USES2 Online Workshop#2
18-22.11.2024

Sicherheit in Technik und Chemie

Bundesanstalt für Materialforschung und -prüfung

18.11.2024

BASICS IN ACOUSTIC EMISSION

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www.bam.de

Bundesanstalt für Materialforschung und -prüfung

Organisation

11 departments divided into

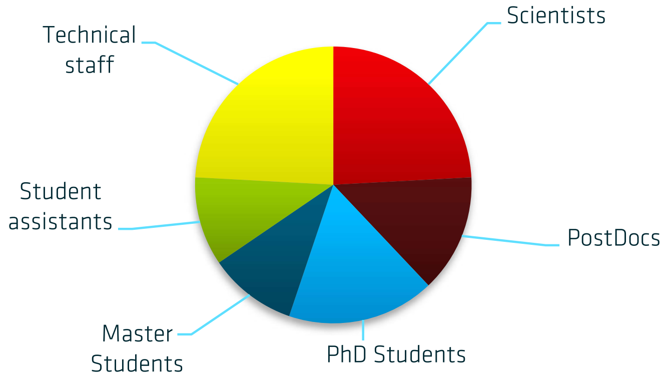
75 divisions and sections

People

1550 staff including trainees, Ph.D. students, post-docs from more than **55** nations

<u>Division 8.2:</u>
Non-destructive Testing Methods for Civil Engineering (NDT-CE)

We are a team of 28 people



Our main fields of application

- NDT-CE for infrastructure/existing structures
- NDT-CE methods in nuclear waste disposal research and decommissioning
- NDT-CE for new materials and construction methods

Content

Acoustic emission – general overview

Content

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Acoustic emission – what is it?

American Society for Testing and Standards

The 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

ASTM (2014)

The European committee for standardization

Transient elastic waves generated by the release of energy within a material or by a process

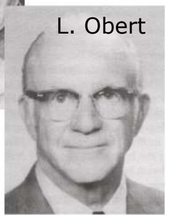
EN (2000)

http://www.idinspections.com/acoustic-emission-phenomenon/

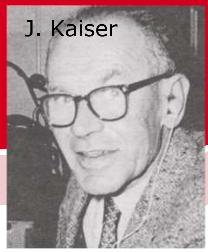
AE describes the spontaneous release of localized strain energy in stressed material

Brief history of AE

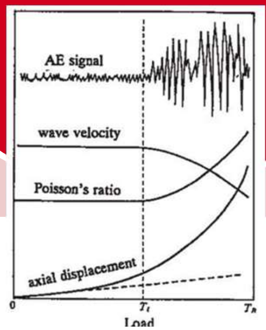
Before 1950
- 1933 F. Kishinoue timber creaking prior to break
- 1936 F. Förster extremely small voltage changes due to resistance variations in nickel-steel specimen
- 1938 L. Obert micro-seismic activity in rocks



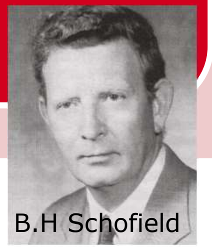
1950 J. Kaiser
- tested tensile specimens of metallic materials recording AE signals.
- Discovery of irreversibility - Kaiser effect



1960 L'Hermite
- Relation between AE, the decrease of ultrasonic velocity, and the increase of Poisson's ratio and axial strain



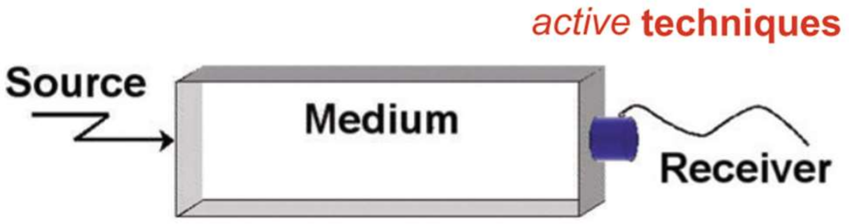
1961 B.H Schofield
- The first use of terminology "Acoustic Emission" in history

