Méthodes de prédiction de la durée de vie résiduelle des matériaux et structures via l'analyse statistique des signaux enregistrés en service

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Motivation : Dilemma of SHM engineer – replace or repair; now or later

Mirepoix-sur-Tarn, 2019

Buildings in Marseille, 2018

CDG Aeroport terminal 2E, 2016

Coussouls de Crau, 2009

Little room for errors in life-time assessment but limited quantitative tools…

> Les méthodologies utilisées actuellement ne donnent pas d'information sur la durée de vie résiduelle. Toutefois, la connaissance de cette durée de vie permettrait d'améliorer la **sécurité** des appareils et d'optimiser la ***planification de leur maintenance***.
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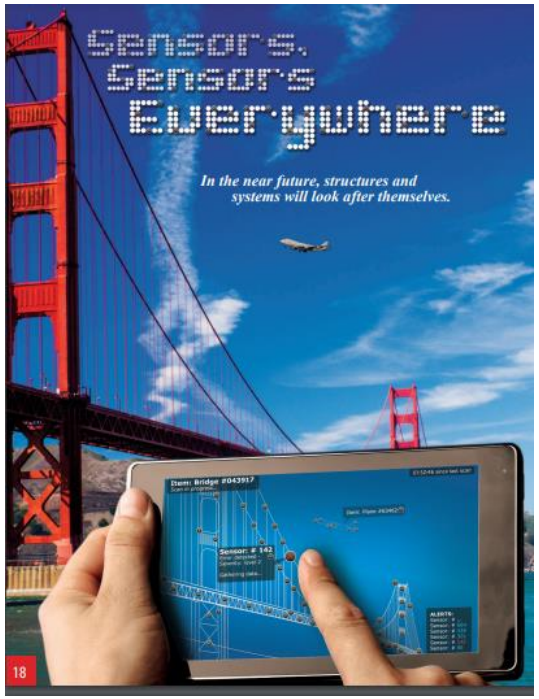
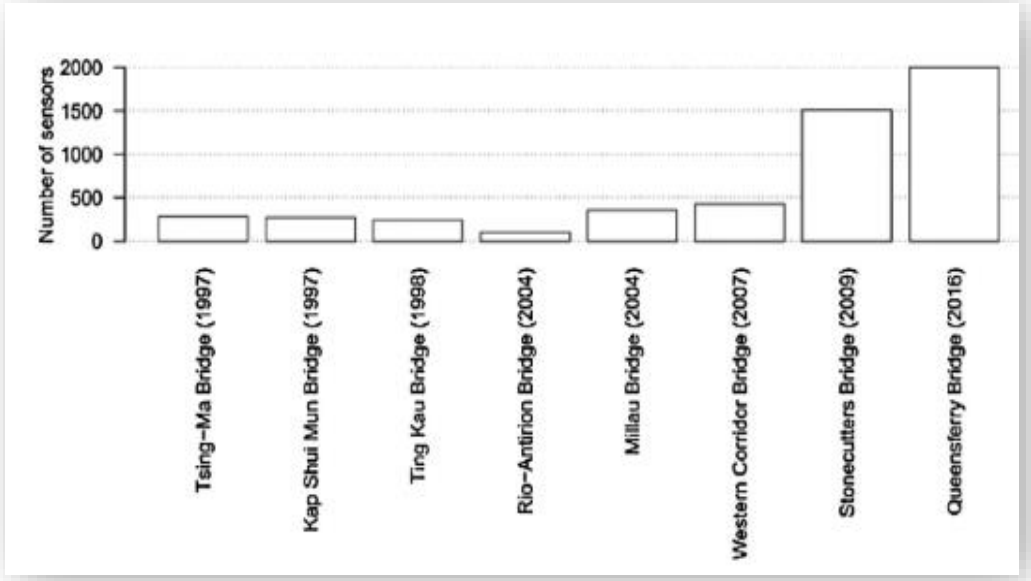
> ***- Cetim***

Challenge : Obtaining mechanics insights from SHM data



Los Alamos Science and Technology Magazine, July 2013



Evolution of number of sensors on major monitored bridges, *Structural Engineering International, 2018*

Current SHM technologies provide more and more data with higher time and space resolution. However, the interpretation of these signals as quantitative damage parameters is still lacking.

Why is it so challenging to make predictions from SHM data ?

