Going from diagnostic to pronostic using Mechanics-based Structural Health Monitoring

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

Aldermyrberget, Sweden, November 2020

Douglas oil complex, North Wales, 2022

Mirepoix-sur-Tarn, 2019

CDG Aeroport terminal 2E, 2016

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***.”
>
> ***- Cetim***

Challenge : Insights for decision making ?

Los Alamos Science and Technology Magazine, July 2013

Focus of current SHM techniques : Provide a diagnosis of the health of structures.

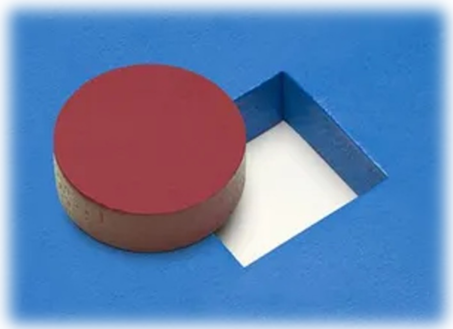
Alert on the presence of damage & cracks

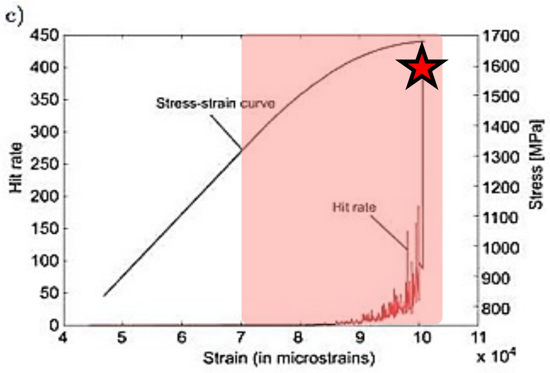
Problem: Will they threaten the mechanical integrity of the structure ? And in how long ?

No clue about the residual lifetime

What about prognosis instead of diagnosis ?

Will the crack grow and what is the actual remaining lifetime ? Can we change the operational parameters to increase it ?





Cracks do not grow continuously!
Precursory acoustic emission signals during tensile failure of M250 steel welds, Wuriti et al. 2020.

Our solution: Mechanics-based SHM approach that can predict the residual lifetime of structures from the precursory damage events.

An argument for physics-based modeling

Illustration of the concept on a cable

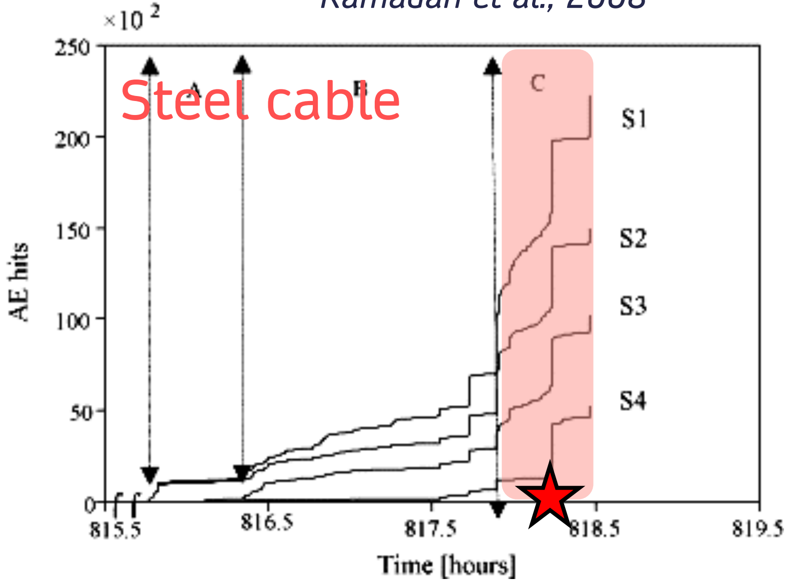
Damage monitoring:

Level of (individual) wires

Damage of cable ?

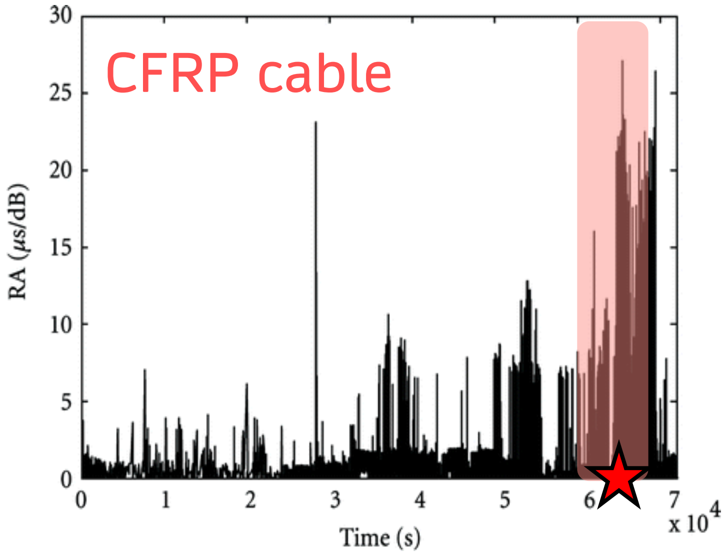
- Wire are imperfect: varied failure properties
- Multiple wires may undergo fail simultaneously.