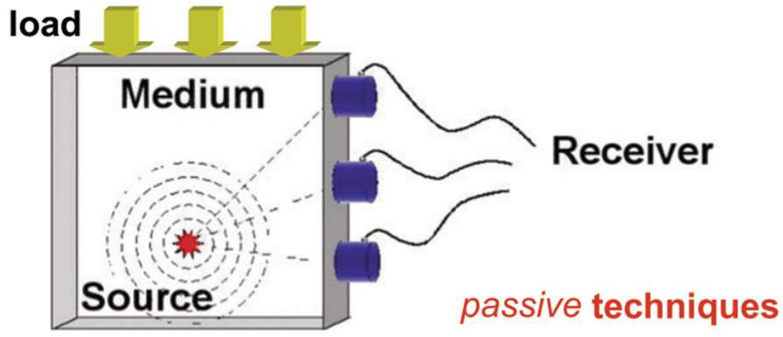


1967-1972
- 1967 Acoustic Emission Working Group (AEWG)
- 1969 Japanese Committee on AE
- 1972 European Working Group on Acoustic Emission (EWGAE)
- 1972 International Acoustic Emission Symposia (IAES)

2016
- International Institute of Innovative AE

Principles of active and passive techniques





Active methods: the source emitting the waves is generally applied to the material

Passive methods: the sources are within the material – they quasi "produce" the test signal

From: Grosse, C. U., Ohtsu, M., Aggelis, D. G., & Shiotani, T. (2021). *Acoustic Emission Testing Basics for Research-Applications in Engineering Second Edition*.

Is AE really non-destructive?

- An active deterioration (a fracture/process) of the material is necessary for testing
- Usually applied during the loading – most other NDT methods before or after loading a structure

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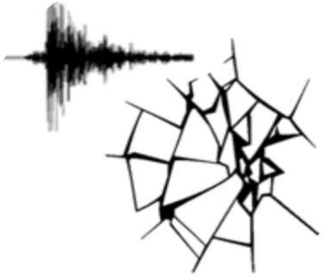
Sources of acoustic emission - examples

Concrete

- Crack formation or plastic deformation due to aging, temperature gradients, or external mechanical forces
- Rebar corrosion and failure
- Interface conditions between concrete and rebar

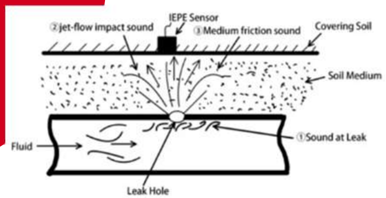
Metallic materials

- Initiation and growth of cracks
- Particle fracture
- Sliding and dislocation movements
- Twinning or phase transformation



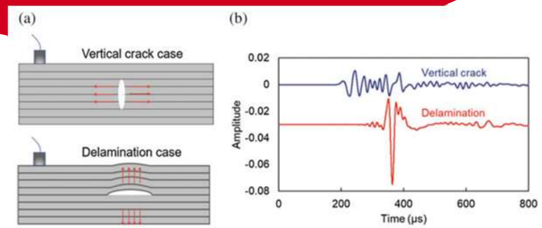
Pseudo-sources

- Liquefaction and solidification
- Friction in rotating bearings
- Solid-solid phase transformations
- Leaks
- Cavitation
- Realignment or growth of magnetic domains



Composite materials

- Generation and propagation of cracks within the matrix material, along the matrix-fiber interface
- The fracture if single fiber filaments or as a bundle
- Friction of existing crack surfaces