Illustration of the concept on a cable

Today, damage is monitored at the level of (individual) wires

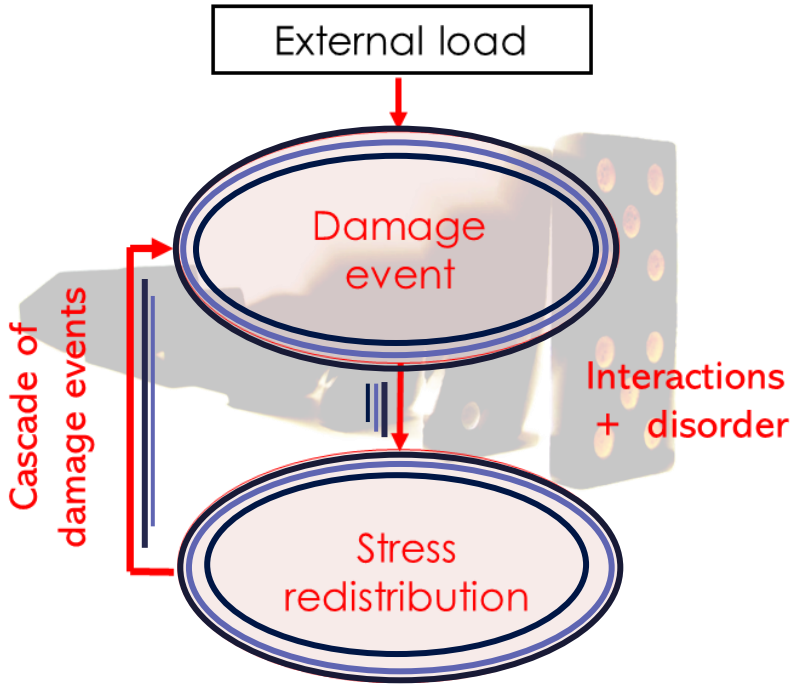
But predicting failure of the cable level is another story

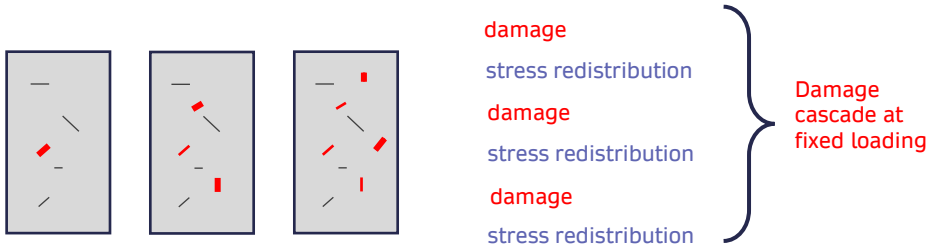
- Wires are imperfect → disorder in their failure strength
- Multiple wires may fail simultaneously.

Material failure at the structural level is a collective phenomenon.

- ➢ Taking into account cooperativity in damage evolution is key to failure prediction.
- ➢ Can we characterize cooperativity in damage evolution from SHM data ?

Damage cascades as a signature of cooperativity





Damage events are not independent but are triggered by each other, leading to cascades

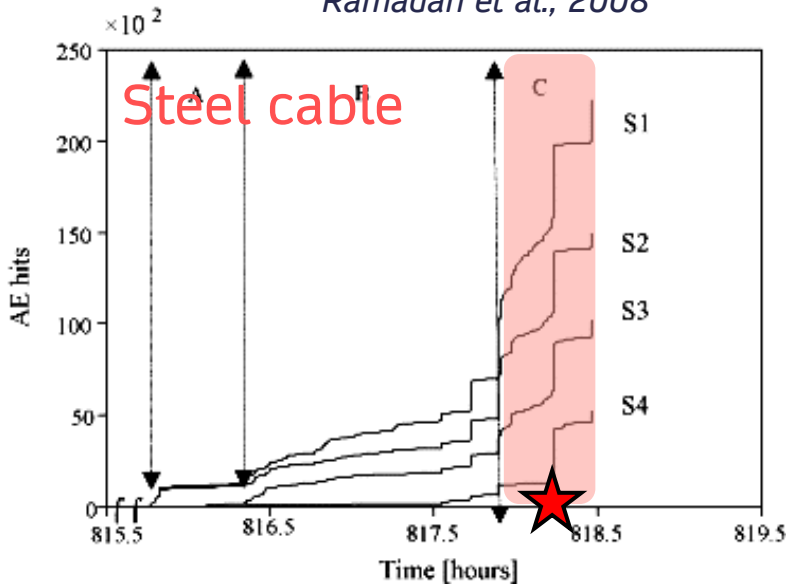
Universality in how materials progressively damage and fail

- **Scaling relations between the different features of a cascade** - energy, duration and spatial extent
- **Increase of the cascade size on approaching failure**
- The cascade size **as a marker of the distance to failure**

