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Criticality hidden in acoustic emission time series from concrete specimen under compression

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Introduction

- Load-carrying capability and evolving crack damage of a cube-shaped concrete specimen have been assessed during a laboratory compression test carried up to fracture.
- Damage assessment has been carried by Acoustic Emission (AE) monitoring technique, through a network of six resonant PZT transducers. Besides classical methods of AE data analysis, including 3D AE source location and b-value analysis, the application of a recently proposed approach based on Natural Time (NT) analysis is herein proposed [1,2].

[1] Varotsos PA, N.V. Sarlis NV and Skordas ES, 2011 *Natural Time Analysis: The New View of Time* (Springer, Berlin).

[2] Potirakis SM and Mastrogiannis D, Critical features revealed in acoustic and electromagnetic emissions during fracture experiments on LiF, 2017 Physica A 485, 11–22.

Introducción

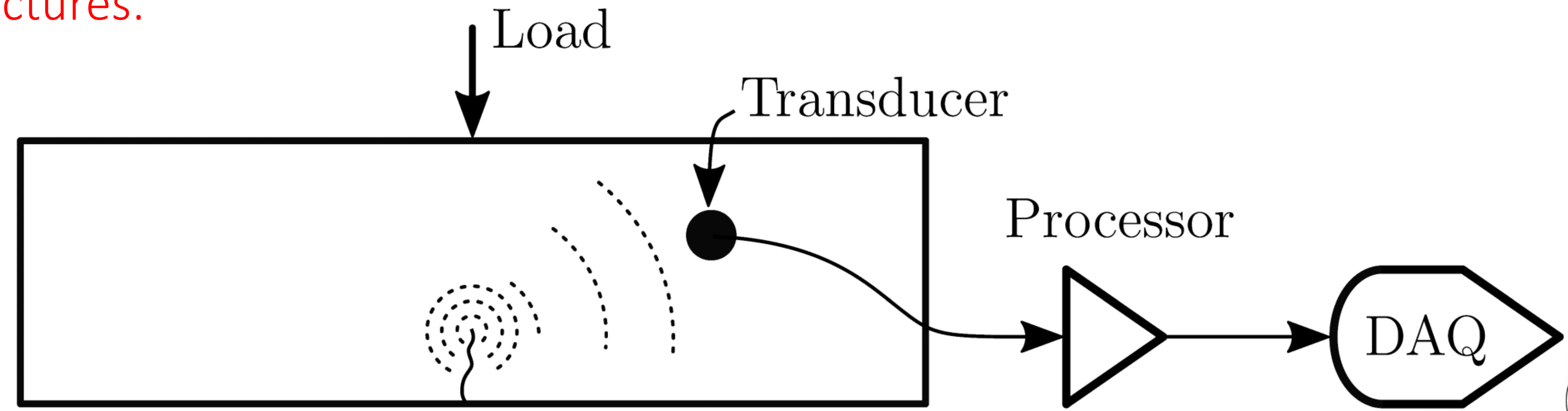
- The present study focuses on identifying the entrance of the system into a critical condition, through the definition of a critical NT parameter, to be extracted from the AE signal time series, as a pre-failure indicator.
- The numerical simulation of this test using a version of the Discrete Element method [3,4] allowed to understand some aspect of the damage evolution in the specimen regions, close to the formation of the critical cracks, that led to the collapse.

[3] Iturrioz I, Lacidogna G, Carpinteri A (2014). Acoustic emission detection in concrete specimens: Experimental analysis and lattice model simulations. International Journal of Damage Mechanics, 23: 327-358.

[4]Iturrioz I, Birck G, Riera JD (2018) Numerical DEM simulation of the evolution of damage and AE preceding failure of structural components. Engineering Fracture Mechanics.

Acoustic Emission

- The Acoustic Emission (AE) technique is applied to identify defects and damage in reinforced concrete structures.
- By means of this technique –considering the fracture propagation as a critical phenomenon– a particular methodology has been put forward for crack propagation monitoring and damage assessment, in structural elements under service conditions.
- This technique makes it possible to estimate the amount of energy emitted during fracture propagation and to obtain information on the durability performances of the structures.



Natural Time Analysis

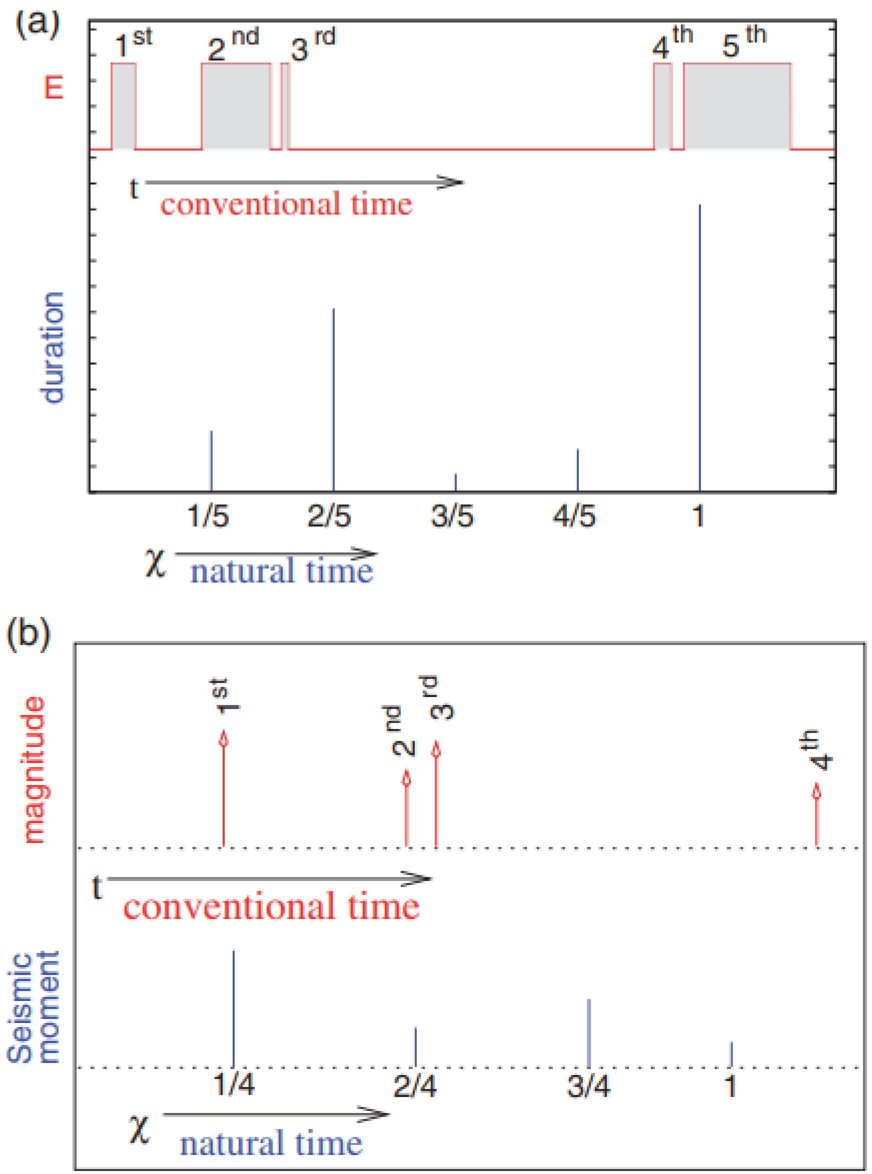


Fig. (a) How a dichotomous series of electric pulses in conventional time t (upper panel, red) can be read in natural time χ (lower panel, blue). The symbol E stands for the electric field. (b) The same as in (a), but for a series of seismic events.