AE applications - examples

Bridges and buildings

Wood and timber structures

Weld monitoring

Pressure vessels

Pipelines

Wind turbines

Corrosion

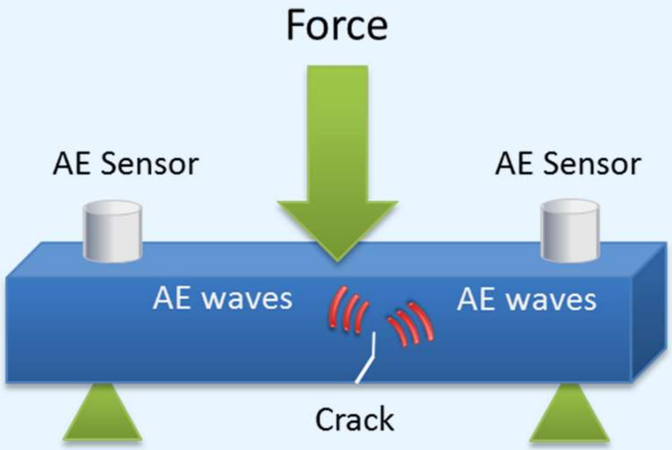
Cultural heritage

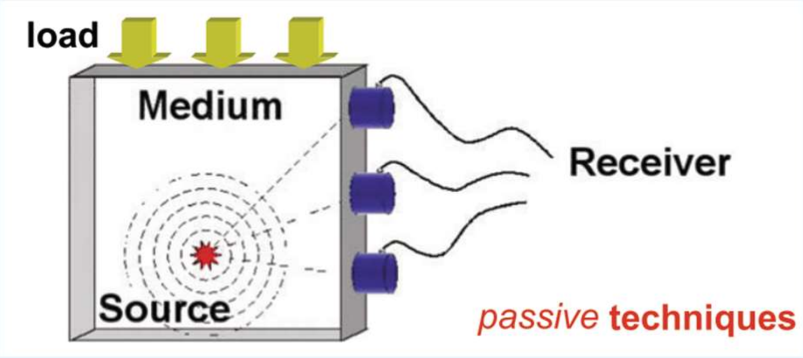
Aerospace structures

Earthquake research

Key Takeaways

1. AE = the spontaneous release of localized strain energy in stressed material
2. This energy release can be due to, for example, microcracking in the material and can be recorded by transducers (sensors) attached to the material's surface
3. Passive method – the sources are within the material – they quasi "produce" the test signal
4. AE sources are varied, e.g.: crack initiation or propagation, matrix and fiber breakage, slip and dislocation movement, …





Instruments and measurement process

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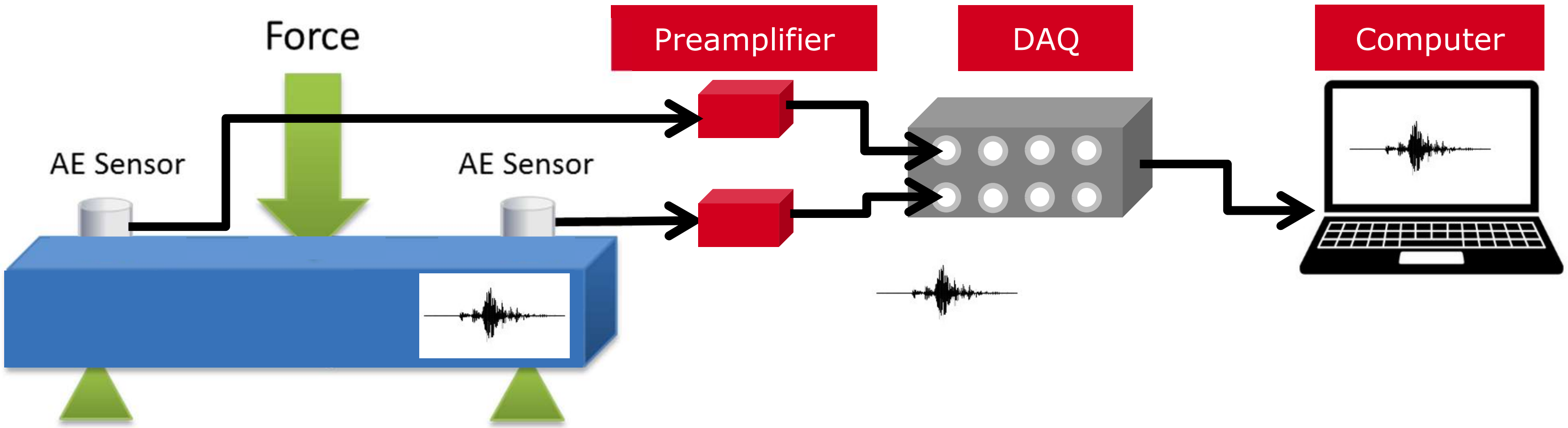
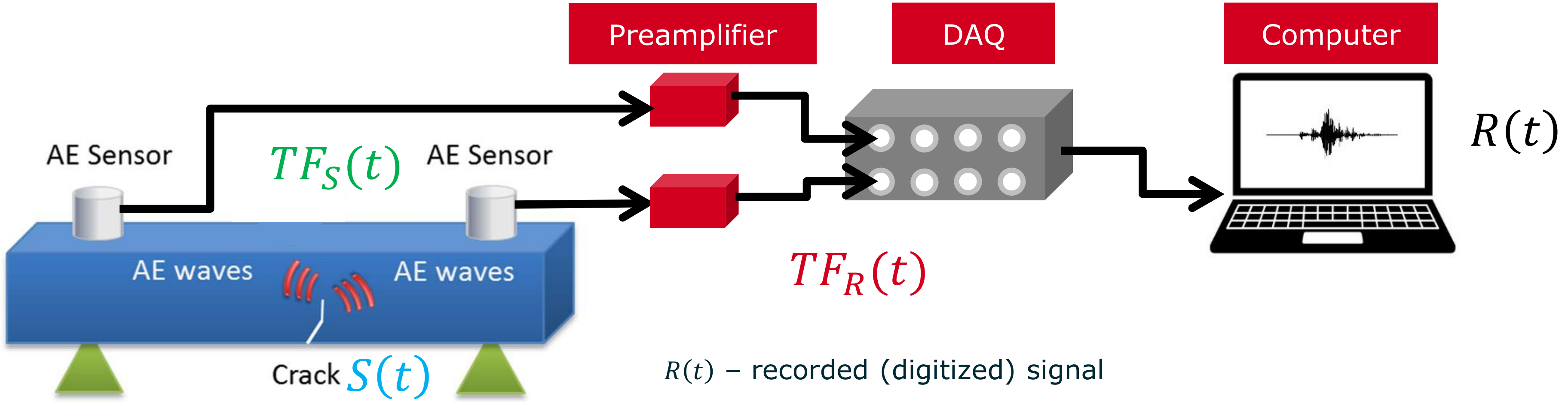
Measurement process