Damage spreading in quasi-brittle disordered solids: II. What the statistics of precursors teach us about compressive failure, ***Journal of the Mechanics and Physics of Solids. 2022 Feb 24:104826***

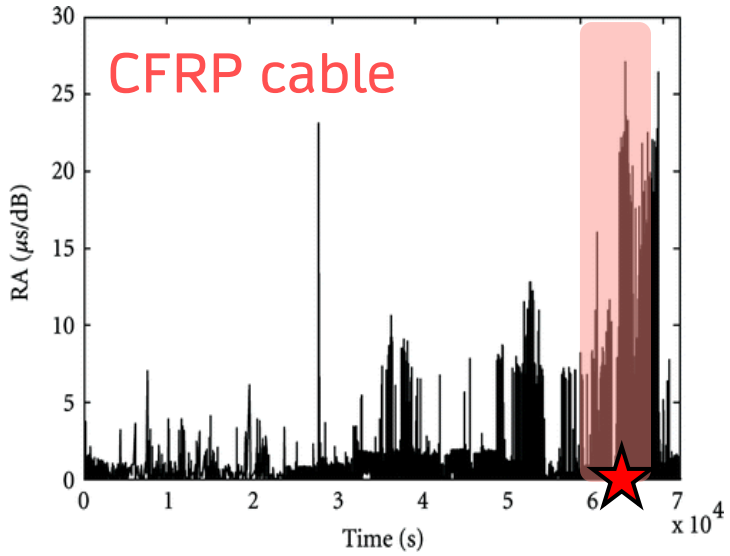
Evolution of damage cascades in a cable

Ramadan et al., 2008



Stress-corrosion cracking

Li et al., 2012



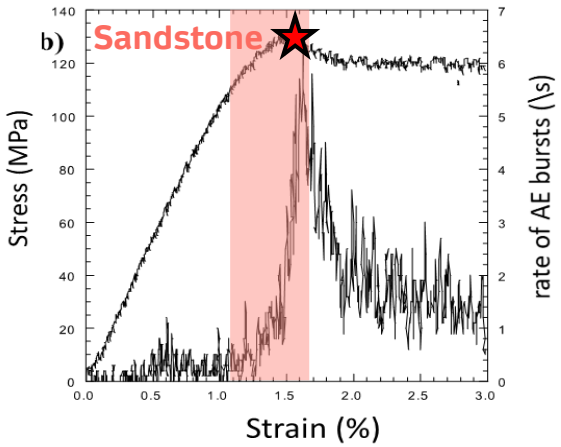
Fatigue failure in tension

Damage cascades (and hence acoustic emission) intensify close to failure.

The **sequence** of damage events reveals the distance to failure that we miss if we only focus on the failure of individual components.

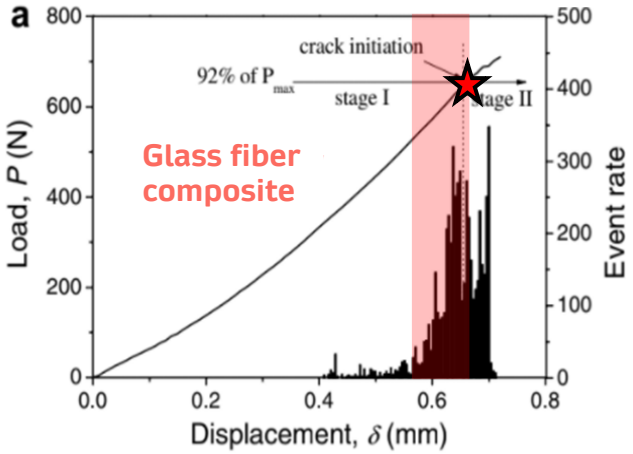
Cascade intensification: a robust feature

