An unsupervised data fusion method to estimate damage onsets and sequence in composite structures using the acoustic emission technique

FEMTO-ST, DMA et AS2M departments
Activité transverse « *Structural Health Monitoring* »

Emmanuel Ramasso, Vincent Placet, Lamine Boubakar
with contribution of Mohamed Kharrat and Xavier Gabrion

SHM: Structural Health Monitoring

Context

Lightweight and high-strength adaptive structures for the transport of the future: Energy saving with enhanced performances. Corner stones of this challenge:

- Composite materials
- Systems of sub-systems

Cryotank in composites (Boeing/NASA 2013)

Airbus A350 (53% of composites)

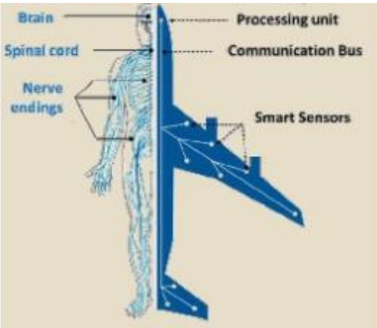
Technological and scientific obstacles related to the design, manufacturing and understanding

- Vibroacoustic control
- Evaluation of the residual properties

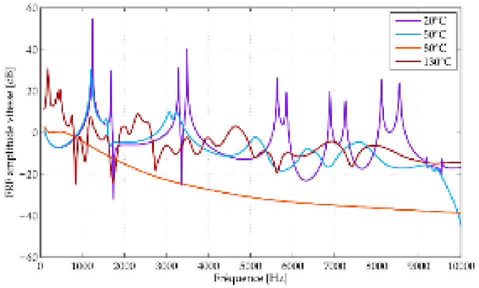
Airbus A380 : « cracking saga » observed on wing tips

Path followed in Labex ACTION to move forward *Smart structures* with

- Damping of selected modes for vibration isolation
- Real time health monitoring during in-service operating conditions (SHM/PHM)



D. Alkeflawi, 2015



Vibration control using temperature [Putaud et al. 2015]

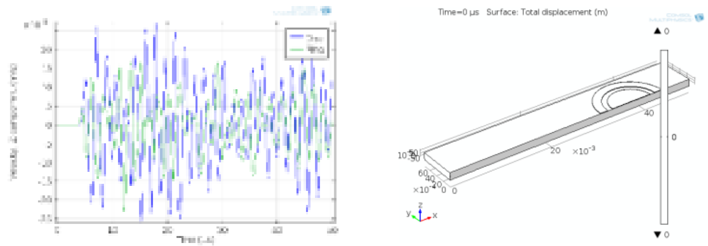
SHM approach

Transdisciplinary approach using first principles physics-based and data-driven models

Damage-related data

Project Smart Composites (Labex, BPIFrance, Région Franche-Comté), 2014-2016

Pattern recognition approaches



Physics-based approaches
(multiscale multiphysics)

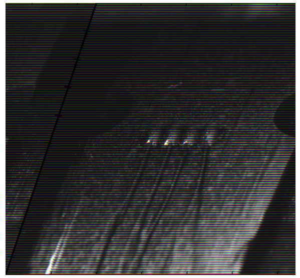
Incipient fault?

DETECT… | LOCALIZE… | IDENTIFY… | EVALUATE… | PREDICT…

…damages and residual properties of structures

Data-driven approach based on acoustic emission (AE)

- Comté control using NDT: « acousto-ultrasonics », active method



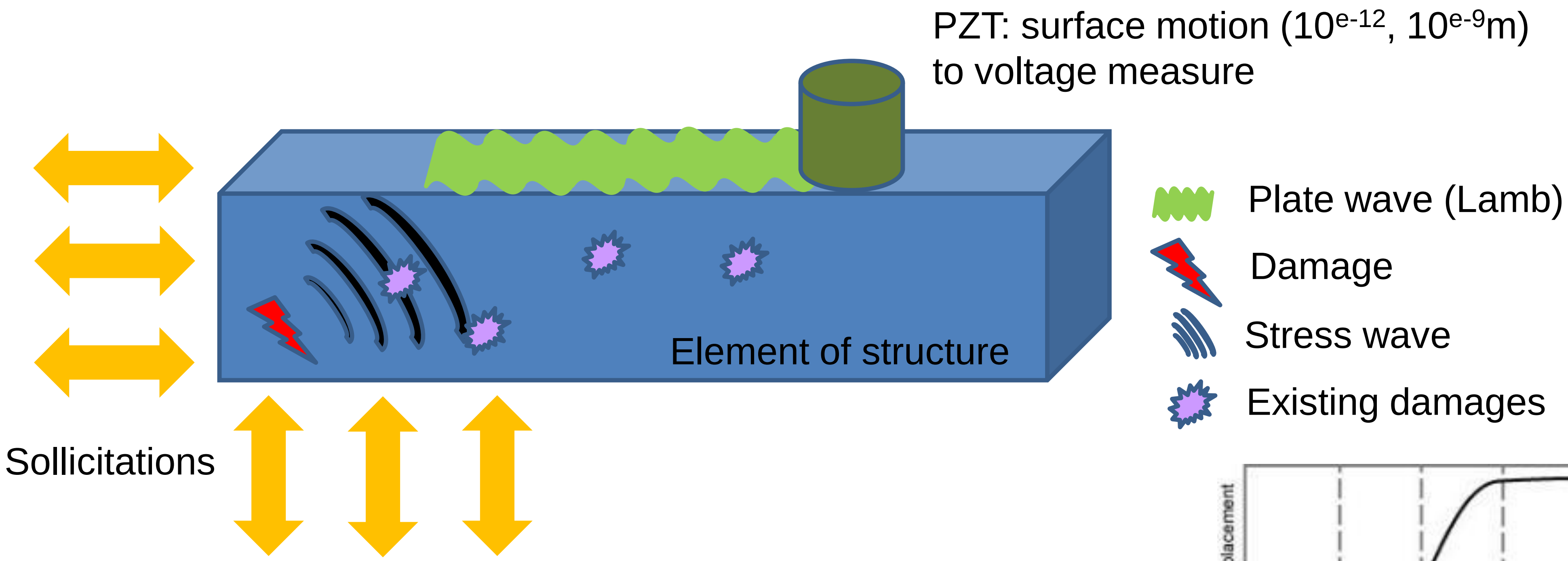
- AE is a passive method that relies on active defects: the AE source is related to an irreversible strain within the material
  - Microscale: matrix µcrack, fibre breakage…
  - Macroscale: crack jumps, debonding, delamination, scission…