Ramadan et al., 2008



Stress-corrosion cracking

Li et al., 2012



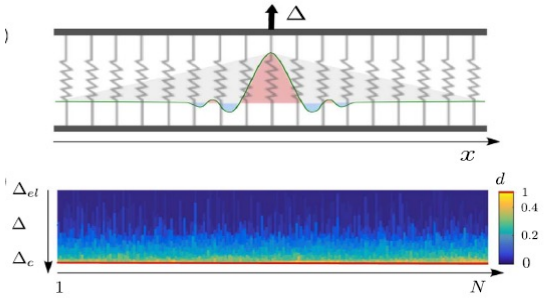
Fatigue failure in tension

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

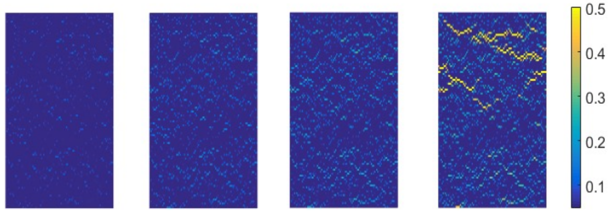
The **sequence** of damage events reveals the distance to failure that we miss if we only focus on the failure of individual components!

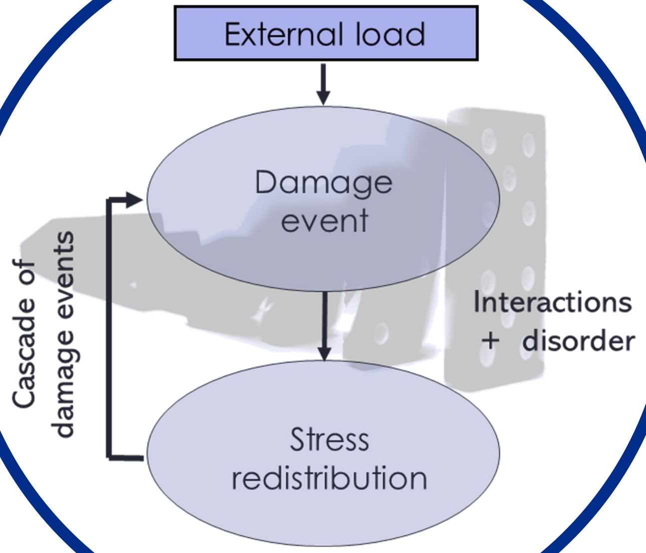
Decade(s) of developing the fracture mechanics of disordered materials

1D modeling: short range interactions

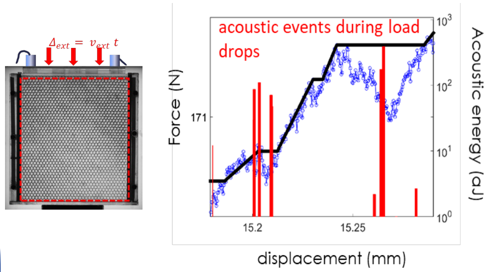


2D modeling: long-range interactions





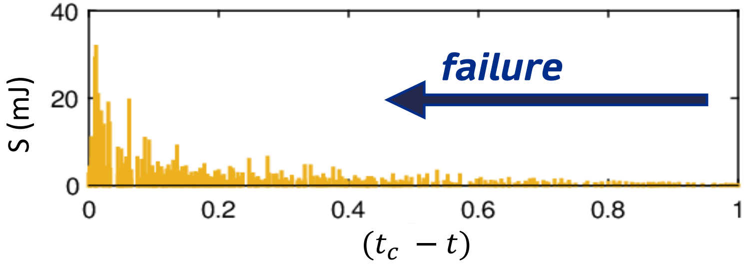
Experiments : model elasto-damageable solids



dissipation as

- mech. energy
- acoustic energy

Evolution of mech. precursors



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

Universality in how materials progressively damage and fail

Intermittent bursts of signals + Behavior close to failure

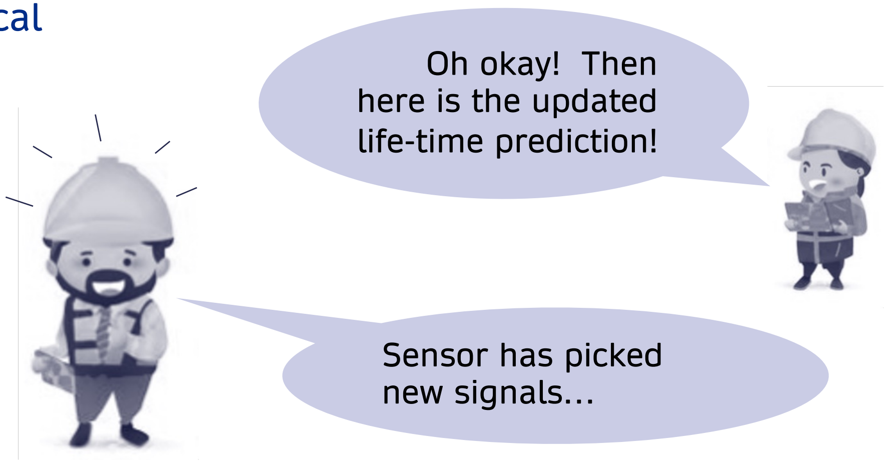
Lifetime estimation using mechanics based statistical tools*

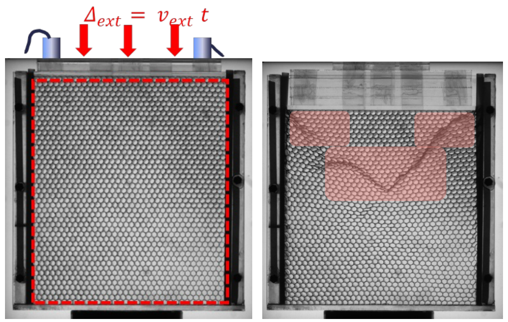
We use precursors occurring before $t_{current}$ (in red) to make a prediction of the failure time, $t_{predict}$.