Baud et al., 2004



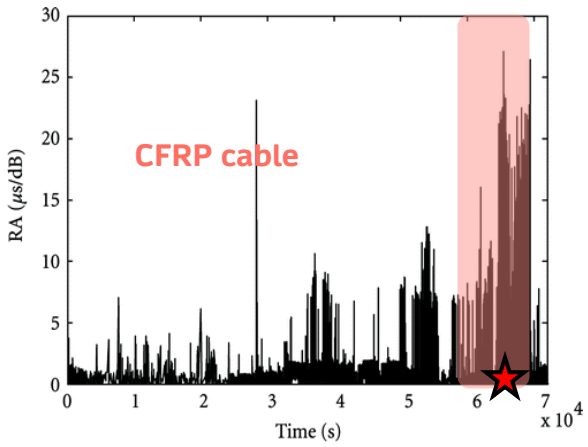
Compressive failure

Woo and Choi, 2007



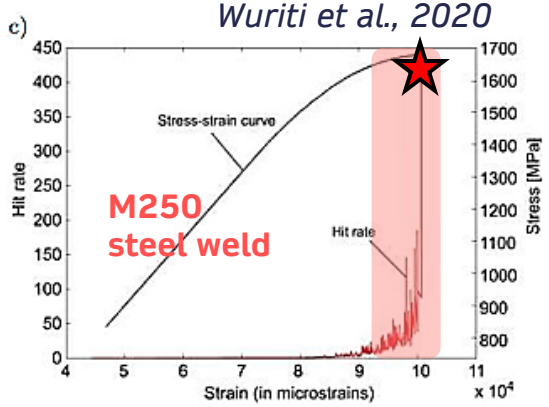
Crack initiation under tension

Li et al., 2012



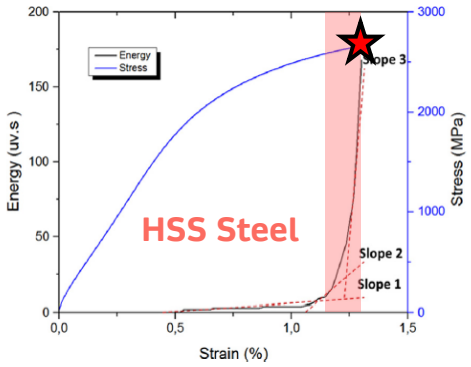
Fatigue failure in tension

Wuriti et al., 2020



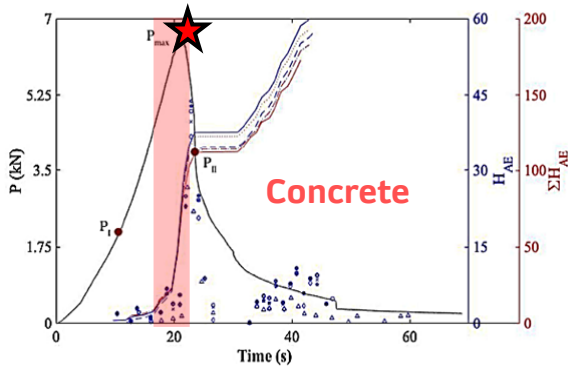
Tensile failure

Toubal et al.., 2020



Tensile failure

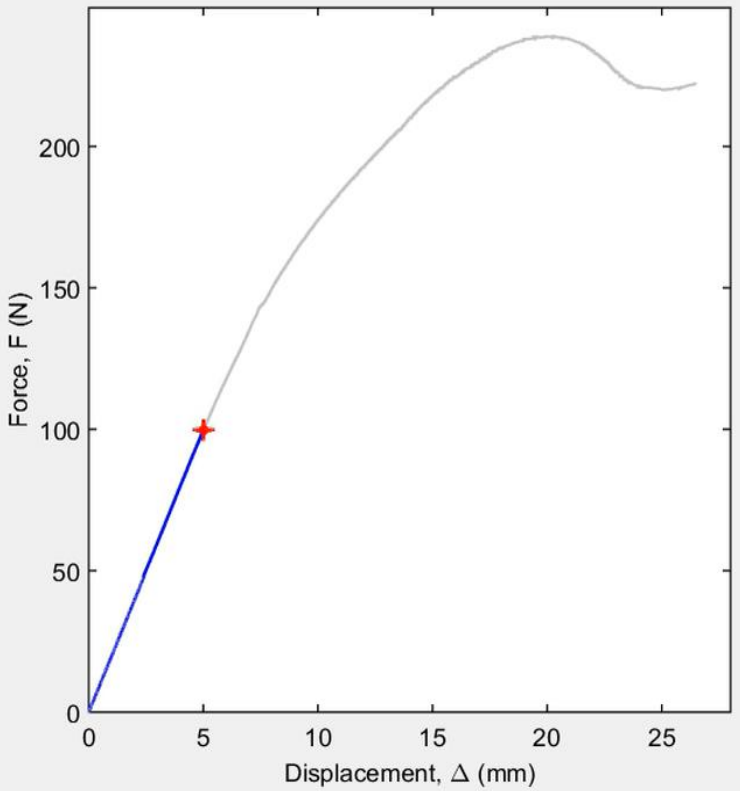
Yue et al., 2020



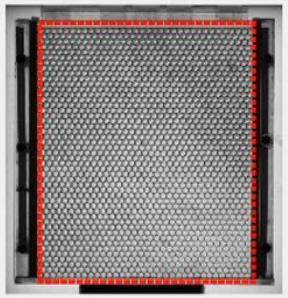
Bending induced failure