http://www.idinspections.com/acoustic-emission-phenomenon/

Measurement process

$$R(t) = S(t) * TF_M(t) * TF_S(t) * TF_R(t)$$



http://www.idinspections.com/acoustic-emission-phenomenon/

$R(t)$ – recorded (digitized) signal

$S(t)$ – source signal

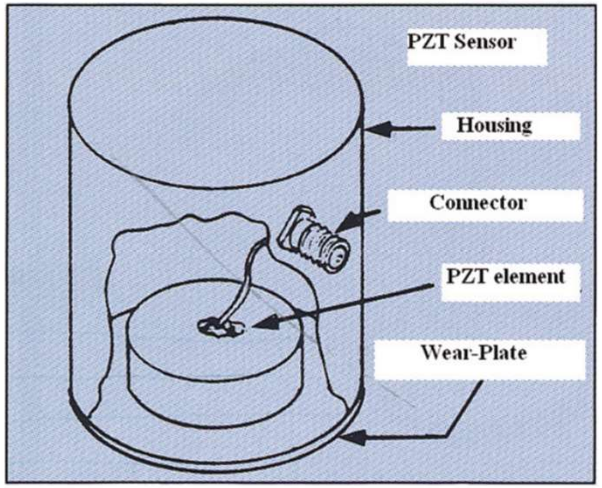
$TF_M(t)$ – Green's functions describing wave propagation in the medium

$TF_S(t)$ – sensor response transfer function

$TF_R(t)$ – data acquisition transfer function (including preamplifiers and filters)

AE sensors

- Transform surface motions into electric signals – they generate electric field when they undergo deformations
- Contact type – commonly used
- Piezoelectric sensors – best combination of low cost, high sensitivity, ease of handling and selective frequency responses
- Two types of sensors:
  - Resonant
  - Broad-band

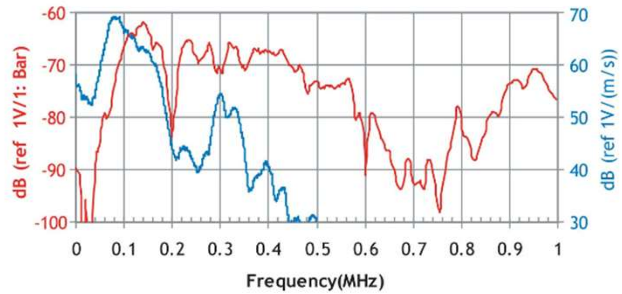


From: Grosse, C. U., Ohtsu, M., Aggelis, D. G., & Shiotani, T. (2021). *Acoustic Emission Testing Basics for Research-Applications in Engineering Second Edition*.