- Multiple independent methods
- Use 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

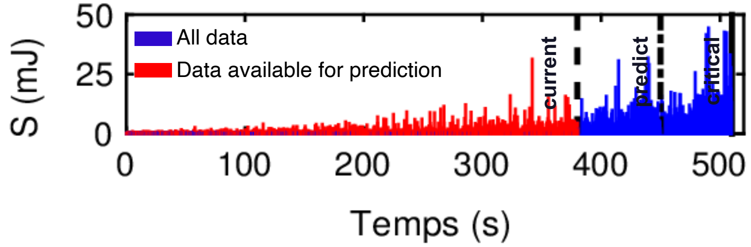
Statistical physics

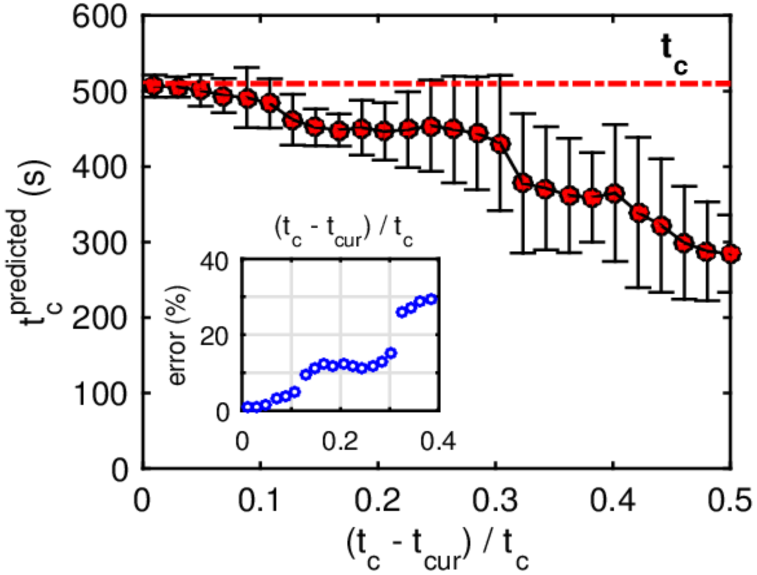
Fracture (damage) mechanics





Model system

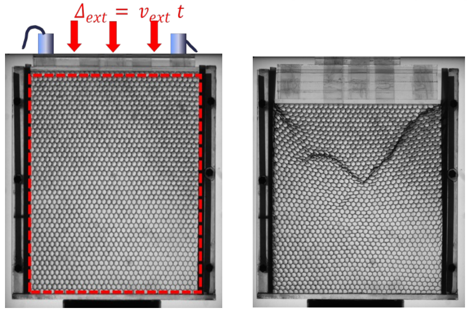




Average size of precursor

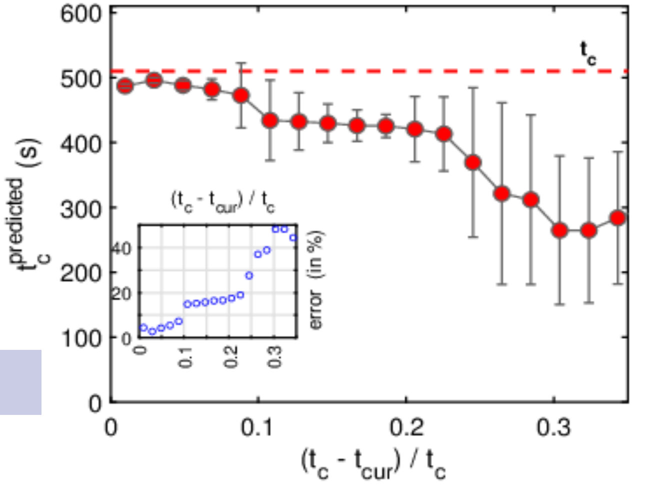
***French patent FR2002824 (Mars 2020),** *Procédé et dispositive d'analyse d'une structure*