Precursors during compressive failure of a model elasto-damageable solid

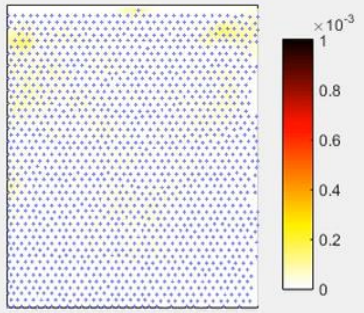
Force – displacement curve



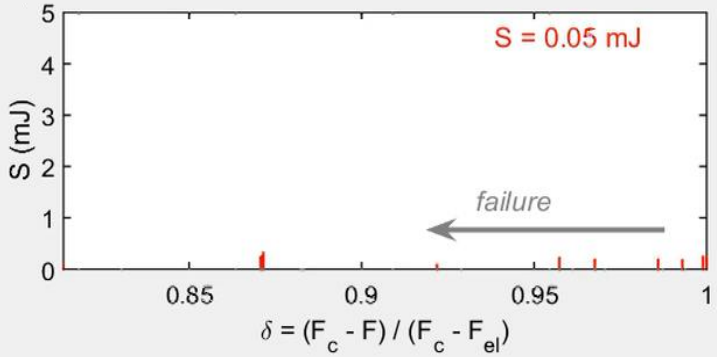
2D cellular solid



Dissipation energy maps



Precursor size S with distance to failure, δ



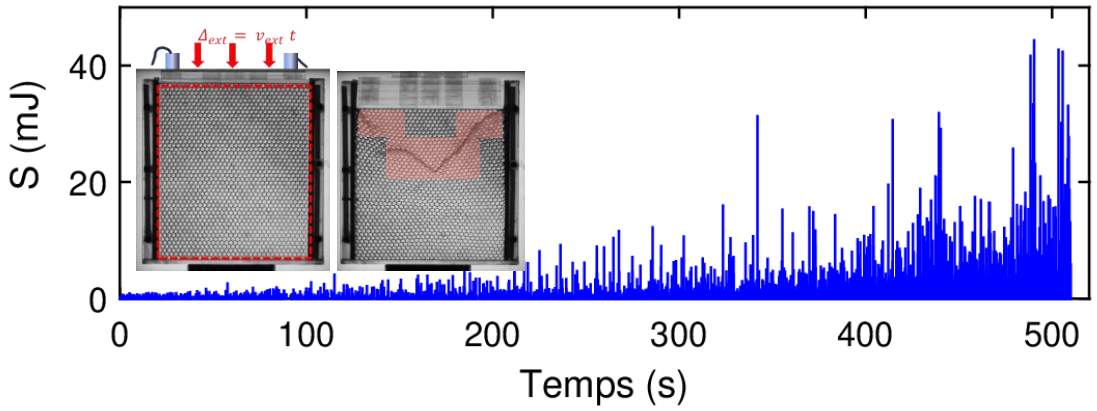
An experiment where cascades are resolved in space and time to obtain :

- Their size, S
- Their duration, T
- Their spatial extent, ξ

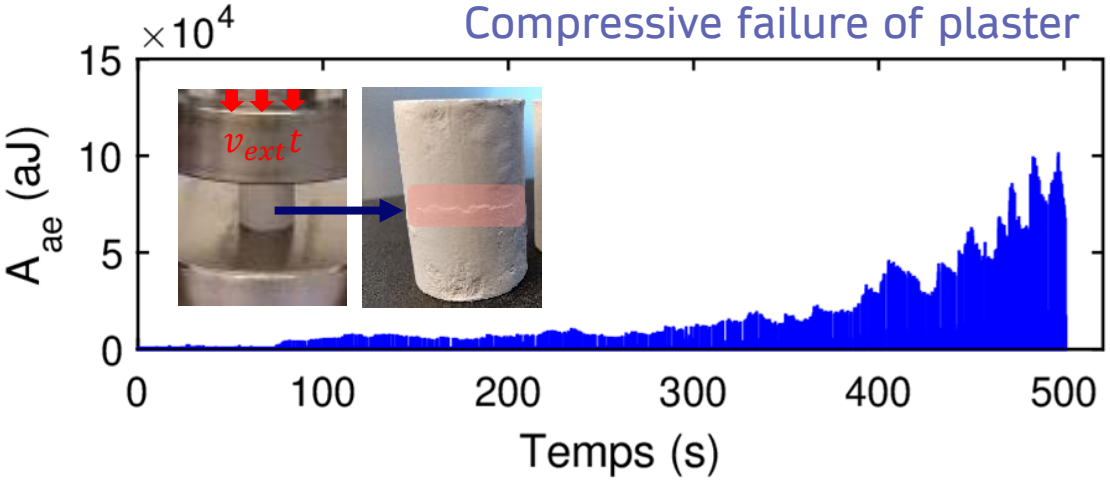
All these quantities follow peculiar scaling laws on approaching failure