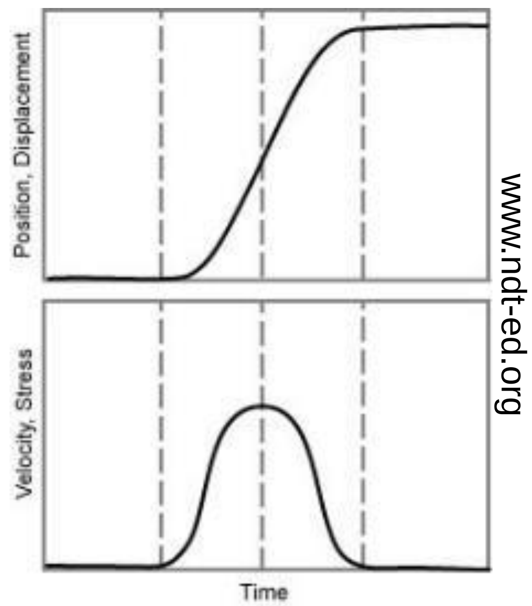
- ASTM E1316-2010 definition:

  Class of phenomena whereby ***transient elastic waves*** *are generated by the* ***rapid release*** *of energy from localized* ***sources*** *within a material, or the transient waves so generated. Acoustic emission is the recommended term for general use. Other terms used in AE literature include: (1)* ***stress wave emission****; (2) microseismic activity; and (3) emission or acoustic emission with other qualifying modifiers*

- In 1950s: PhD of Joseph Kaiser (Germany) "*Results and Conclusions from Measurements of Sound in Metallic Materials under Tensile Stress*"
  - Followed by Bradford Schofield (USA): Beginning of AE as known nowadays
  - 1969: Dunegan, creation de Dunegan Corp., became a society of Mistras Group
  - In 1986, Hamdstad counted around 500 publications of AE

AE source and stress wave





- Sudden displacement: Step-like (permanent)
- Stress: pulse-like, with characteristics dependent on the dynamic of the source
  - In a few µs: crack jumps
  - Amplitude and energy vary enormously
- Stress waves recorded are mostly elastic waves, radiating in multiple directions (w.r.t. material)

AE technique for SHM: Pros and Cons

Among Non Destructive Techniques, Acoustic Emission is a powerful method

Advantages:
- **Detection** and **localisation** of growing defects
- **Passive** method (low power required)
- Sensitive to "small" events
- **Real time**
- Scan **large areas/entire** structures
- **In-service**
- Allow the control of inaccessible components

Weak points:
- Sensitive to electromagnetic and mechanical interference
- Does not provide information on the size and shape of defects
- The detection capacity depends on damping capacity of materials

Acoustic Emission for Health Monitoring of Composite Structures: a tried and proven technology?

- Vast amount of research literature
- Numerous uses and applications
- Commercial systems are available (including sensors, electronics and softwares…)

- But we have identified **many hiding scientific and technological challenges and bottlenecks**

In particular for **mobile structures** (vehicles, wind turbines…) and **in-service applications**
AE is generally use for monitoring "static" structures such as storage tanks, pipelines and civil engineering structures…

Acoustic emission (AE)
Applications

www.nde-ed.org *www.ndt.net*

Weld Monitoring

Bridge

Aerospace Structures

Bucket Truck

Gas trailer tubes

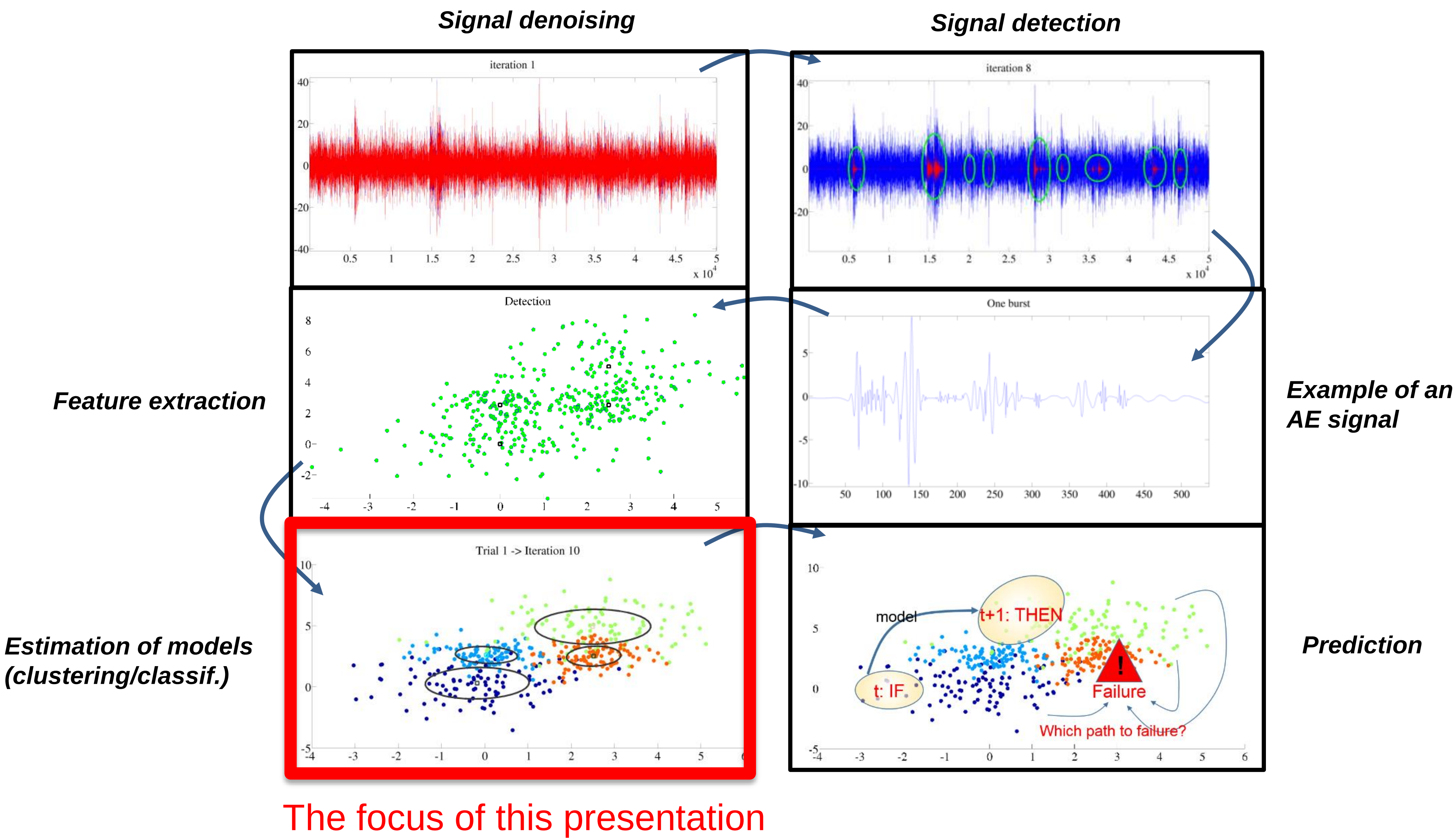
Gears (wind turbines)