The transformation of a time series of "events" from the conventional time domain to the natural time domain is done by ignoring the timestamp of each event and retaining only its normalized order (index) of occurrence.

- In a time series of N successive events.
- Q_k represents different physical quantities for various time series.

$$\chi_k = \frac{k}{N}$$

$$p_k = \frac{Q_k}{\sum_{k=1}^{N} Q_n}$$

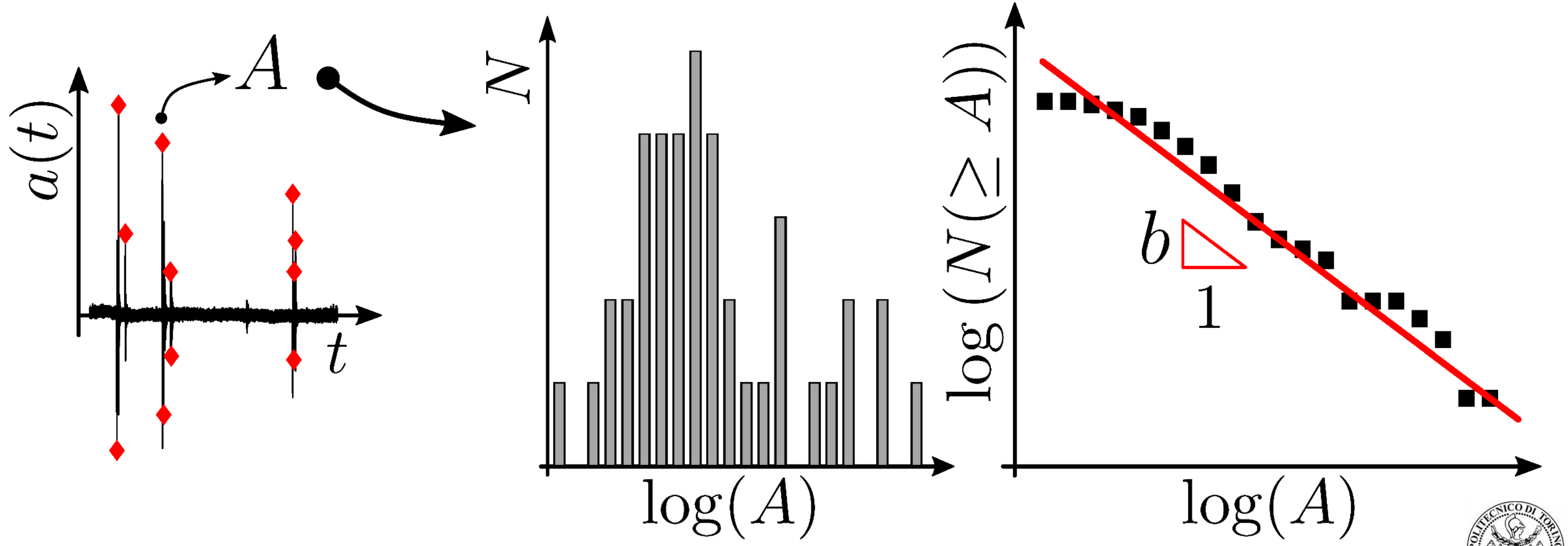
$$\kappa_1 = \sum_{k=1}^{N} p_k \left(\frac{k}{N}\right)^2 - \left(\sum_{k=1}^{N} p_k \frac{k}{N}\right)^2$$

Critical state if $\kappa_1 <= 0.07$

Parameter b-value

The (Gutenberg-Richter) GR relationship has been tested successfully in the acoustic emission field to study the scaling of the “amplitude distribution” in AE waves.