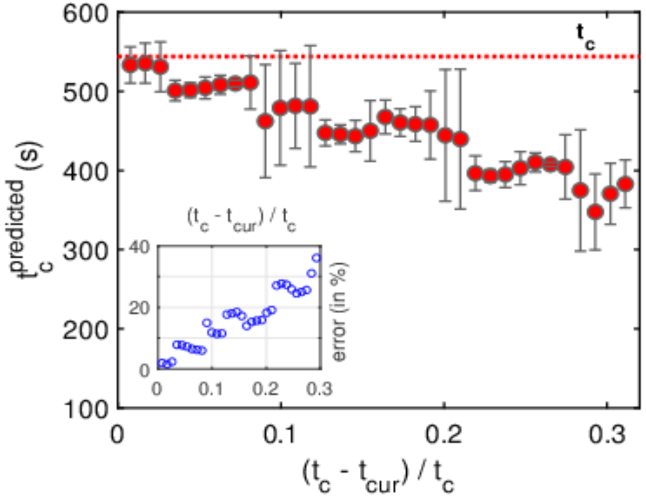
Proof of concept: Lab-scale testing

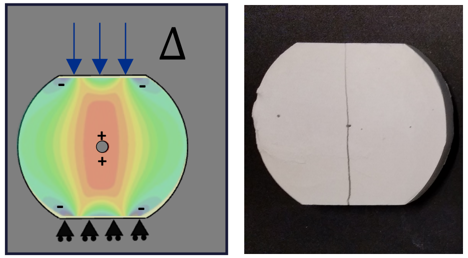


2D cellular solids

Precursor size

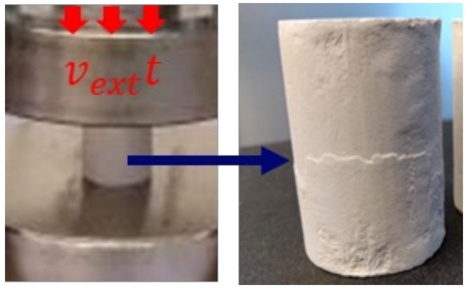






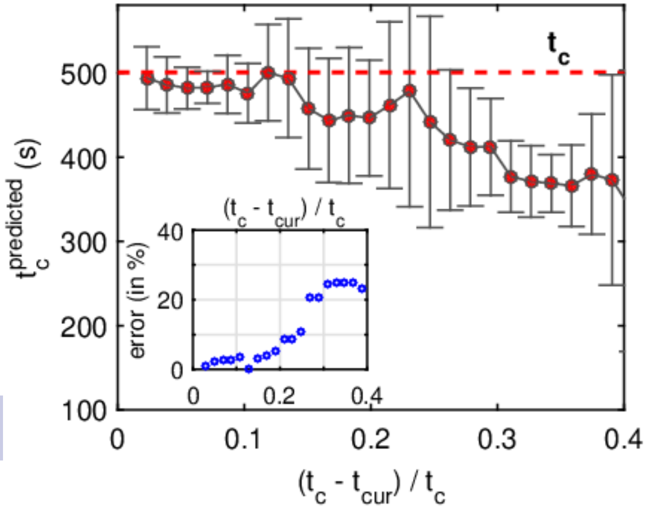
Crack initiation in a modified Brazilian disk test.

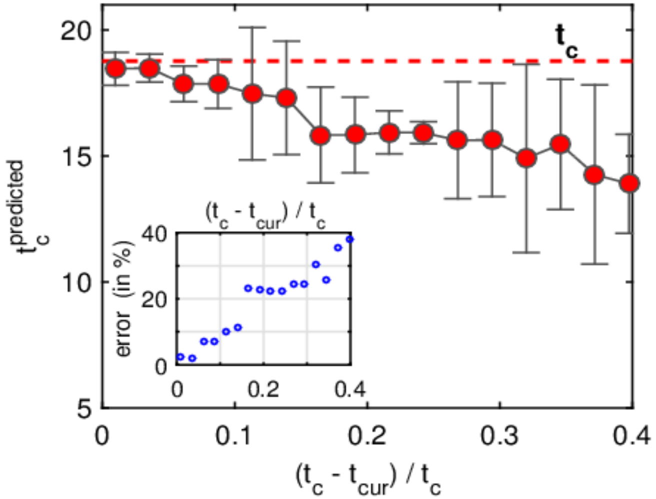
Acoustic energy rate

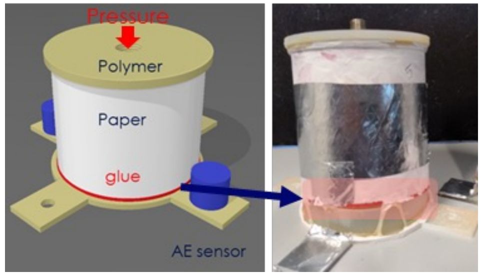


Compressive failure of plaster

Acoustic energy rate





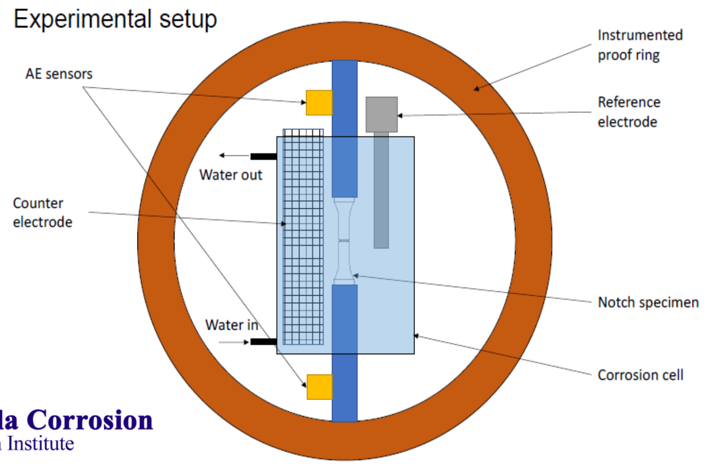


Leak of a paper-tube based pressure vessel

Frequency of precursors

Acoustic emission time-series reveal the upcoming failure irrespective of the material and the loading conditions