- Real-time leakage test and location (valves, steam lines, tank bottoms)
- Detection and location of high-voltage partial discharges in transformers

- Fiber-reinforced polymer-matrix composites (glass, carbon), more recently biocomposites

→ AE can help to investigate material properties, breakdown mechanisms, damages

AE data processing

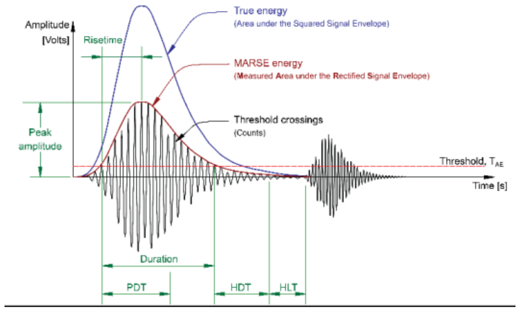


Pattern recognition

Paradigms dependent on prior knowledge

- Extract features: represent an image of the AE source parameters
- PR aims at bridging the gap between AE signals and sources by finding « rules » that provide the damage family given AE signal features

Feature extraction



Supervised classification

Unsupervised classification

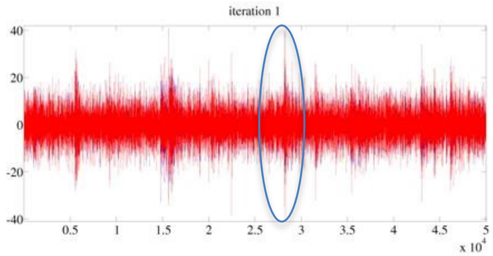
Semi-supervised classification

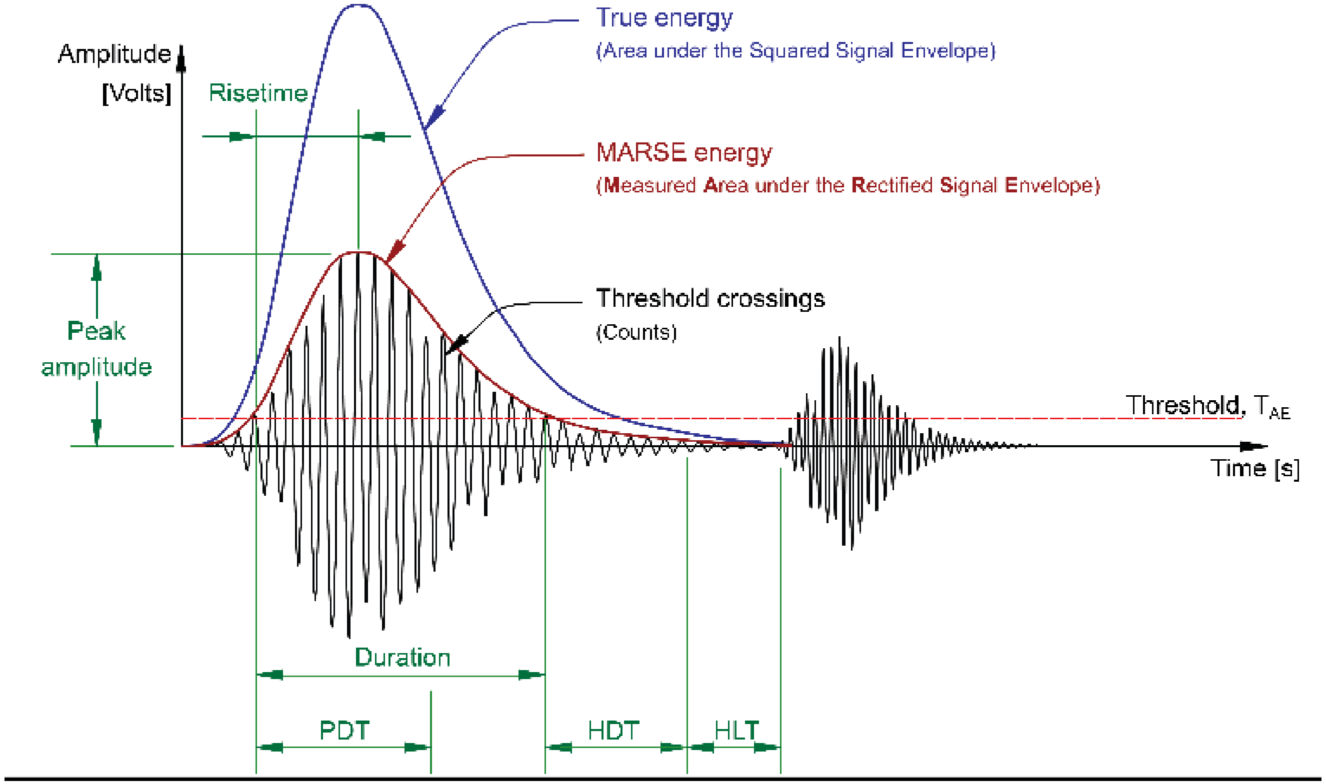
Partially supervised classification

Damage type **3**

AE hit / signal
Standard approach

❖ Several parameters to set, multiple features extracted



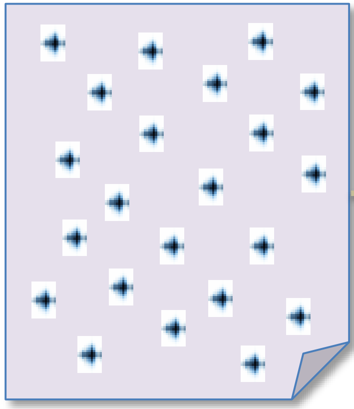


Which subset of features should be used for clustering AE signals? Which parameters?