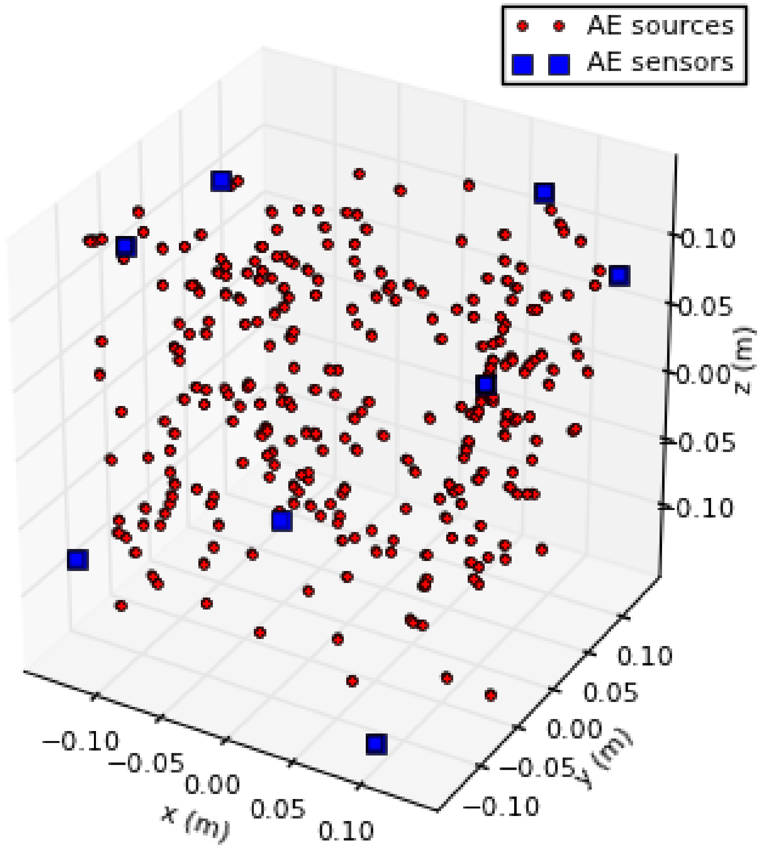
$$N(\geq A) \propto A^{-b}$$

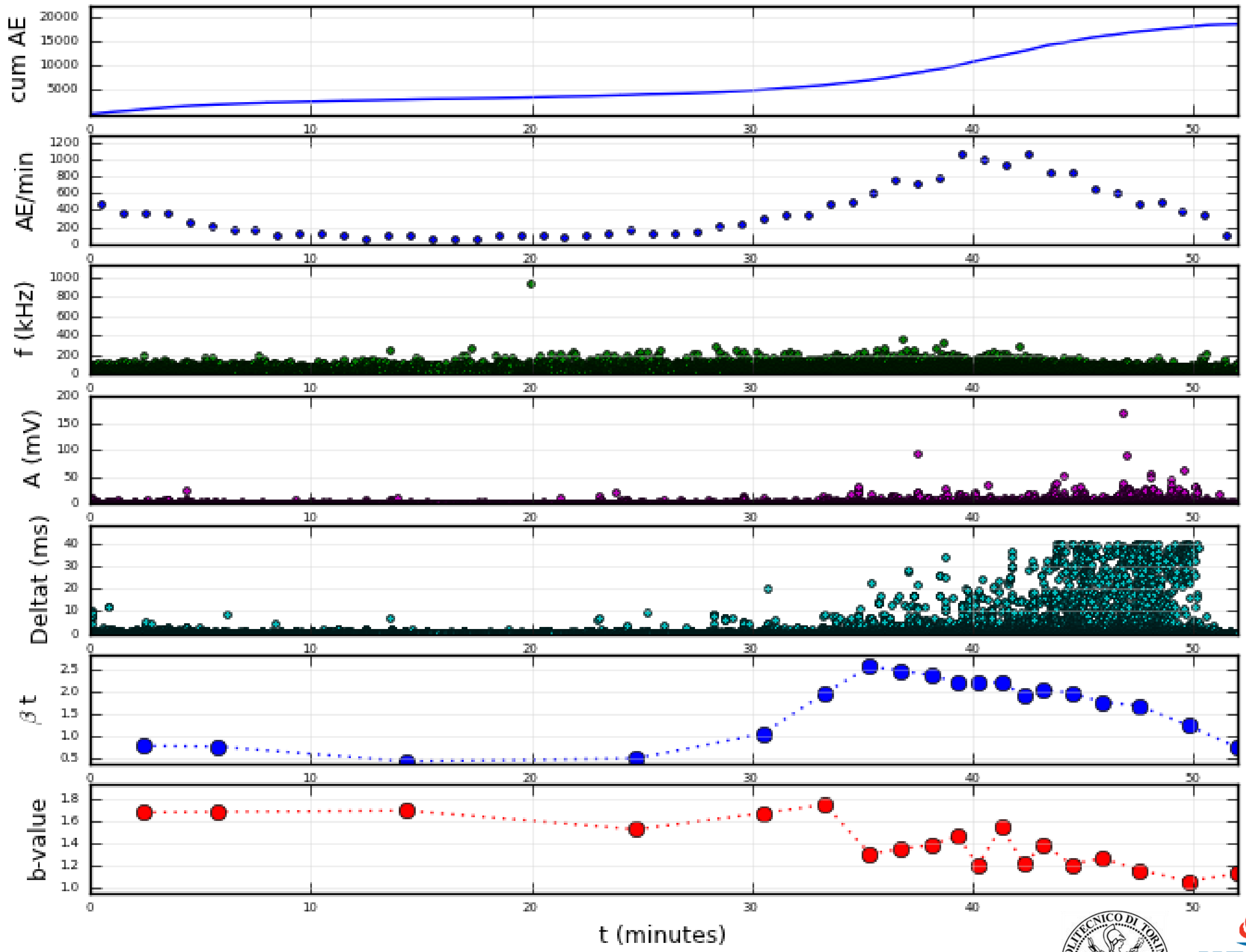


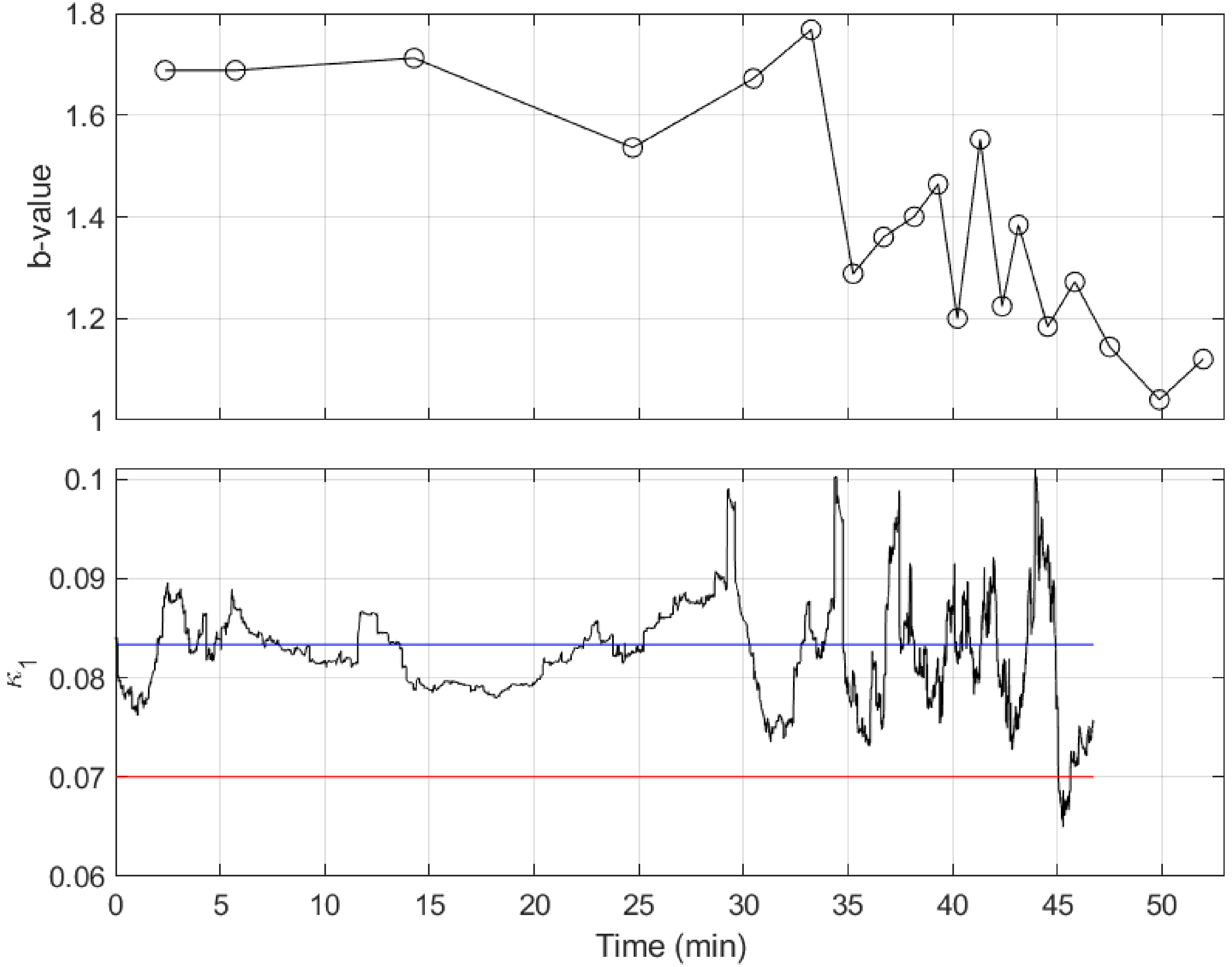
Test: Cubic concrete specimen submitted to uniaxial compression