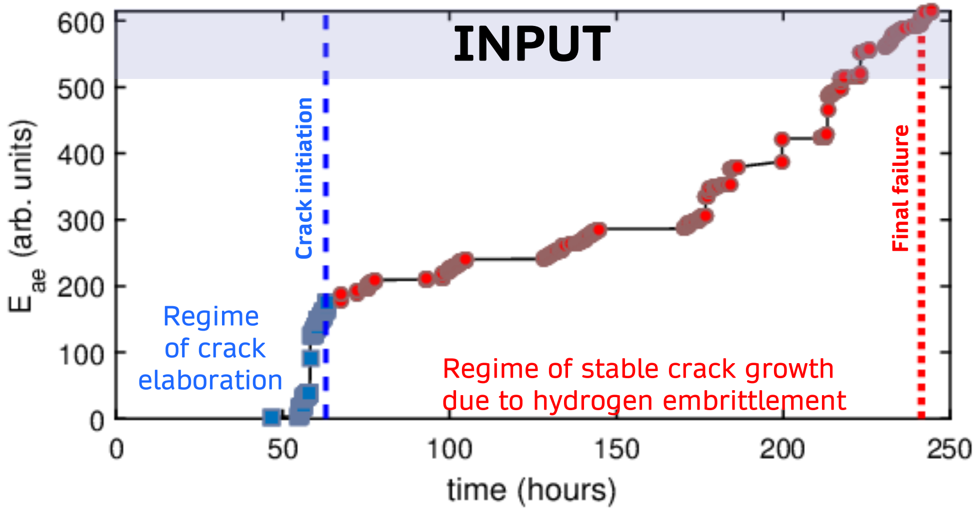
Proof of concept: Industrial component



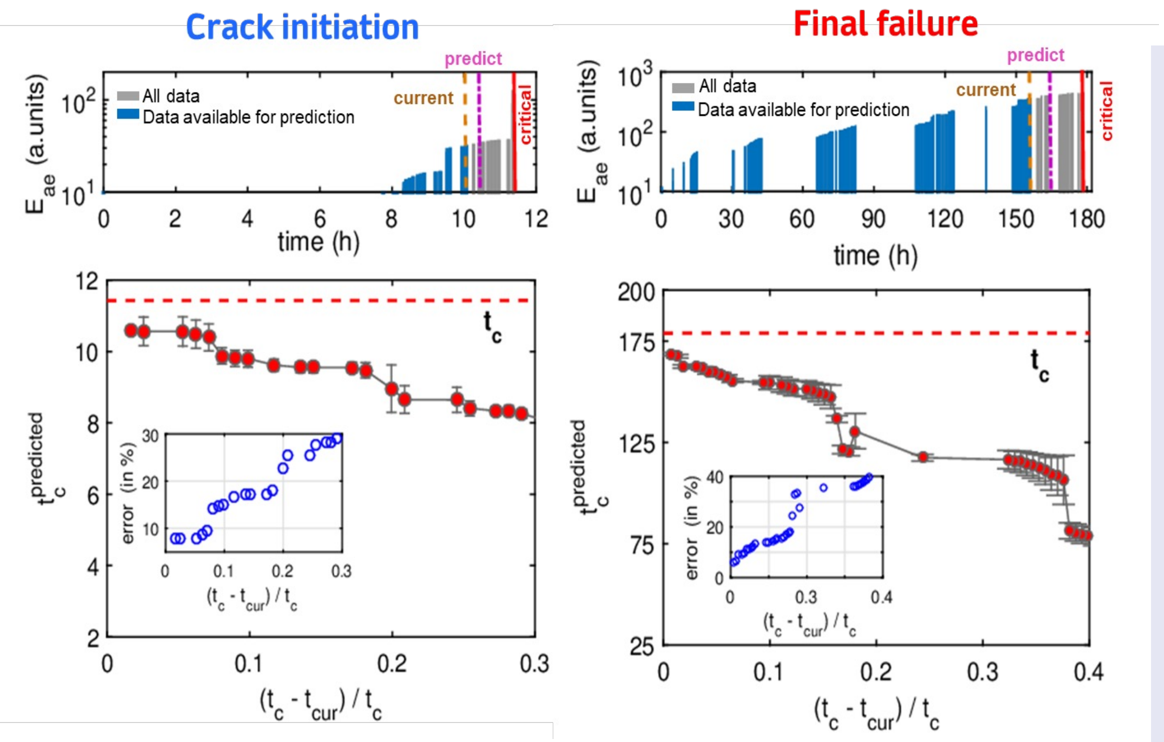
TOTAL

Institut de la Corrosion
French Corrosion Institute

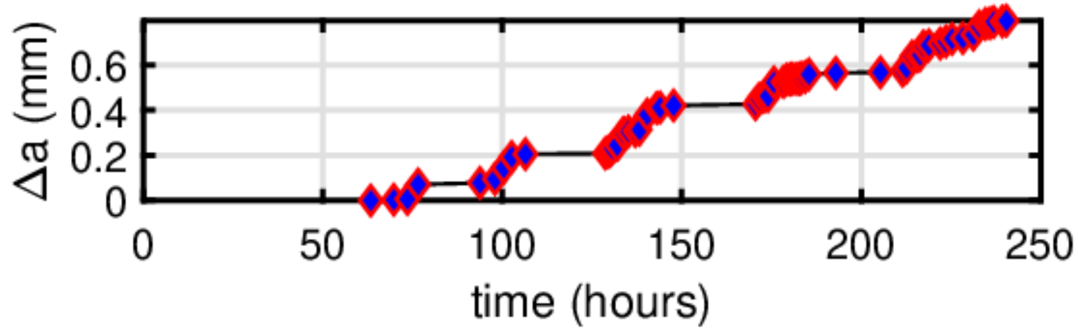
Tensile failure of a subsea fastener due to stress corrosion



