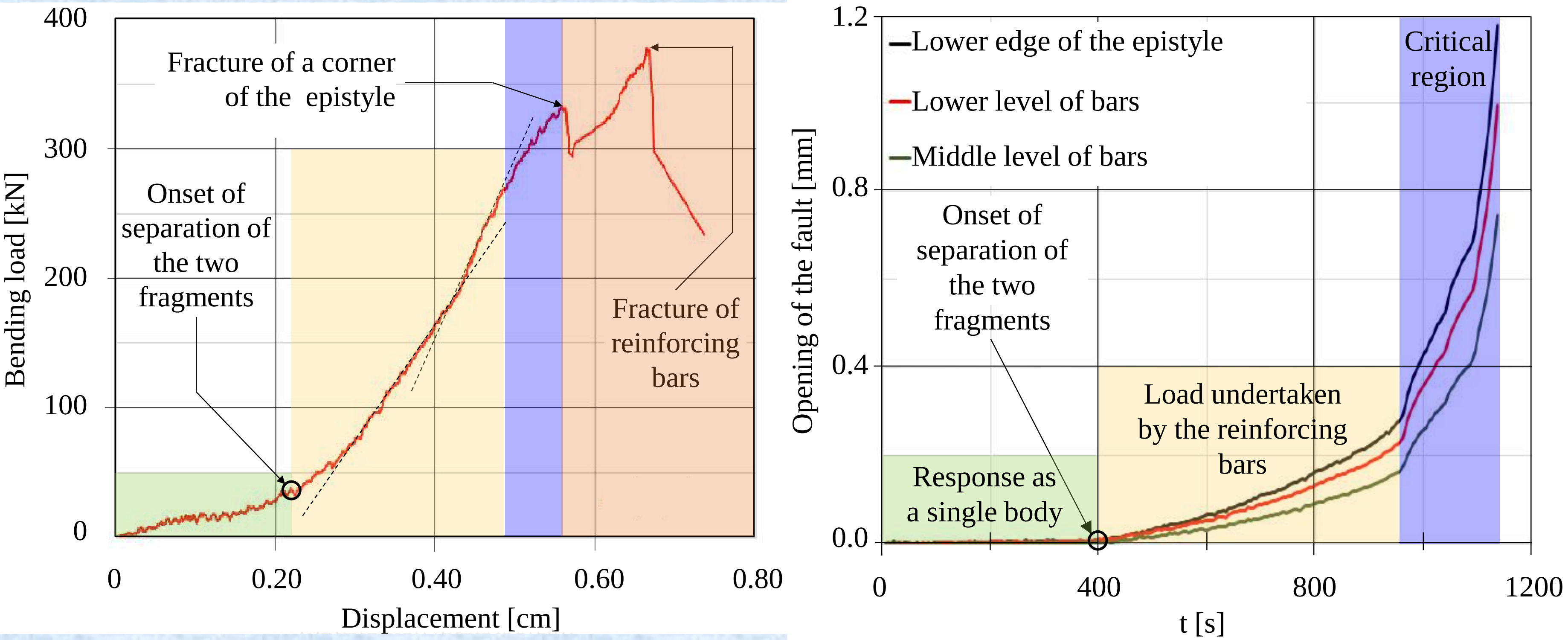
1. Kourkoulis S.K., Dakanali I., Pasiou E.D., Stavrakas I. and Triantis D., Acoustic Emissions versus Pressure Stimulated Currents during bending of restored marble epistyles: Preliminary results, Fracture and Structural Integrity, 41, 536-551, 2017.

Bending of an asymmetrically fractured and restored epistyle



The bending load versus the displacement (deflection of the epistyle's central cross section) (left); The temporal evolution of distance between the two fragments, at various heights, until the instant of local fracture of one of the epistyle's corners (right) (1).