- **Information:**
  - Cube 300x300x300 mm
  - 8 sensors (2 per face)
  - Compression Test: 1.5 kN / s
  - Resistance 60 MPa
  - Estimated Maximum Load 5400 kN
  - Test duration 51 min
  - Load Reached: 4500 kN
  - Elasticity Module: 40 GPa

- **AE:** 18532 events detected






1.8
1.6
1.4
1.2
1
b-value
0.1
0.09
0.08
0.07
0.06
κ_1
0 5 10 15 20 25 30 35 40 45 50
Time (min)

Simulation with a Lattice Discrete Element Method (LDEM)

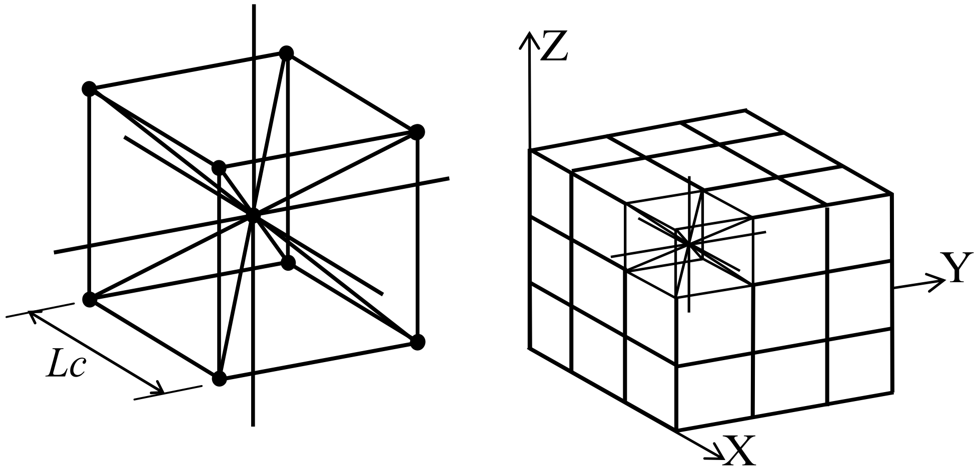
In this numerical approach the solid is modelled by means of a periodic spatial arrangement of bars with the masses lumped at their ends.

Each node has **three degrees of freedom**: nodal displacement (x, y, z);

The basic cubic module has **20 bar** elements and **9 nodes**.

$$\eta = \frac{9\nu}{4-8\nu}, \qquad EA_n = EL_c{}^2 \frac{(9+8\eta)}{2(9+12\eta)},$$

$$EA_d = \frac{2\sqrt{3}}{3} A_n,$$



LDEM – Non-linear Constitutive law

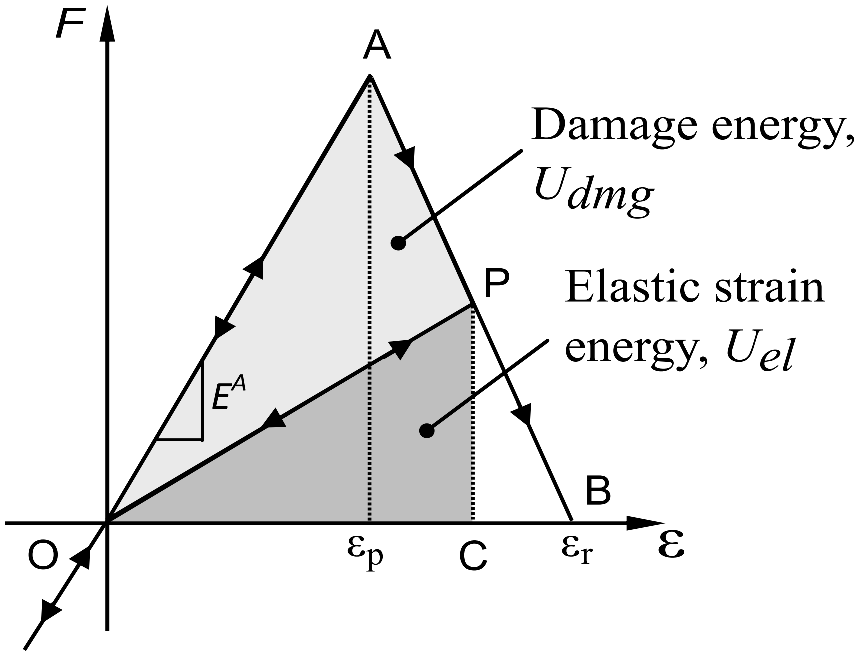
Bilinear constitutive law between axial force and axial strain for each bar.

A bar is removed when the resistance limit is reached, respecting the energy balance.

$$\varepsilon_p = \sqrt{\frac{G_f}{d_{eq} E}}$$

$$\varepsilon_r = K_r \varepsilon_p$$

$$K_r = \left(\frac{G_f}{E \varepsilon_p^2}\right)\left(\frac{A_i^f}{A_i}\right)\left(\frac{2}{Lc}\right) = (d_{eq})\left(\frac{A_i^f}{A_i}\right)\left(\frac{2}{Lc}\right)$$



LDEM- Time integration

The resulting motion equations, obtained with this spatial discretization is:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{F_r}(t) - \mathbf{P}(t) = 0$$

Explicit central finite difference scheme is used to time domain integration;

Since the nodal coordinates are updated for each time step, **large displacements** can be accounted in a natural and efficient manner

LDEM – Random distribution

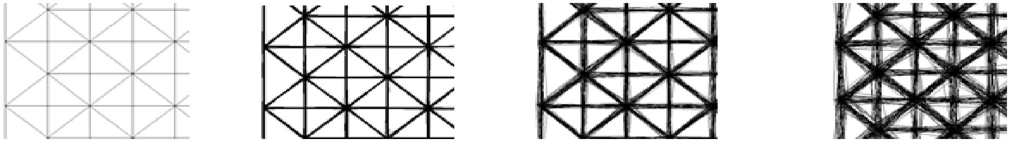
Material Parameters

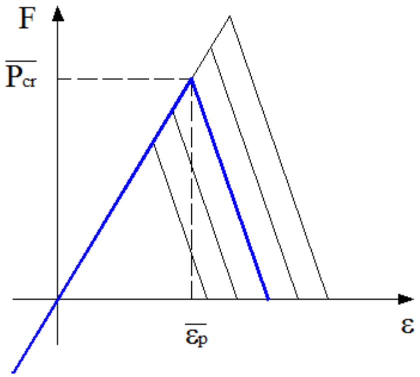
Young's Modulus (E), density (ρ) and Specific fracture energy (Gf) may be described by random fields, i.e. they can vary randomly throughout the structure.