Proof of concept : Lab experiments

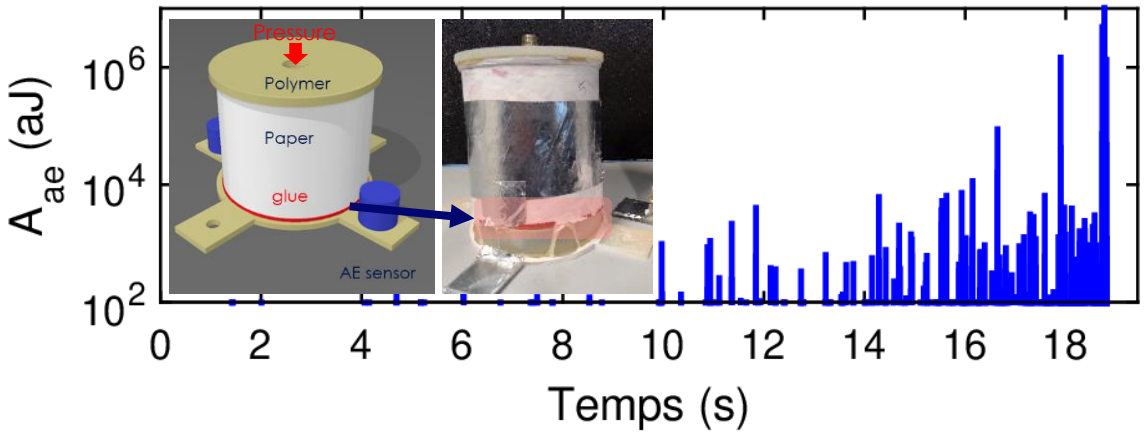
Precursors in a model solid :
Compressive failure of a 2D cellular solid



Acoustic precursors :
Compressive failure of plaster



Acoustic precursors :
Leak of a pressure vessel

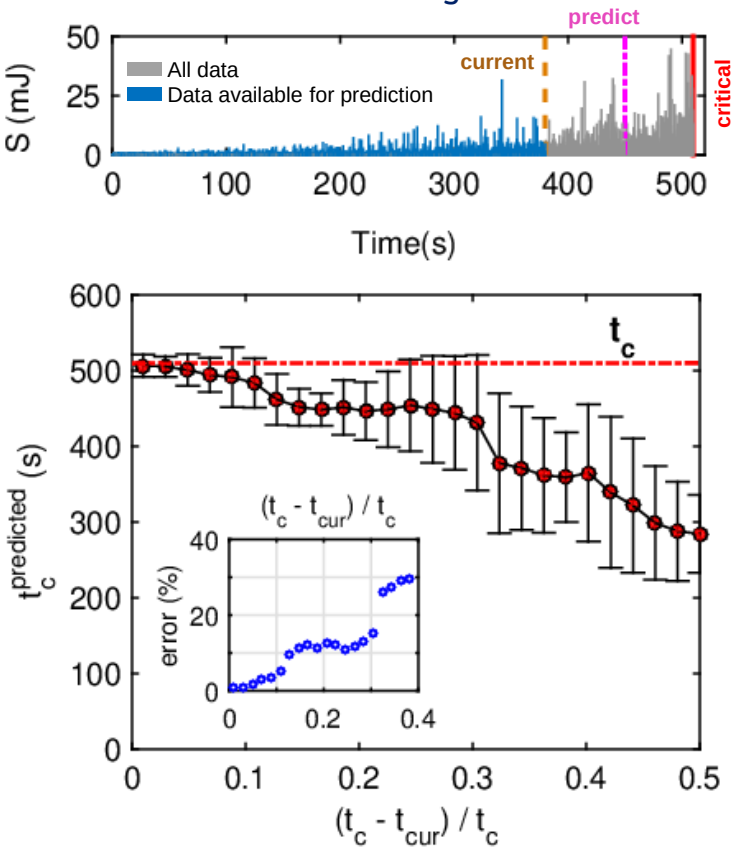


Study of the precursory activity to specimen failure [under compression, increasing pressure, for crack initiation, non-uniform stress distribution…]