AE sensors

Resonant sensor

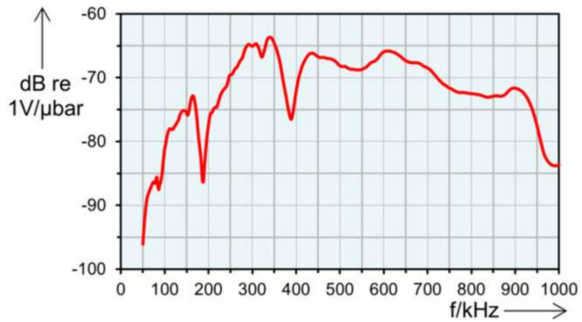
- Narrow frequency response
- Peak sensitivity higher than broad-band
- The size of the PZT element affects the resonant frequency
- Higer resonant frequency for smaller piezo-elements
- Common frequency range 150 kHz – 300 kHz



https://www.physicalacoustics.com/by-product/sensors/R15a-150-kHz-General-Purpose-AE-Sensor

Broad-band sensor

- Wide (up to 2 MHz) and considerably “flat” frequency response
- Lower sensitivity (lower voltage than resonant sensor for the same displacement)
- Used when frequency analysis required in signal post-processing

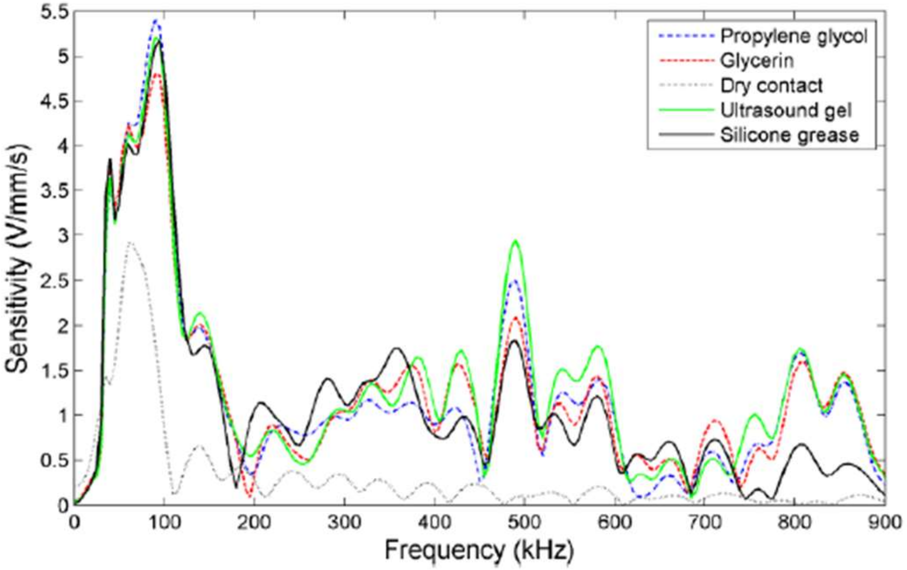


https://www.vallen.de/sensors/broad-band-sensors/vs900-m/

Mounting of AE sensors

- Coupling between sensors and a specimen is important due to the low amplitudes of AE signals
- The coupling should reduce the loss of signal energy and should have a low acoustic impedance compared to the material to be tested
- To decrease the attenuation of waves, it is necessary to avoid air bubbles and thick glue/couplant layers
- Mounting surface should be smooth and clean – good adhesion
- Sensor must always be stationary