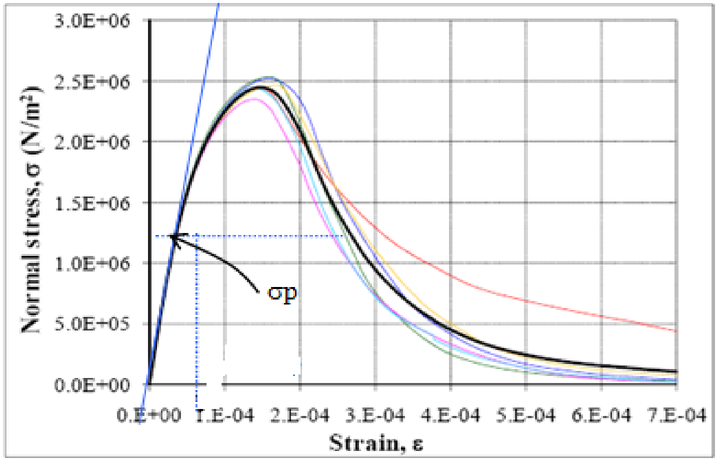
Gf is a random field F(mean, CV) with a Weibull distribution and a spatial correlation length (Lcorr)

The resulting motion equations, obtained with this spatial discretization is:

Field of ***imperfection in the mesh*** - perturbations of the cubic arrangement







The relationship between the energy released during the fracture process, E_s, and signal amplitude, A, is analyzed. Considering Chakrabarti et. al. (1997), E_s is linked with the drops in potential energy taking place during the damage process. With the aim of capturing the energy released, E_s, in the DEM context, we propose to compute the increments in kinetic energy between two successive integration times, using the following expression:

$$\Delta E_k(t_i) = E_k(t_i) - E_k(t_{i-1}),$$

$$\text{Log } N\,(>=\Delta E_k(t_F)) = \text{Log } t + d \text{ Log } \Delta E_k(t_F)$$

Notice : It is possible to infer that d ~ 2b (d = fractal dimension of damage domain). Then if b-value range is [1.5,1], the waited d range will be [3, 2]

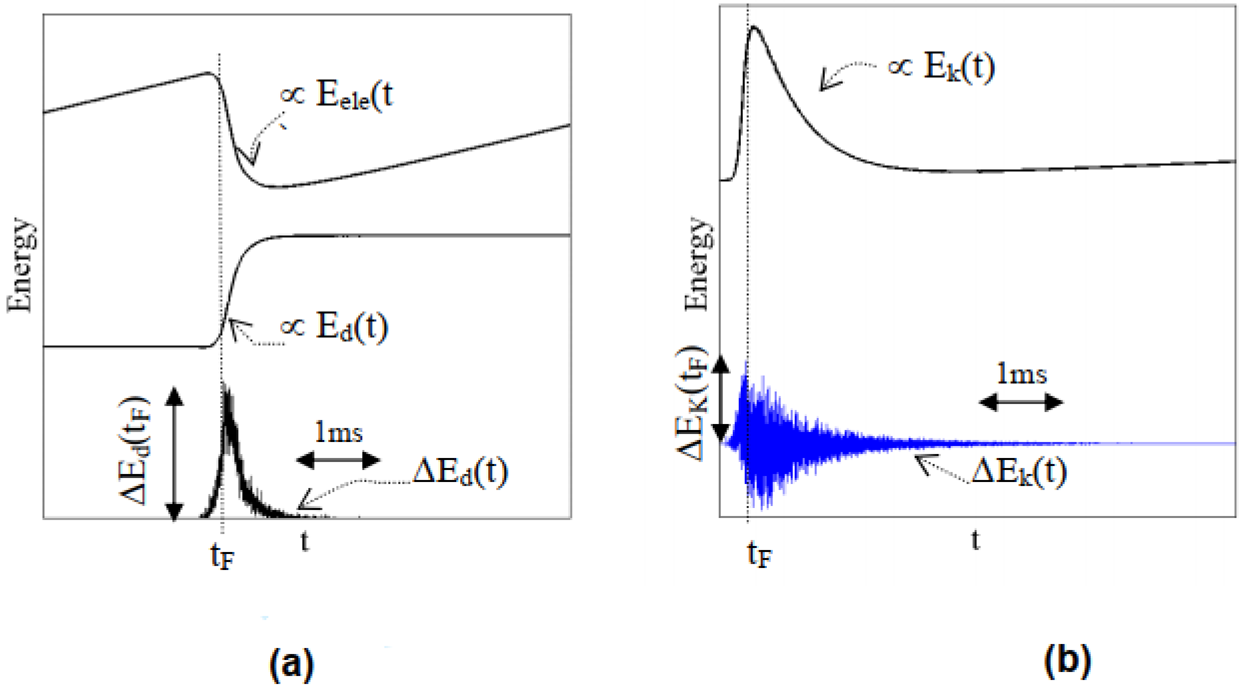
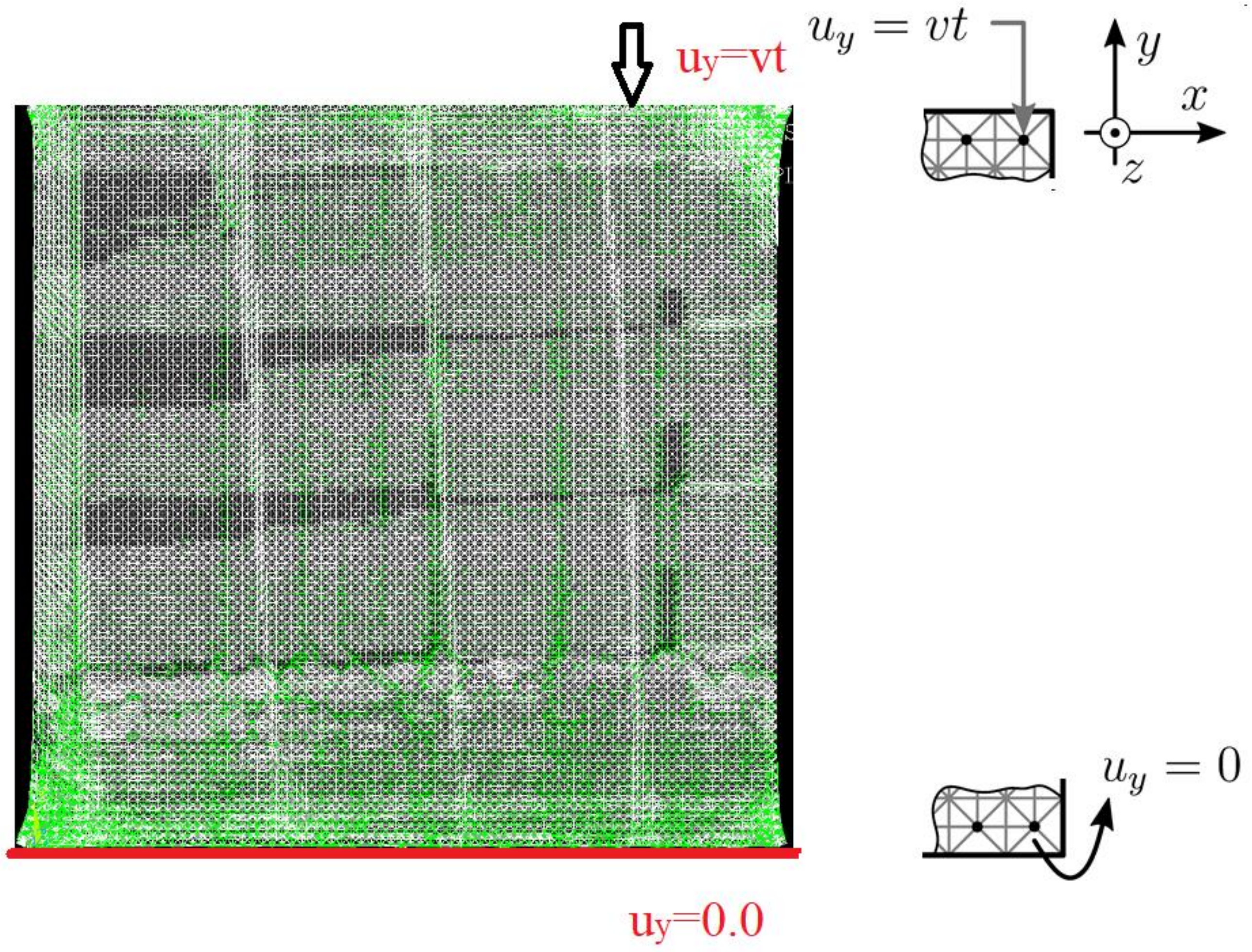