Cumulated Acoustic Emission (AE) energy



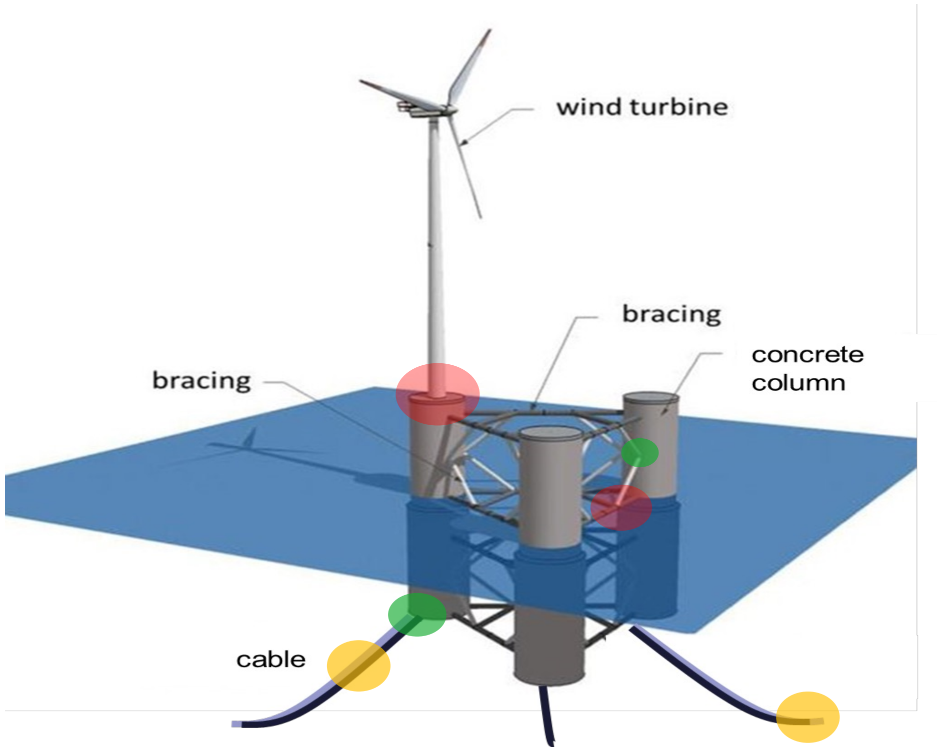
Crack length evolution inferred from AE signal



OUTPUT

Deployment in large-scale structures ?

Potential use-case: Off-shore Wind Turbines

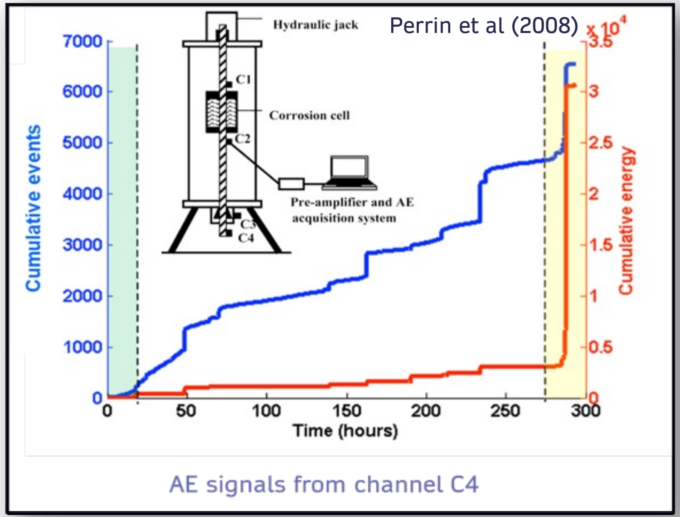


- Initiation and growth of cracks in supporting cable.
- Stress-corrosion / fatigue cracks in crucial weldments.
- Cracks within the anchorage and in concrete columns.

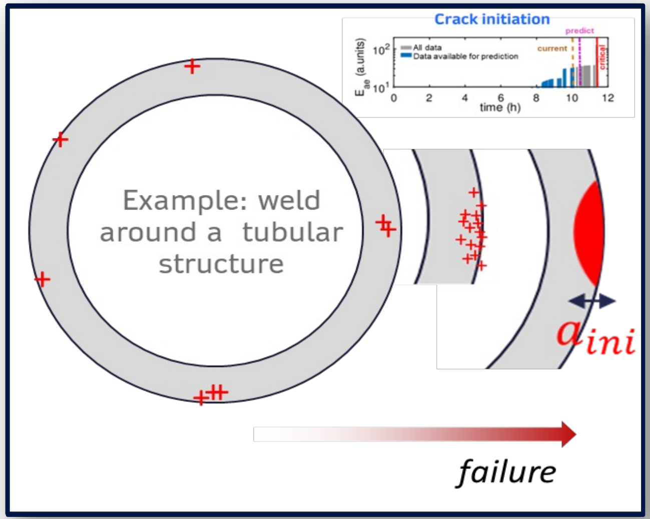
Employing our methods, AI post-treated data can then be used for prognostics.

- ✓ Mechanics enabled statistical tools for SHM data analysis.
- ✓ Numerical modeling fed by SHM data.