- Statistical characterization of precursors
- Acceleration of precursory activity

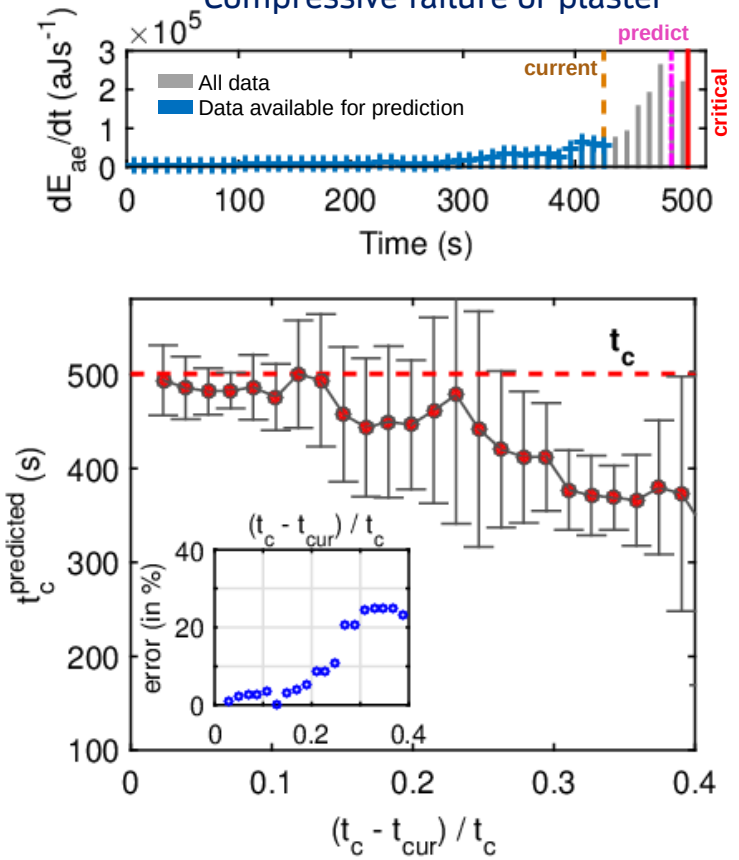
Proof of concept : Failure prediction*

Model elasto-damageable solid



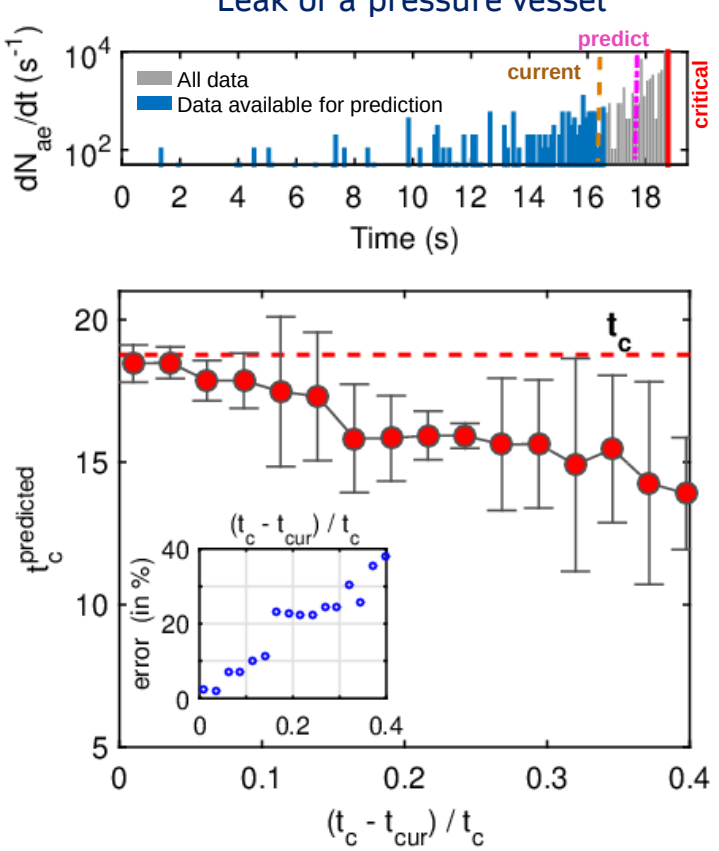
Average size of precursor

Compressive failure of plaster



Rate of increase of acoustic energy

Leak of a pressure vessel



Activity rate

- Requires only events from recent history
- Conservative prediction on residual life-time (t_c - $t_{current}$)
- An error margin of 10 % on t_c after 3/4 of the total lifetime

***French patent FR2002824 (Mars 2020),** Procédé et dispositive d'analyse d'une structure*

Vision : An interactive modeling approach

A bridge between the numerical modeling and sensor data so that they can ‘talk’ to each other.