Should be driven by **robustness** and **fidelity to data**

Unsupervised method: Clustering

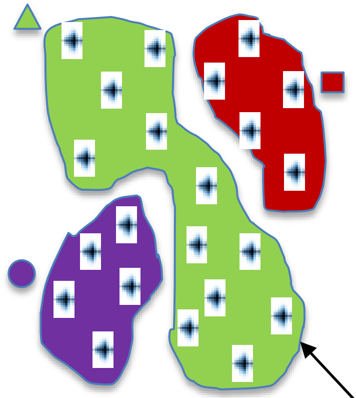
Standard and proposed approach



Features (~30)

CLUSTERING
(Algorithm with parameters)

That is a <u>partition</u>



Treated as static patterns

That is a <u>cluster</u> (pattern)

Multiple parameterizations

Algorithm A
Parameterizations: $\theta^1, \theta^2 \dots \theta^n$

Algorithm B
Parameterizations: $\kappa^1, \kappa^2 \dots \kappa^r$

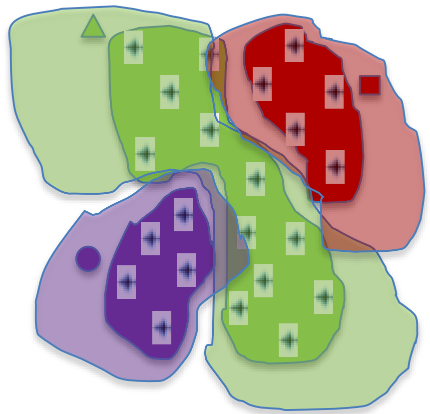
⋮

Algorithm Z
Parameterizations: $\beta^1, \beta^2 \dots \beta^p$

Automatic selection of some parameterizations

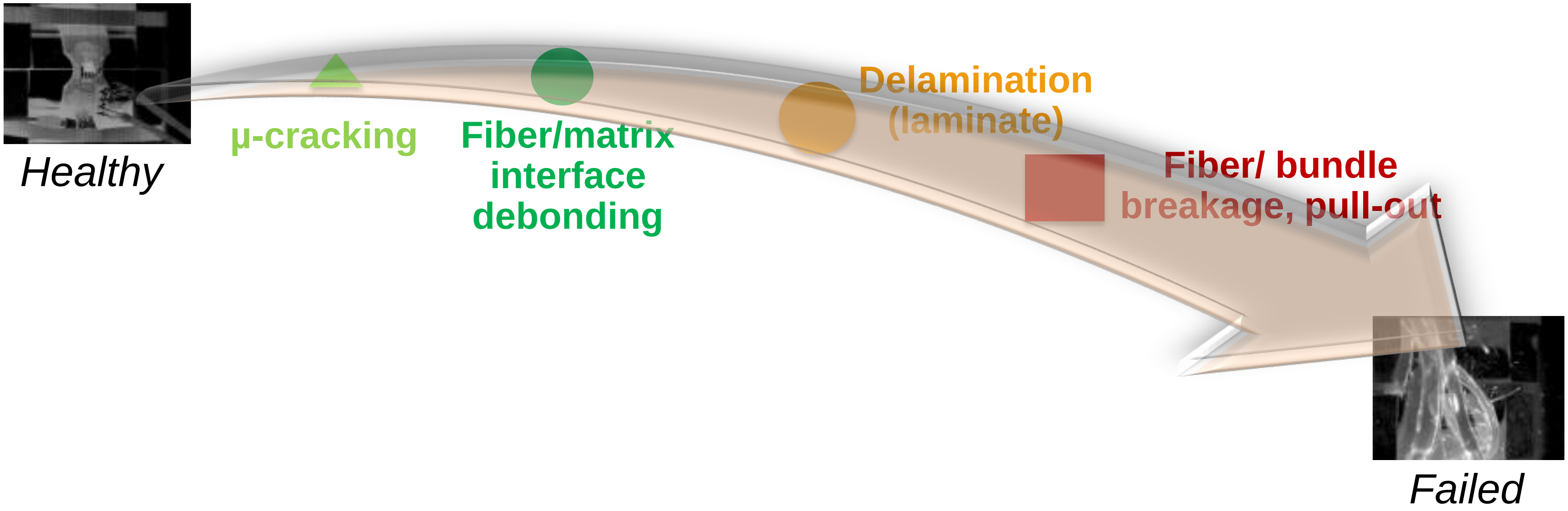
Criterion based on a dynamic patterns

Fusion



Uncertainty envelop

A consensus and sequence-based approach



The proposed approach pays attention to

- The estimation of the story of the damaging process:
  - Sequence of damages (cascades of events) more important than finding static patterns
  - It is a time-dependent stochastic process: Uncertainty on results should be quantified
- The robustness of the method against parameterizations (of algorithms)
  - A change in the features (e.g. erroneous computation)
  - A change in the parameters
  - A change in the initialization of clustering methods