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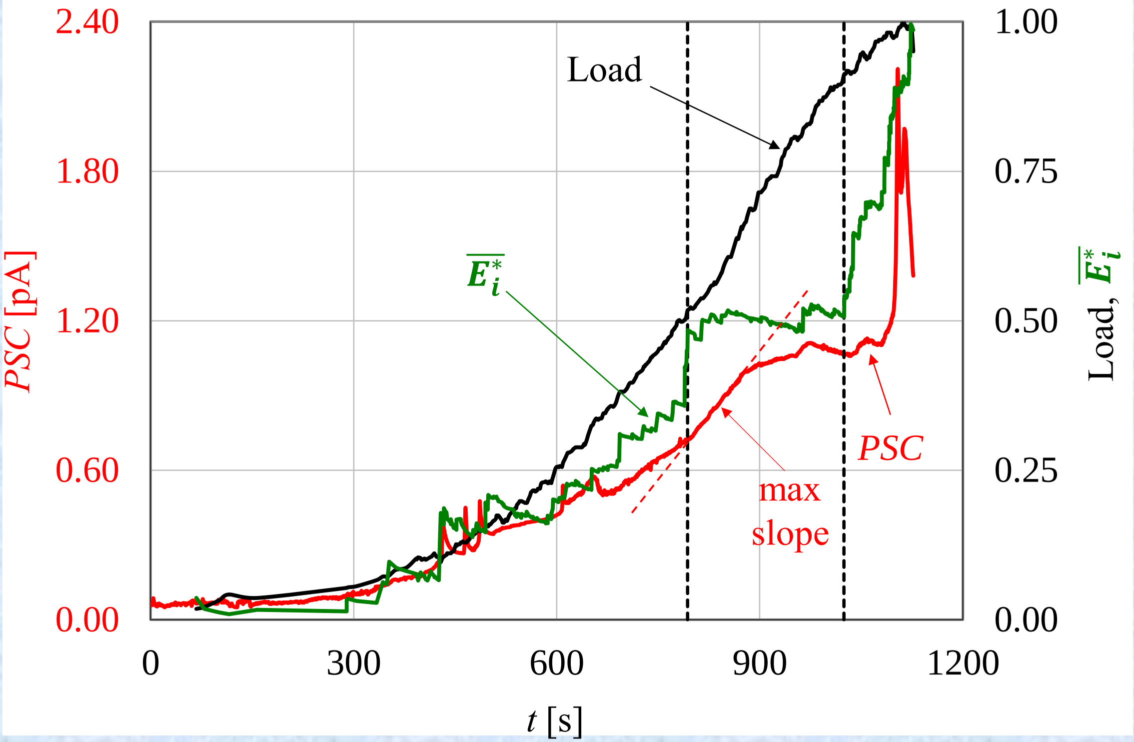
1. Kourkoulis S.K., Pasiou E.D., Stavrakas I. and Triantis D., Assessing structural integrity of non-homogeneous systems by means of Acoustic Emissions and Non-Extensive Statistical Mechanics, Fracture and Structural Integrity, 68, 440-457, 2024.

Bending of an asymmetrically fractured and restored epistyle

When the energy of the acoustic events forms a plateau the PSC attains its maximum increase rate (at an almost linear manner), and just after it exhibits, also, a stabilization tendency. ***The instant at which the slope of the PSC is maximized coincides with that at which the plateau of the energy of the acoustic events appears***.



The PSC in juxtaposition to the load and the acoustic energy

The plateau of the PSC is terminated abruptly at t=1090 s (with a slight delay compared to the respective instant of the plateau of the energy of the acoustic events) and is followed by a quite abrupt increase, which is **considered as a clear warning signal of upcoming macroscopic fracture, which was indeed observed about 40 s later**, i.e., at the instant at t=1130 s.

National Technical University of Athens
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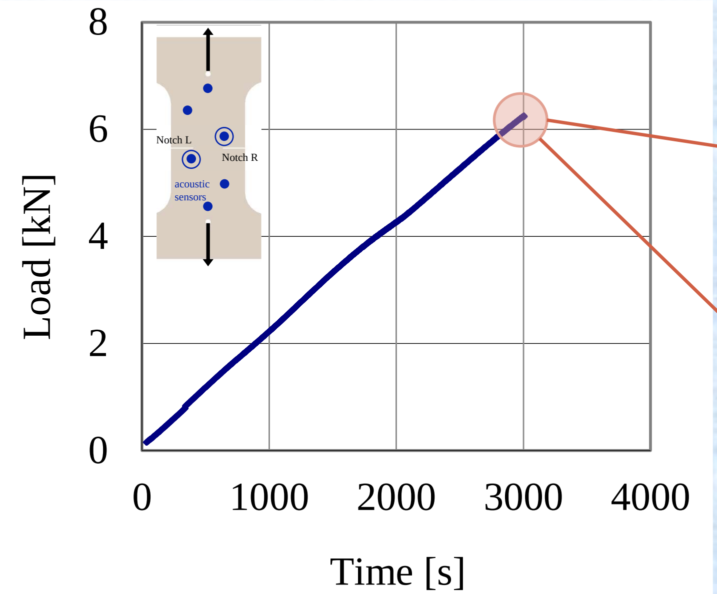
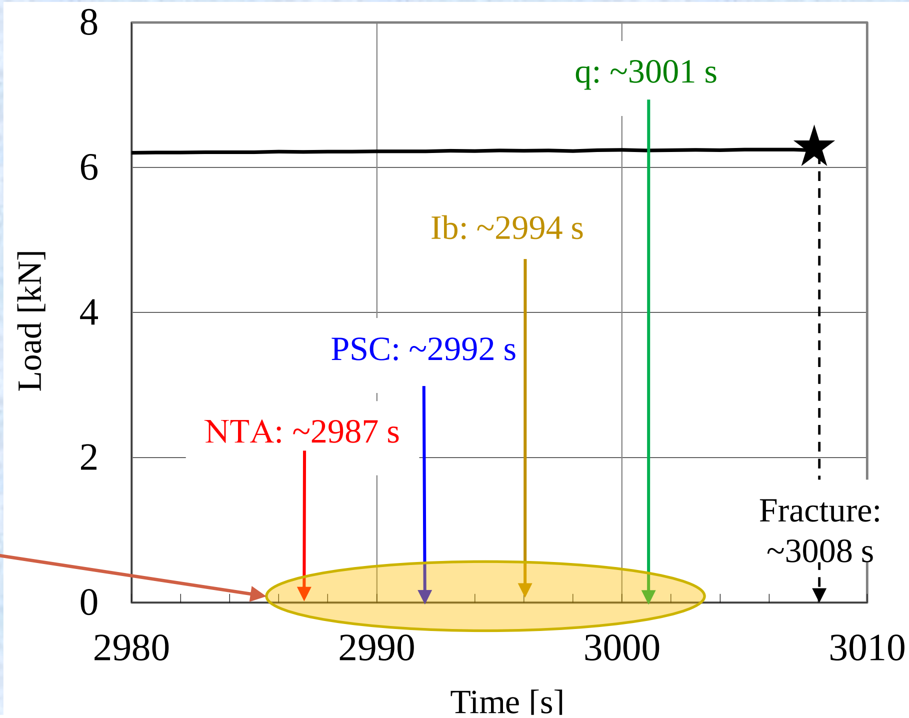
Department of Mechanics, Laboratory for Testing and Materials