Sensitivity of AE sensor using different couplants

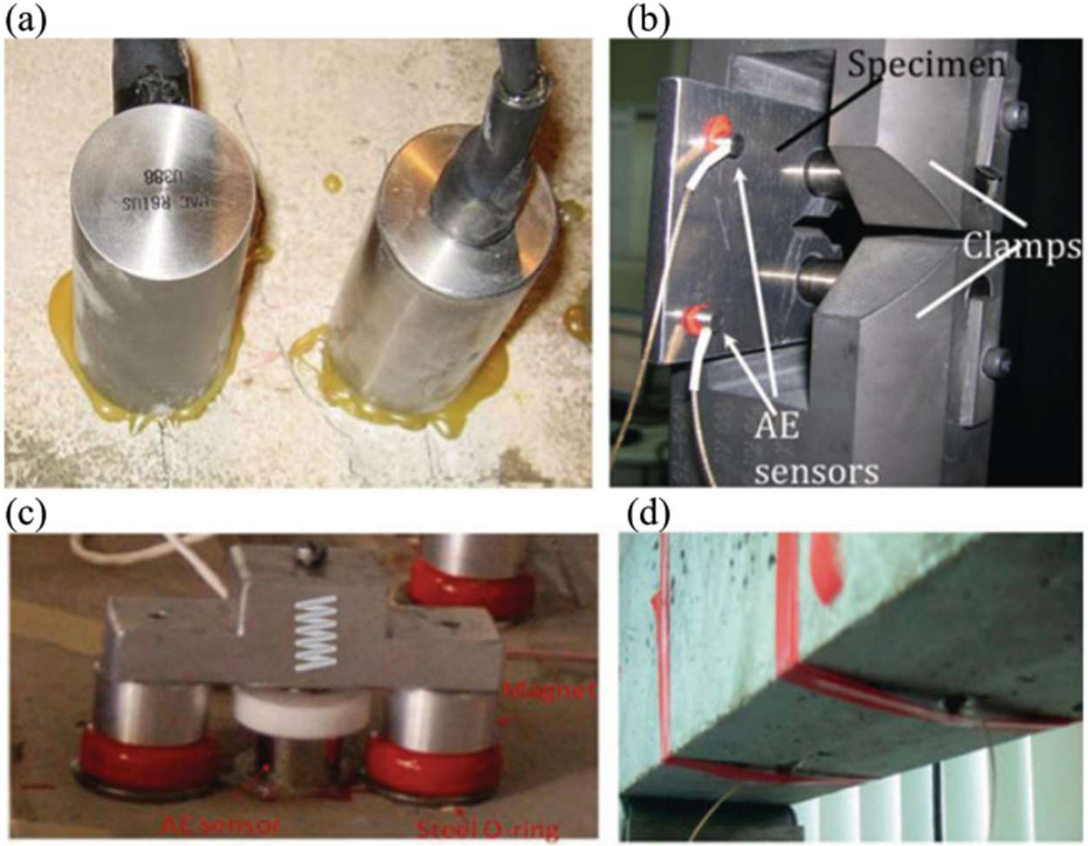


From: P. Theobald, B. Zeqiri and J. Avinson, "Couplants and their influence on a AE sensor sensitivity," Journal of Acoustic Emission, vol. 26, pp. 91-97, 2008.

Mounting of AE sensors

Wax, hot glue
On concrete

Wax on metal



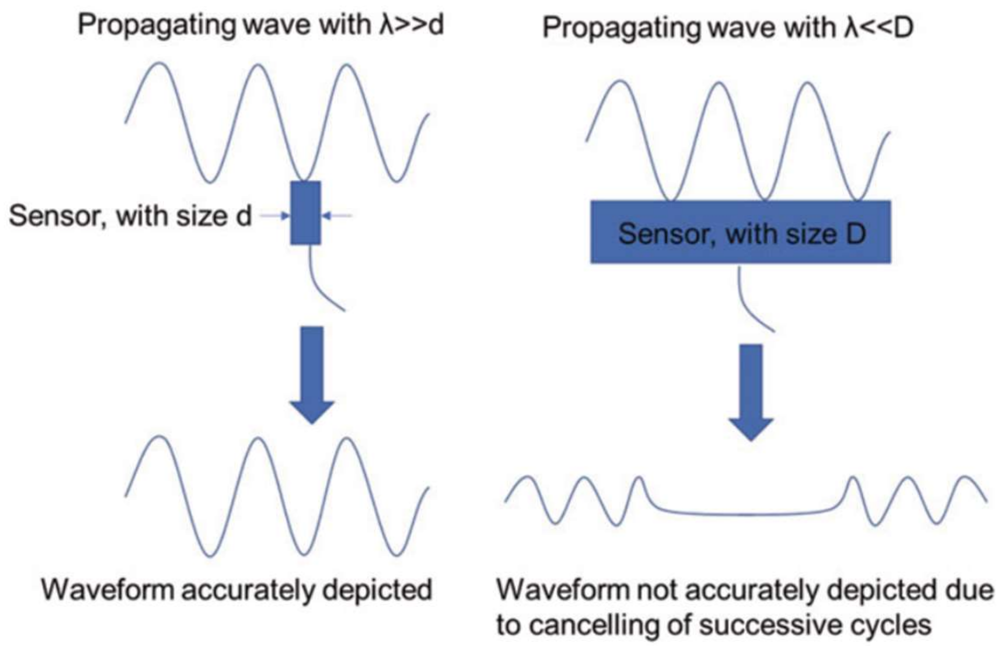
With
magnetic
clamps

With grease
and tape

From: Grosse, C. U., Ohtsu, M., Aggelis, D. G., & Shiotani, T. (2021). *Acoustic Emission Testing Basics for Research-Applications in Engineering Second Edition*.