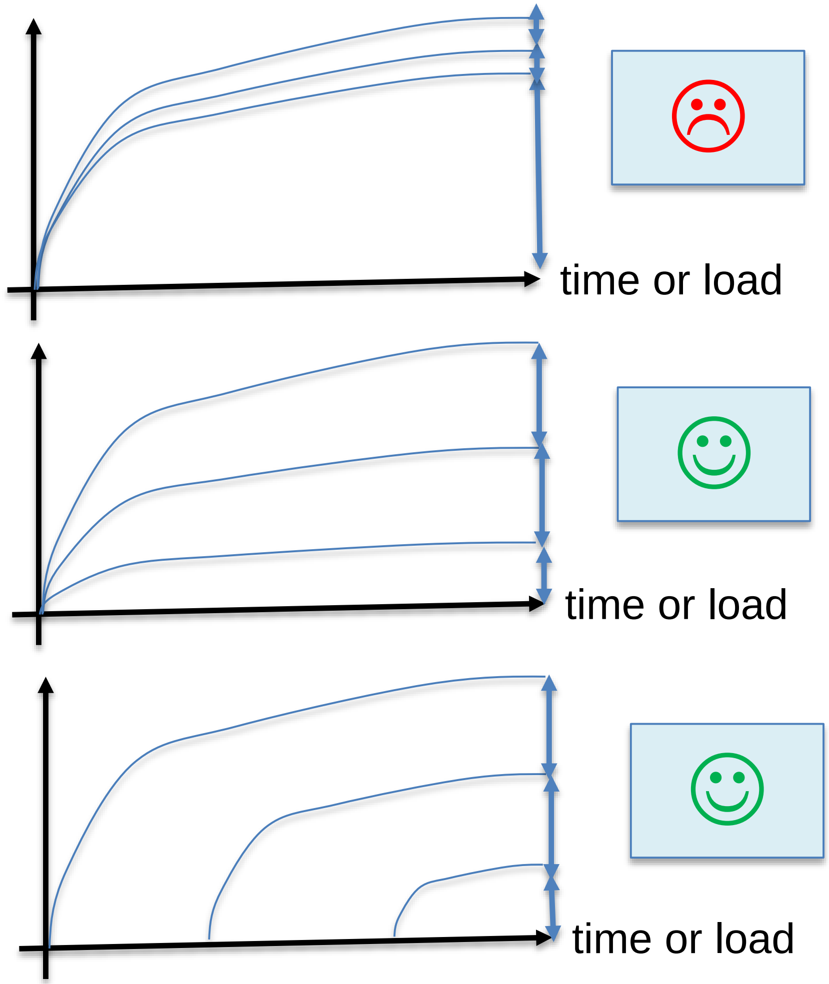
should not impact too much the results

A consensus and sequence-based approach

Sequence-based – Criterion 1: How to sort the parameterizations/features subsets?

- Should we assign a probability to each damage, then, among all possible distributions, the less arbitrary one maximizes the Shannon entropy
- Hypotheses:
  - Damages are supposed to have different kinetics and frequency of appearance.
  - The probability of damages is assumed to be related to their relative frequency

Practically means that damages occur at different rate, and that some damages are related one to each other



⇒ The Shannon entropy computed on relative frequency is used to sort parameterizations. The 90th percentile allows to get a subset of relevant ones.

A consensus and sequence-based approach

Sequence-based – Criterion 2: How to select *robust* parameterizations?

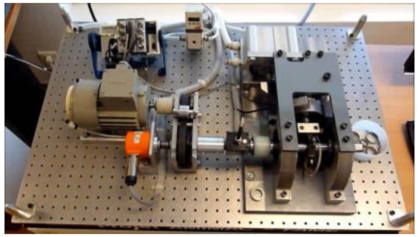
- Given a fixed number of damages and a subset of parameterizations, should we remove one parameterization, then the final result should not change too much.
- Algorithm:
  1. Vary the number of clusters
  2. Apply a boostrap strategy to create ensembles
  3. Compute the normalized mutual information (NMI)

  Then select the number of clusters with minimum variance on NMI (proposed by Fred and Jain, 2005), or better (in practice for AE) on maximum NMI

$\Rightarrow$ The Shannon entropy and the mutual information are information-theoretic measures which depend only on clusters proportions (not on features nor additional distances as in standard methods)

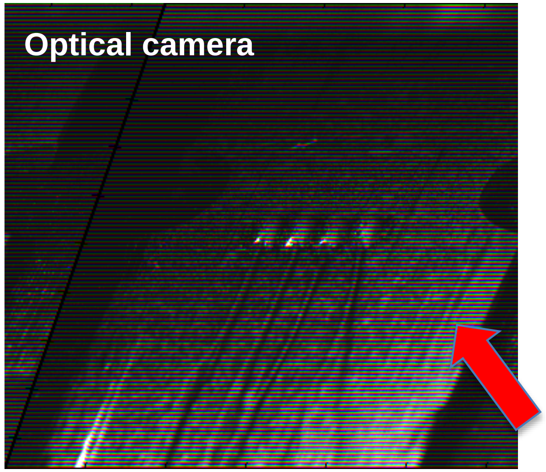
Results

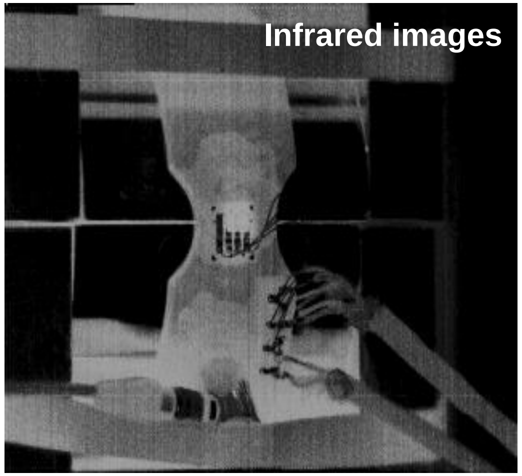
- The method has been applied on acoustic emissions originating from composite materials with
  - ✓ different resins (thermoset and thermoplastic thermostable)
  - ✓ made of various fibers (carbon, glass, flax).
  - ✓ Under various loading conditions (quasi-static tests & high cycle fatigue)
- Some tests have been made on vibration data from accelerometers mounted on rolling bearings for PHM
- Following results concern health monitoring of a high performance thermoplastic thermostable **ring-shaped** composite used in the transportation domain in high-speed rotating equipments in harsh environment (PhD, X. Gabrion, FEMTO-ST)