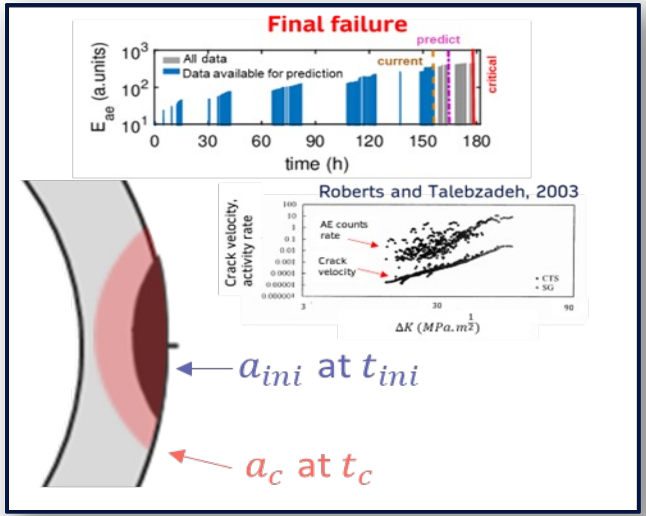
#1. Mechanics based statistical tools [1]



Failure of cables : crack initiation and growth



Failure of structural elements: crack initiation



Monitoring (fatigue) cracks in real-time

On-coming possible failures anticipated in real-time [1]
Drop a sensor & estimate the remaining lifetime.

[1] French patent FR2002824 (2020), Procédé et dispositive d'analyse d'une structure

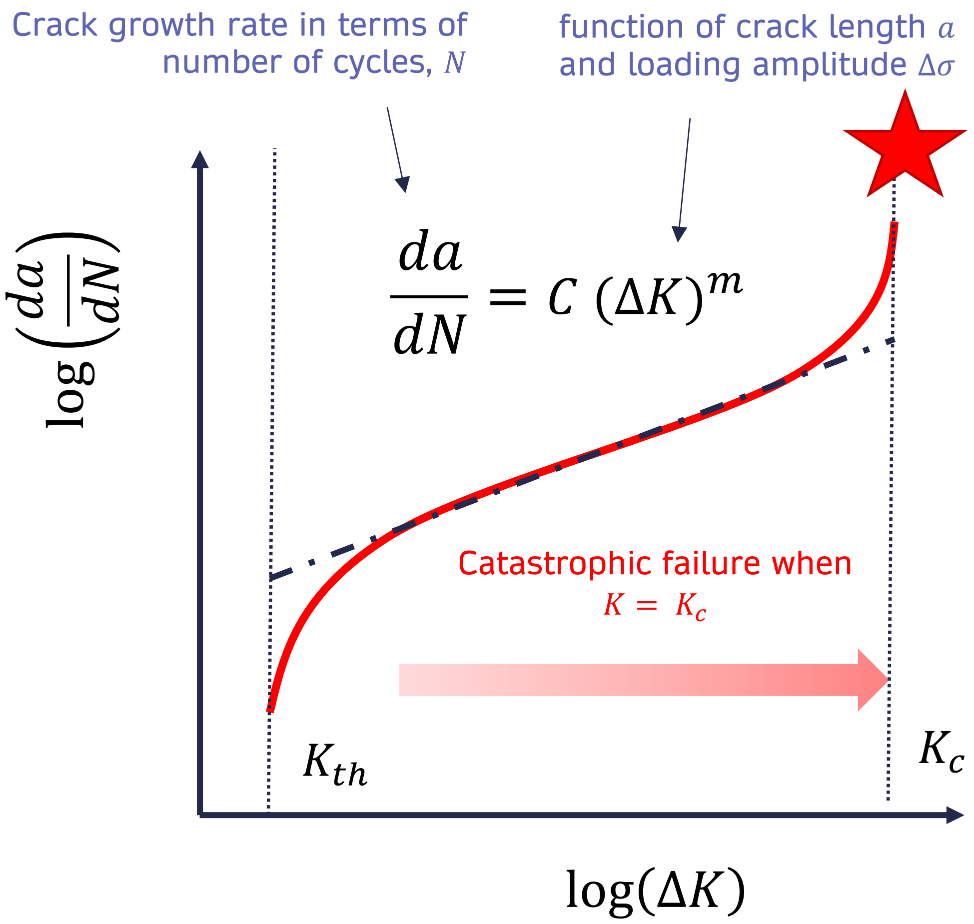
#2. Numerical twin from SHM – enhanced prediction for prolonging lifetime

Fracture mechanics can predict fatigue crack growth.

However, predictive mechanics models require :

- In-service mechanical properties
- In-service loading conditions

Crack speed is not a constant !