AE sensors – aperture effect

- In plate structures: the wave direction is predominantly parallel to the sensor face
- In bulk medium: AE wave comes at an angle or even ~90° (if the source deep inside the material)
- “Aperture” effect: decrease in the recorded wave amplitude at high frequencies due to multiple wavelengths being averaged over the area of contact of a sensor.
  The larger the surface area of a transducer, the higher is the possibility to interfere with the waveform shape.



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AE sensors – aperture effect

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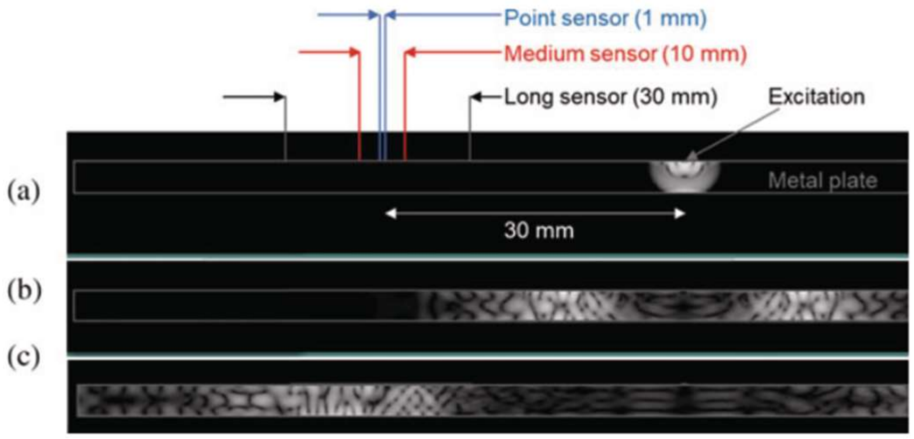
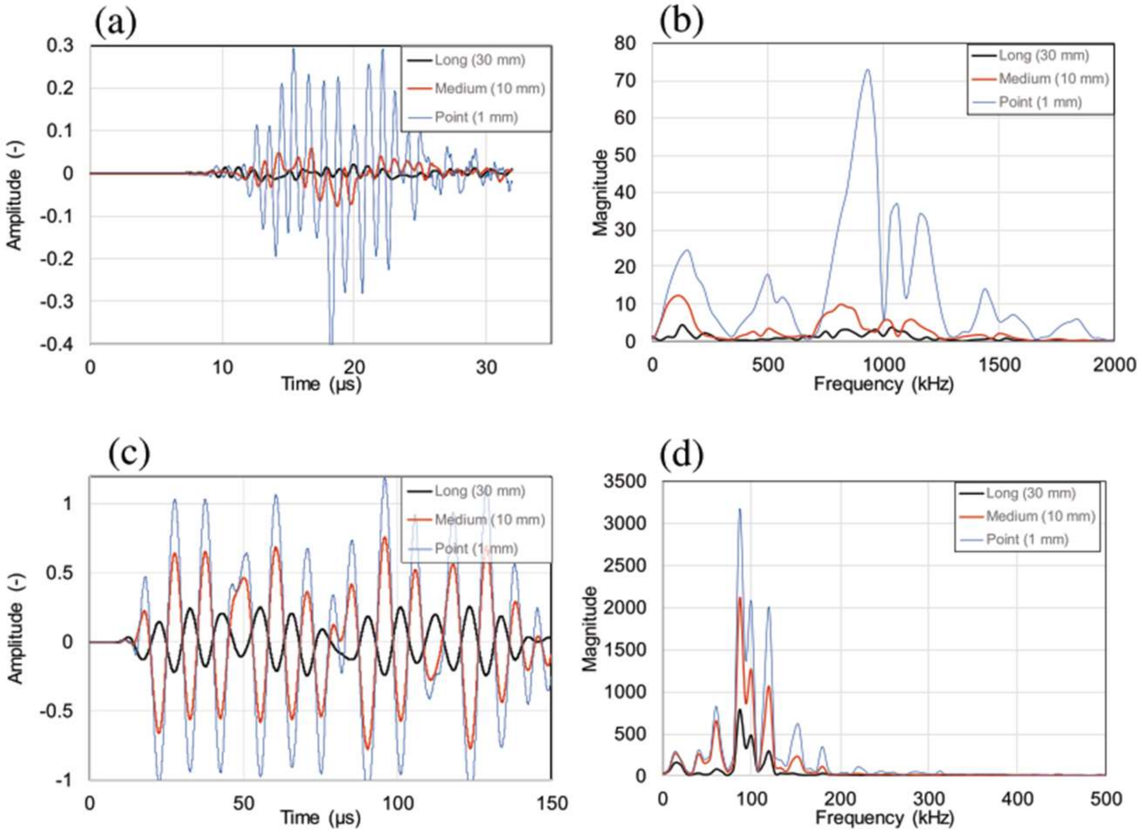