Figure : (a) Variations of dissipated energy increments ΔE_d, dissipated energy E_d and elastic energy E_{ele} during the entire simulation process. (b) Variations of kinetic energy increment ΔE_k and kinetic energy E_k during the entire simulation process.

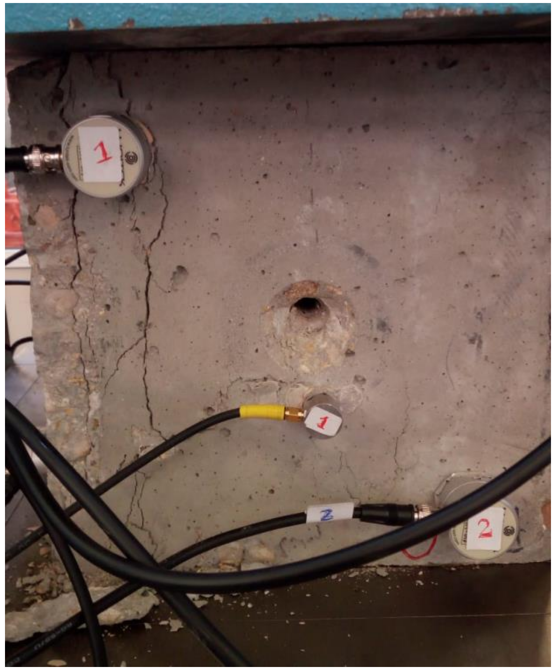
LDEM Model of the test performed

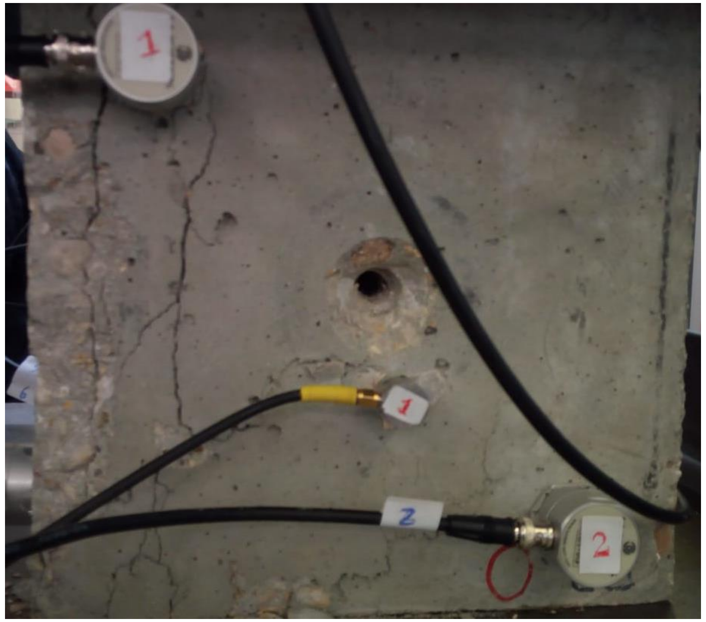
- **Simulation:**
  - Cubic module size: 4 mm
  - Number of modules: 75x75x75
  - Elasticity Module: 40 GPa
  - Density = 2400 kg/m3
  - Poisson = 0.25 (DEM)
  - Gf = 200N / m
  - deq = 4.47cm

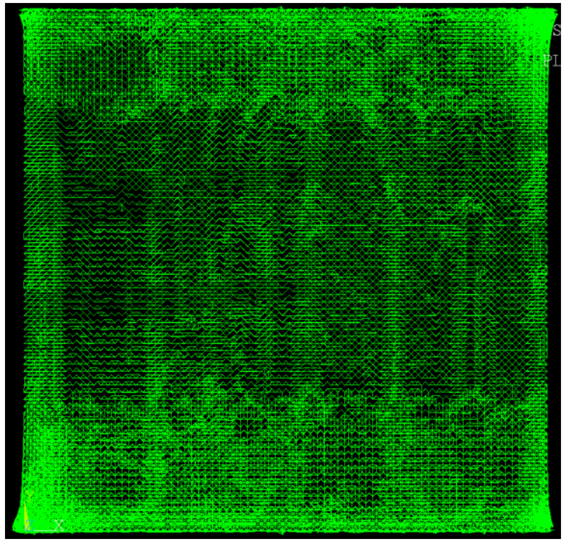


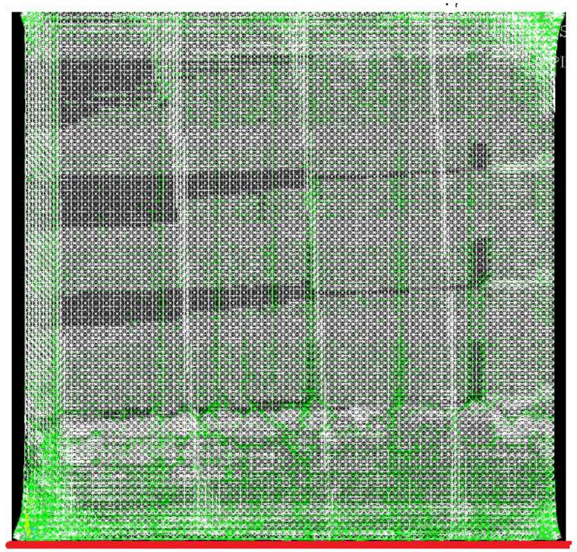
LDEM Final Configuration (in Green the failure elements)