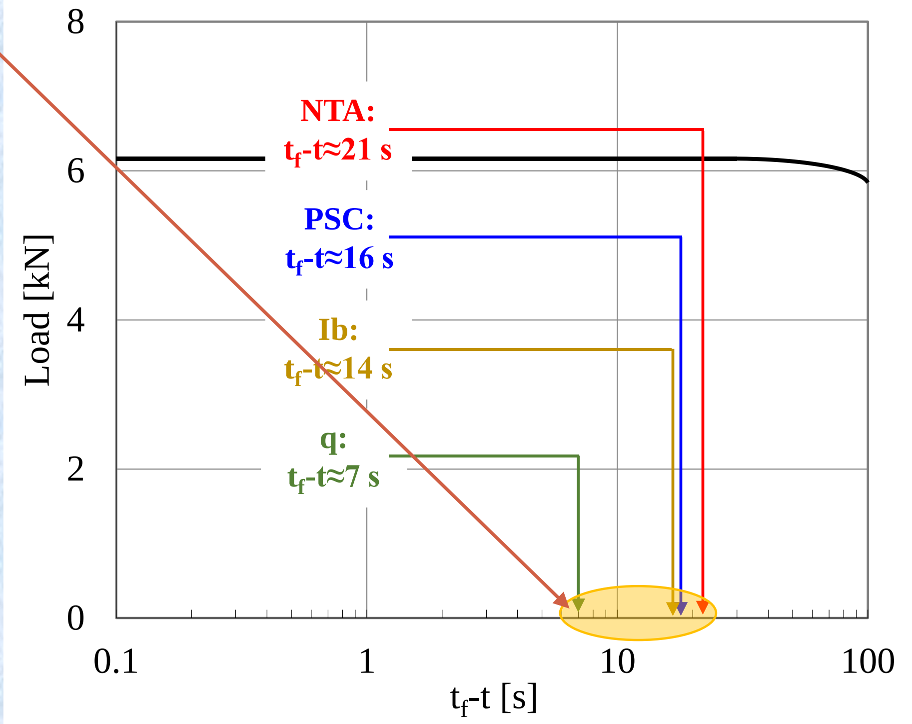
Comparative consideration of various criticality indices



The time evolution of the load applied and the criticality instants as predicted by NTA, PSC, Ib and NESM, for a DEN specimen, made of Dionysos marble, subjected to uniaxial tension

IAMON Workshop "Reinforced interfaces between structural members in ancient monuments", July 10, 2024, Athens, Greece





Coming to an end …

Two sensing techniques were comparatively considered: A mature and well established one, i.e., the ***Acoustic Emissions*** technique, and a relatively recently introduced one, i.e., that of the ***Pressure Stimulated Currents***.

They ***were proven to follow, according to a very satisfactory manner, the loading schemes imposed***, both at laboratory and structural level. Therefore, both of them are excellent tools for SHM purposes.

Moreover, the outcomes of these sensing techniques when analyzed in the Natural Time Domain are in very good mutual qualitative agreement and both of them appear providing ***indices that can be considered as pre-failure indicators***.

However, even in the laboratory scale, there are still quite a few open issues that must be properly addressed before definite and convincing suggestions and guidelines are drawn.