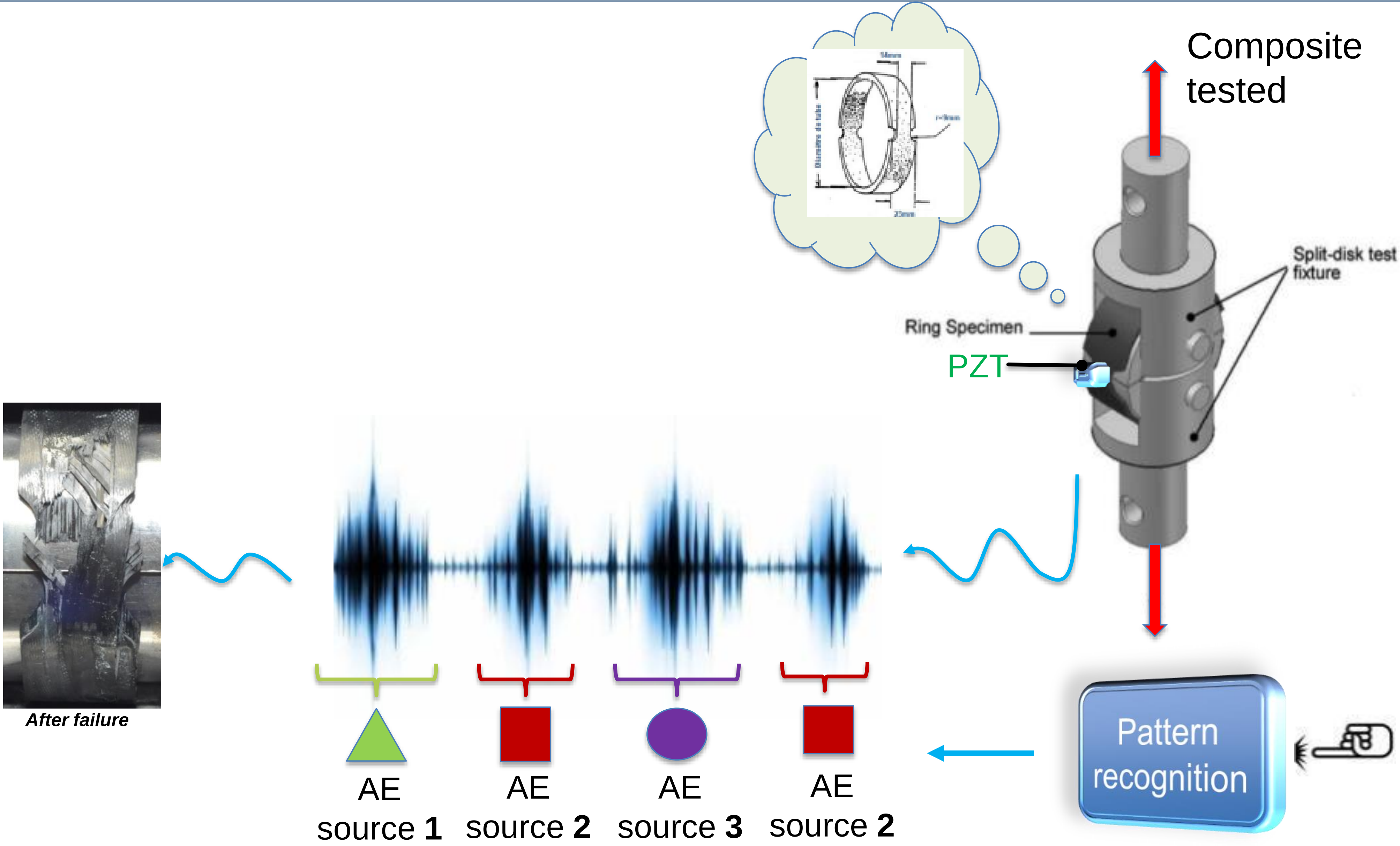
PRONOSTIA platform

Preliminary study: Observation of macro-cracks (hoop splitting) and fibre breakages

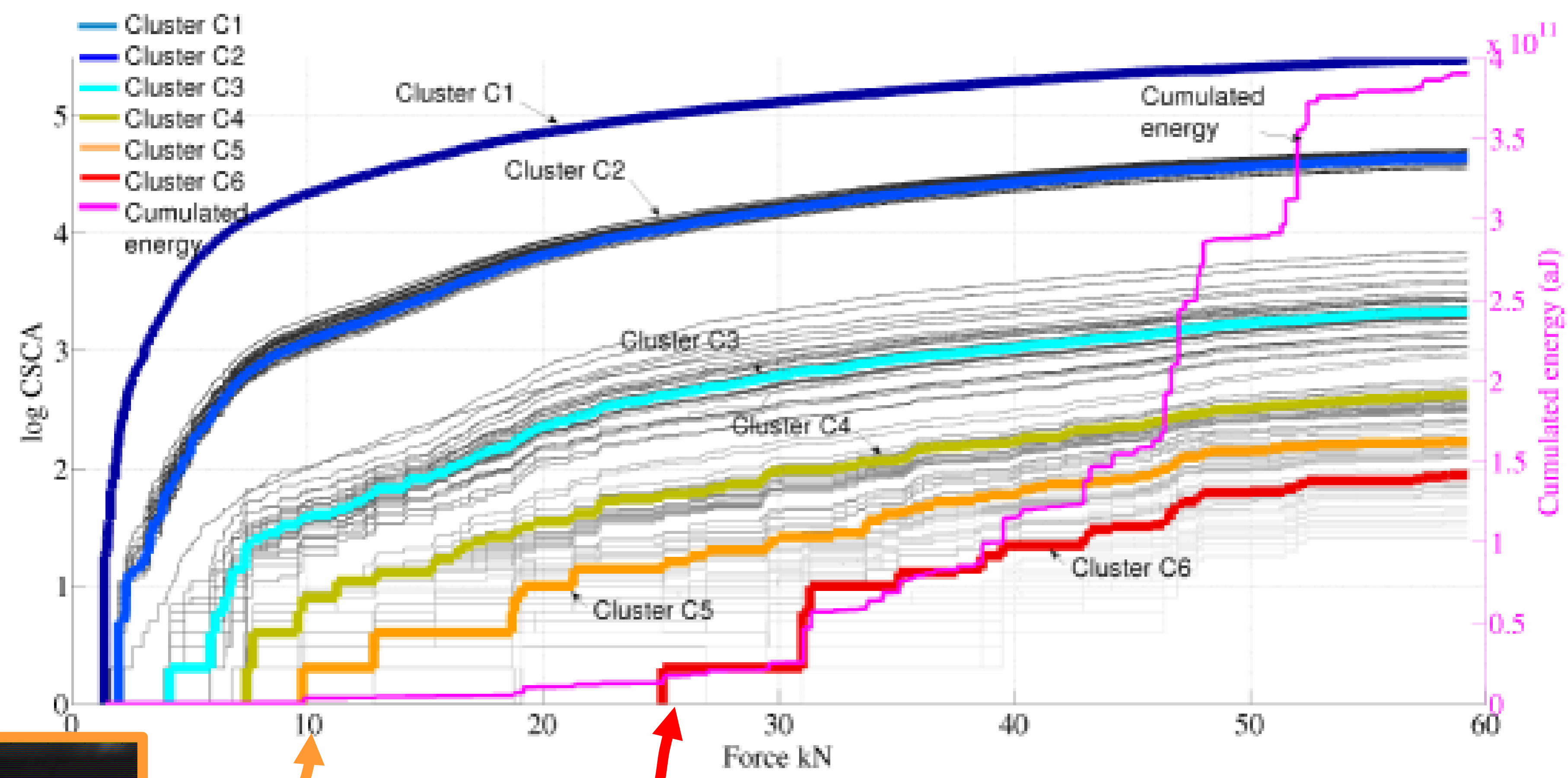


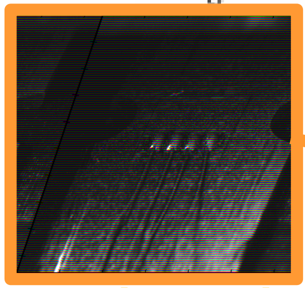


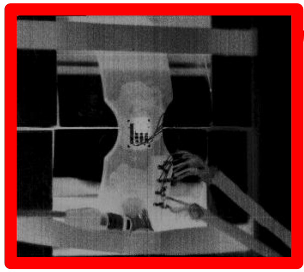
Method


Composite
tested
Split-disk test
fixture
Ring Specimen
PZT
After failure
AE
source 1
AE
source 2
AE
source 3
AE
source 2
Pattern
recognition