Experimental and LDEM comparison in terms of final configuration



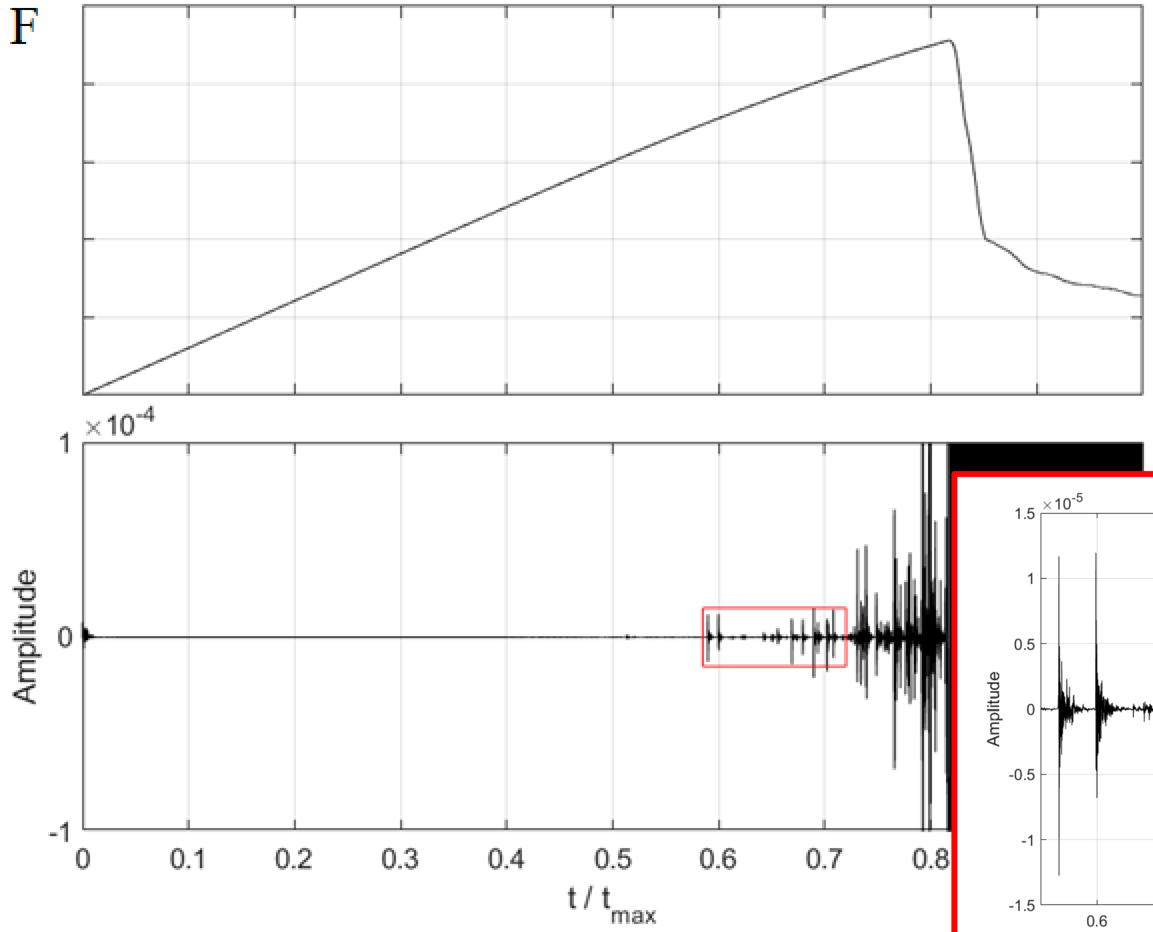


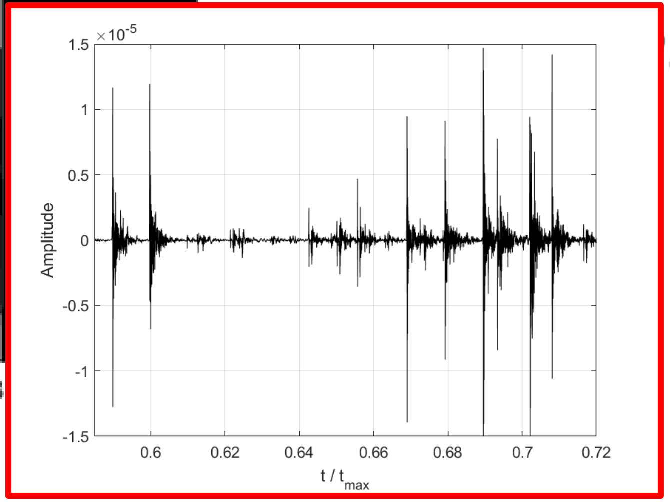


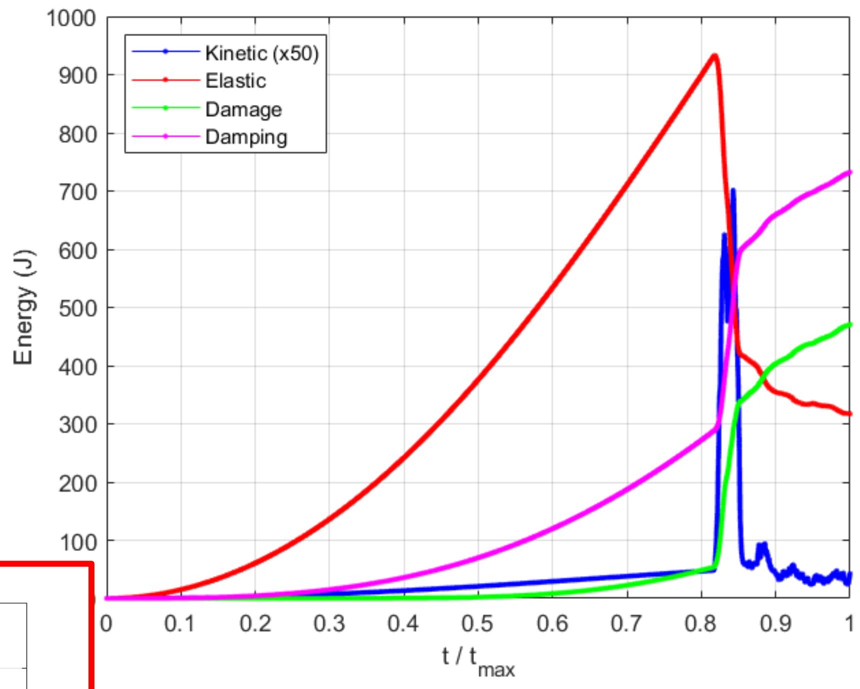


LDEM Final Configuration (in Green the failure elements)

LDEM Model Results: preliminar results showed lower AE activity than the experimental tets, the LDEM model must be adjusted.