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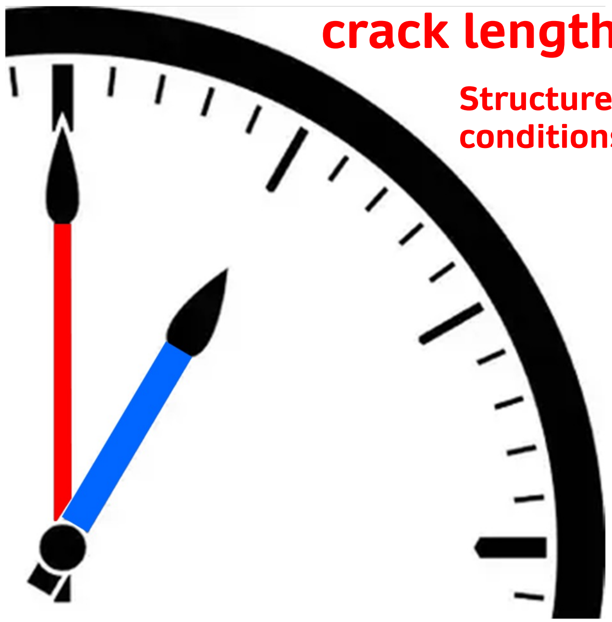


Real-time monitoring of crack length[1] and loading conditions : $\Delta K \rightarrow (\mathrm{a}, \Delta\sigma)$

Structure-specific prediction of in-service loading conditions that can be used in designing reinforcements .

Structure-specific material constants: C, m [2]

Calibration in lab aids in determining real-time fracture properties

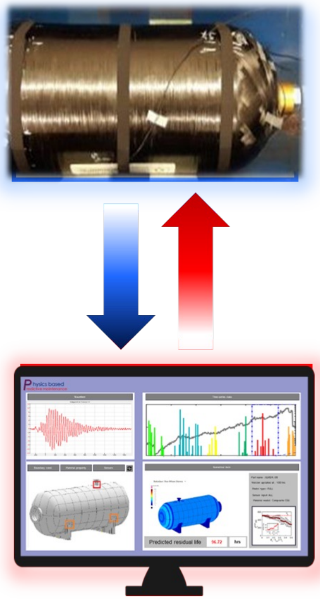
An agile strategy of continuous learning

Physics-based modeling
- intermittent damage

Update with more signals

Validate decision-making
first on the numerical twin

sensor data



Numerical twin

Predictions can be updated with more signals and measures of prolonging life can be validated.

[1] Crack length is measured once and then tracked using sensor signals following our method.
[2] An iterative method can be developed from signals-based crack length measurements.

A role for AI: Enabler of mechanics-based tools

Key ingredients for predictive SHM solutions

Data from sensors

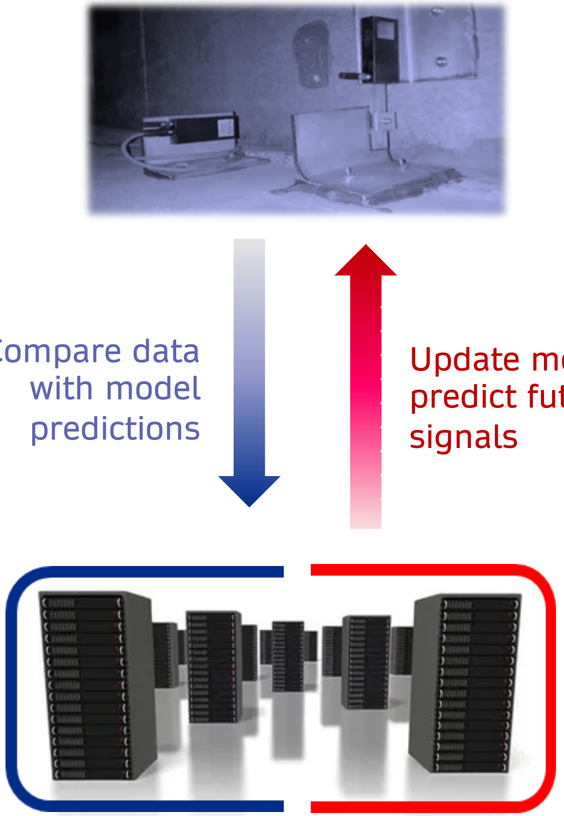
Collected in-service, noisy

Mechanics enabled predictions

In-service mechanical loadings & materials properties inferred from the sensor data are used in numerical modeling.

Artificial intelligence that improves the signal to noise ratio

Optimal and transparent use of AI techniques on raw data to avoid a post-treatment bias in our analyses



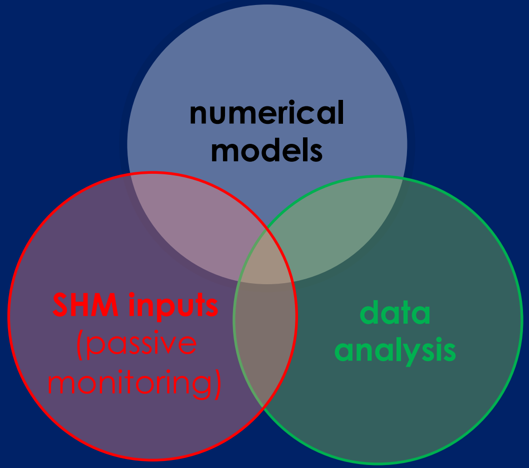
Beyond enhanced predictions of residual lifetime, this SHM approach based on **the mechanics modeling of the component failure (or numerical twins) paves the way for**

- The design of optimized repairing strategies and maintenance plan
- The optimal use of the component by tuning the operation parameters in response to sensor data

} **Prolong remaining lifetime**

Towards frugal health monitoring

Mechanics-enabled SHM



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Doing more with the available data

- Structure specific predictions
- Quantitative risk evaluation (execute now or later ?)
- Inputs for improved interventions
- Beyond prediction, towards prolonging lifetime

As our methods are based on the intermittent nature of failure in structural materials, they are also relevant for data from **optical fibers**, **damage levels** from full-field **ultrasound measurements, strain gauges** etc.