Statistical analysis of precursors to interpret :

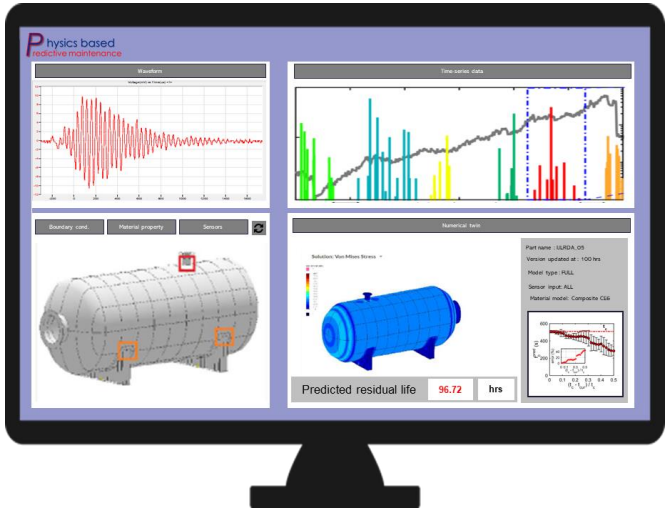
- cascades from individual hits
- local failure mechanisms

I. Compare sensor data with model predictions

II. Update the model and predict future signals

Fracture (Damage) mechanics; **disorder**; **elastic interactions** requiring inputs as

- material properties;
- loading condition



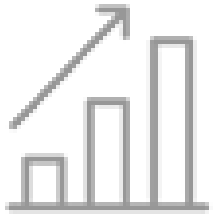
Data collected on site

Data analysis and numerical twin

Assessing residual life : How, When and Why ?

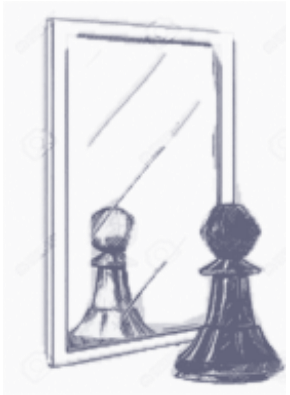
1 Predicting residual lifetime from statistics of precursors

However, analyzing the acoustic precursors with the current technique does not provide any hint on how to extend the residual lifetime



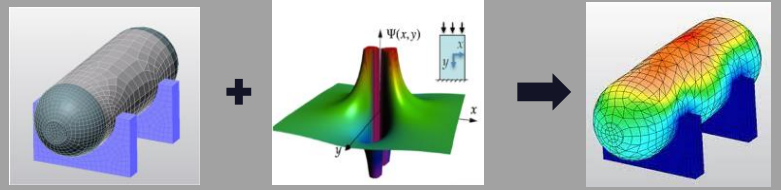
2 A numerical twin to (i) enhanced the confidence in the lifetime prediction and (ii) design solution to extent it

- Detailed modeling and prediction of future acoustic events
- Design of solutions using simulated scenarios



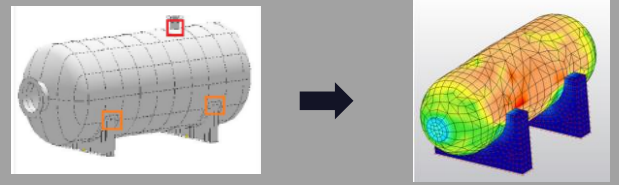
Numerical modeling of acoustic precursors

Physics-based modeling **– intermittent damage**



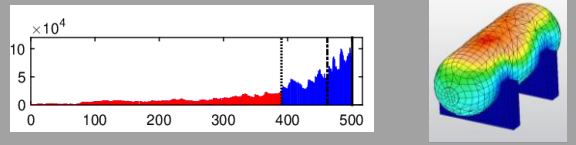
Structure specific calibration

Updated model from sensor data



Inputs for predictive maintenance

Prolonged service-life



A step towards frugal health monitoring

Doing more with the available data

- Structure specific predictions
- Quantitative risk evaluation (execute now or later ?)
- Inputs for improved interventions

- Developing **SaaS** that can be integrated in current SHM systems
- Also relevant for data from **optical fibers**, **damage levels** from full-field **ultrasound measurements, strain gauges** etc.

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