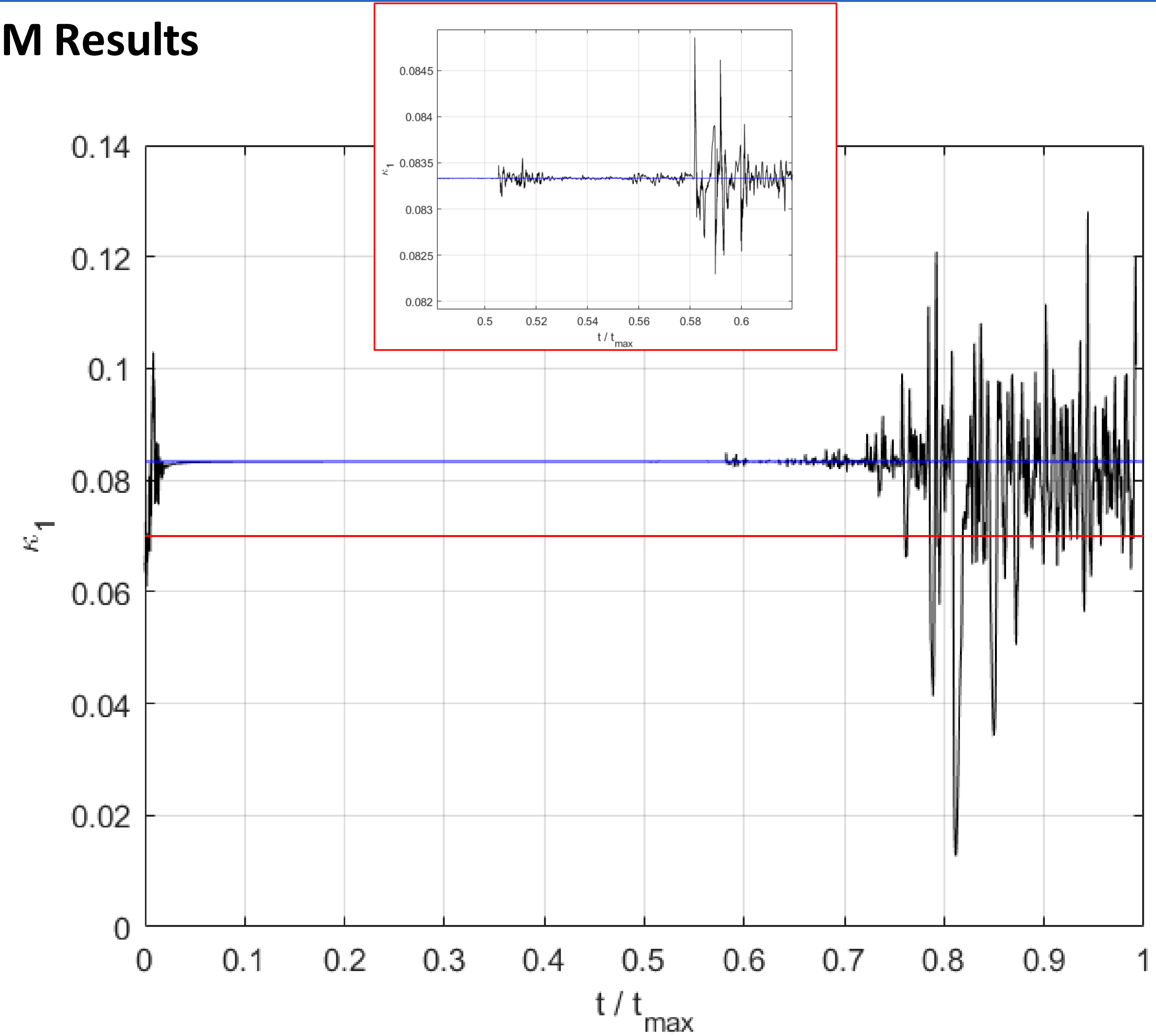


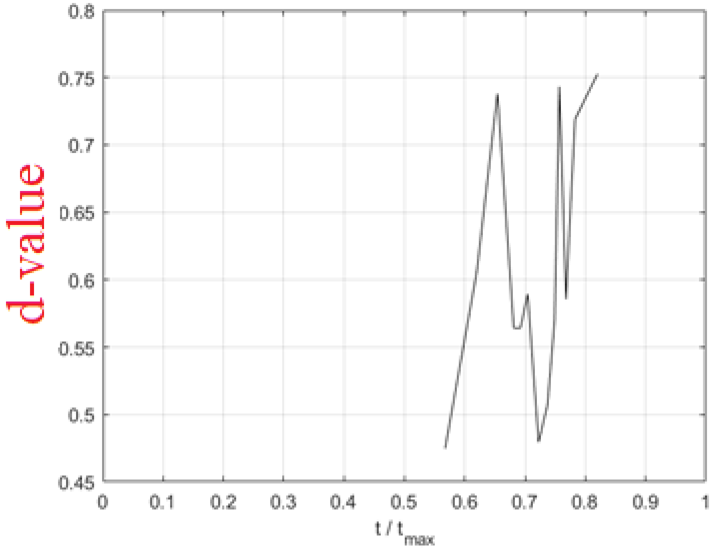




The events were defined in the Simulation using the increment of Kinetic Energy (ΔE_K)

LDEM Results





$$\Delta E_k(t_i) = E_k(t_i) - E_k(t_{i-1}),$$

$$\text{Log } N\ (>=\Delta E_k\ (t_F))=\text{Log } t + d \text{ Log } \Delta E_k\ (t_F)$$

Notice : It is possible to infer that d ~ 2b.
Then if b-value range is [1.5,1],
the waited d range will be [3, 2]

Conclusions

In the present work the simulation of a concrete submited to uniaxial compression test is performed, and also its simulation using a version of Lattice Discrete Element Method was done.
Global parameter results base on the AE data were computed in the experimental test, and the $\kappa 1$ coeficient obtained using the natural time analysis was made .

During the test not only the traditional global AE parameters but also the $\kappa 1$ coeficient evolution showed the expected behaviour. In the case of the $\kappa 1$ evolution the serie reach values lower than 0.07 when the collapse was eminent.

Preliminar results obtained from the numerical simulation in terms of d value evolution (the exponential coeficient of the Acoustical emission energy distribution) and the $\kappa 1$ evolution also present the waited behaviour.

Thank you, please for any question enter in contact by our e-mails:

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