- Cumulated damages during quasi-static test, with uncertainty







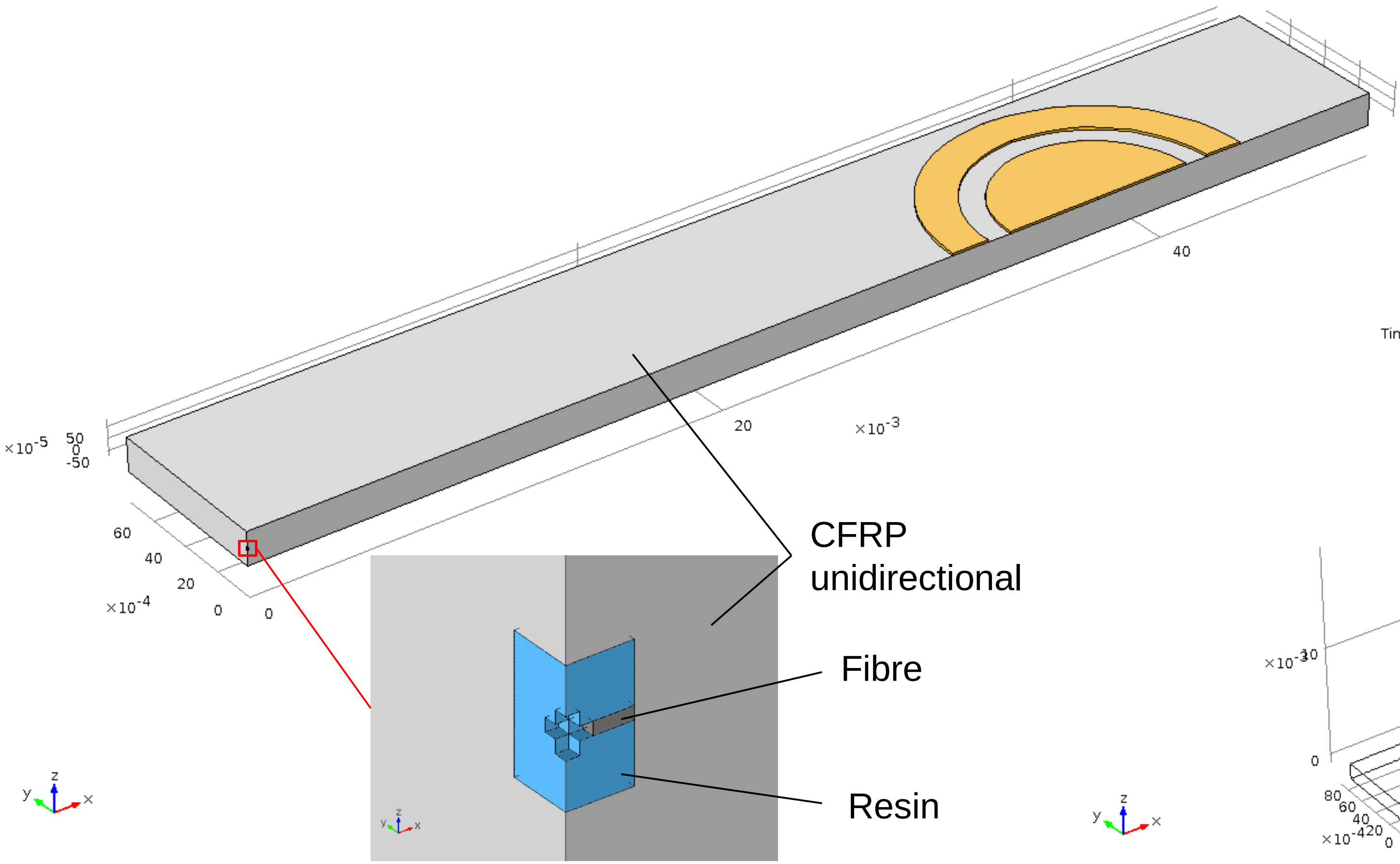
Fibre breakage monitoring

Crack monitoring

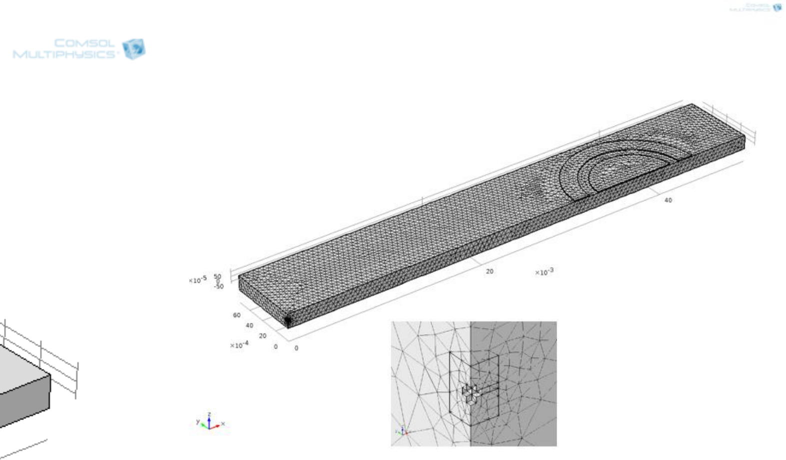
Perspectives

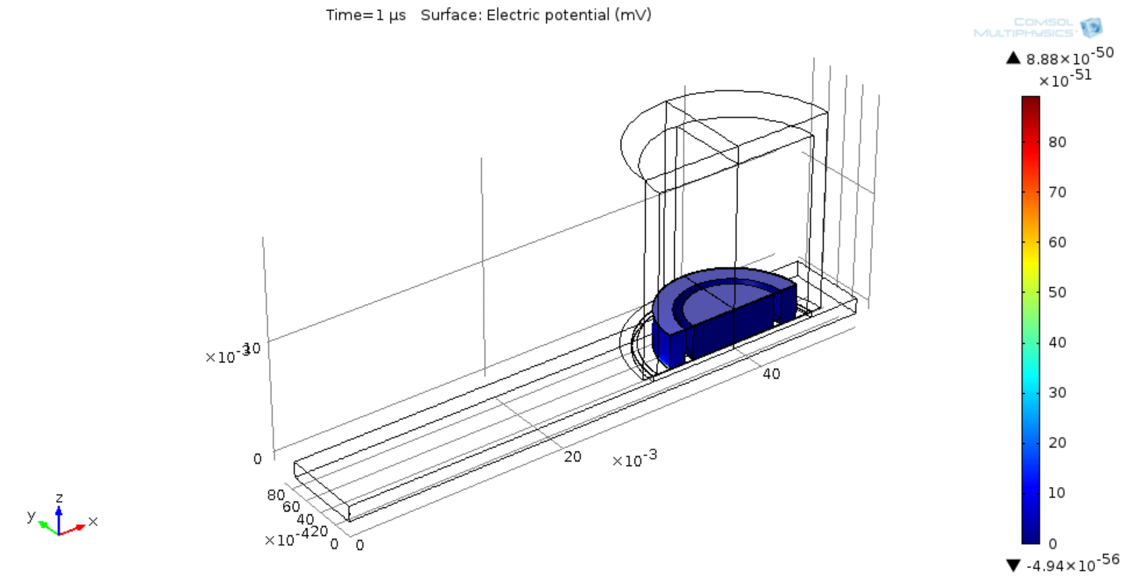
- Relation with multiscale-multiphysics models:

Can we explain the signals observed in practice?

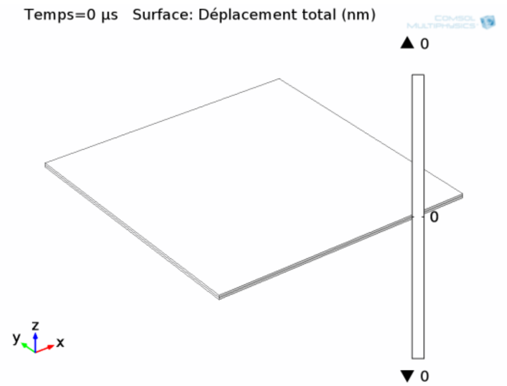


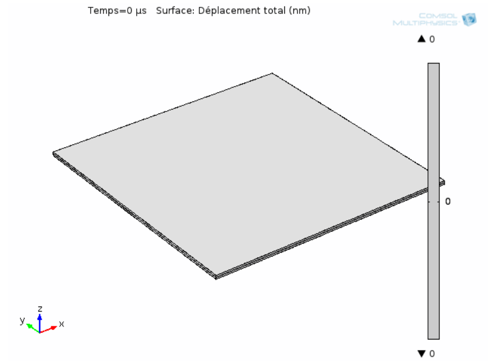
EA source model

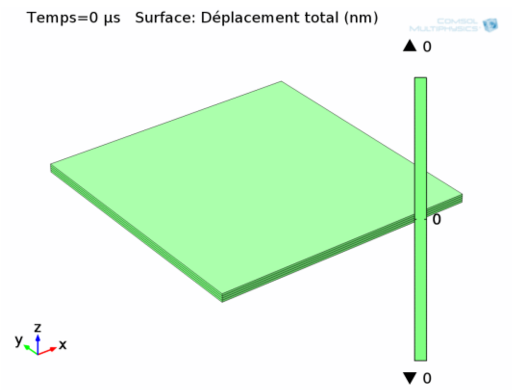


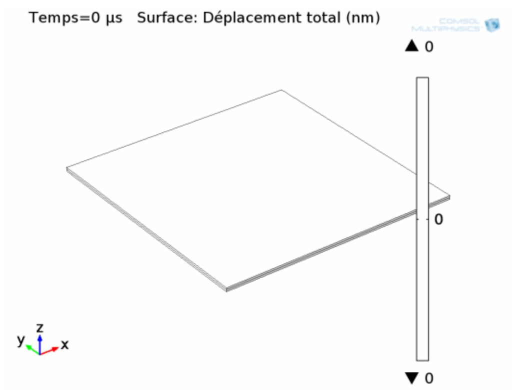


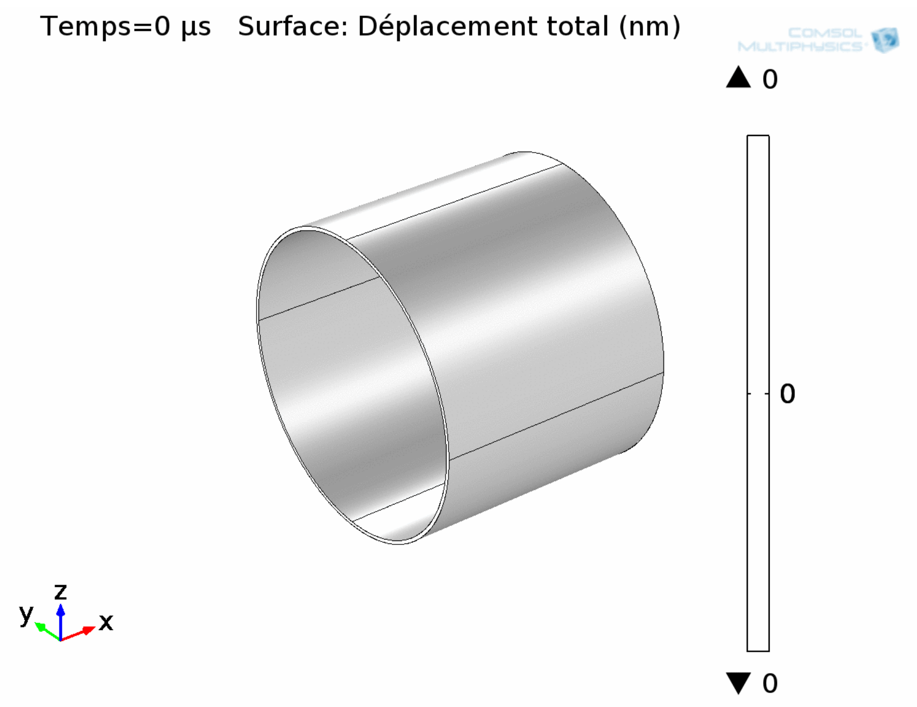
- AE propagation in anisotropic, heterogeneous, damaged (discontinuity), viscoelastic materials, with different geometry and plies configuration











Demo under development

Model of an A320 (credits to W. Morbin)

Duplication with aeronautics materials, upgraded to A350 with funds from

Labex Action
Integrated smart systems

Current team : L. Galvez, S. Thibaud, E. Sadoulet, G. Chevallier
Y. Meyer, S. Drujont

Goal : Integration of SHM/PHM algorithms for in-service vibroacoustic control for research and education purposes

Thanks for attending