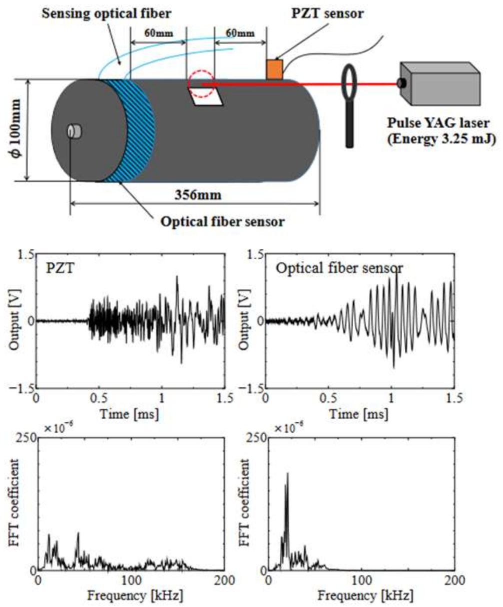
Snapshots of the transient strain field in a metal plate after three cycles of 1MHz excitation a) 1 µs, b) 8 µs, and c) 10 µs after the excitation



Simulated waveforms collected on metal specimen by sensors of different size after excitation of a) 1MHz, b) corresponding power spectra, c) 100 kHz, d) corresponding power spectra

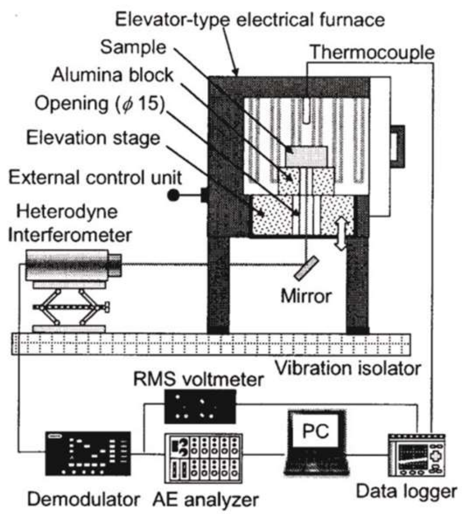
Alternative AE sensors

Optical fiber sensor



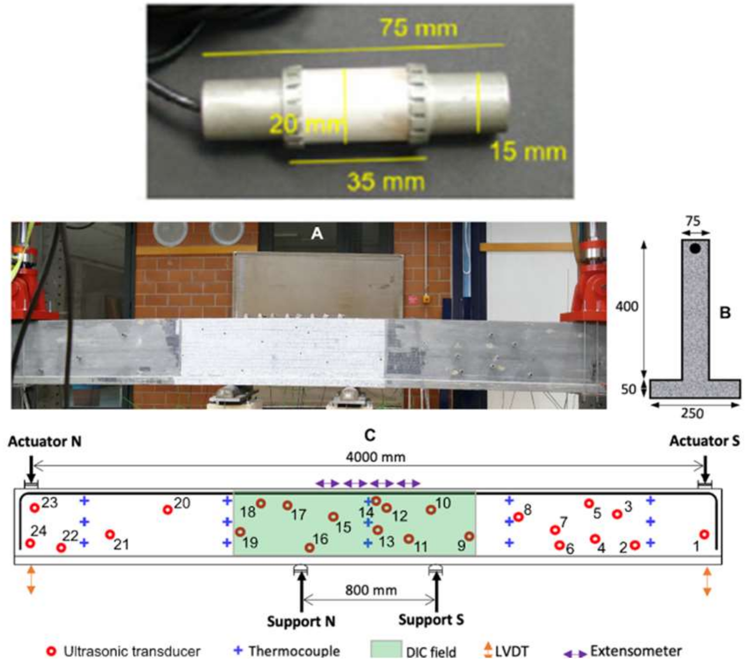
Matsuo T., Orito H., and Hase K. (2019) Development of damage detection method in type-III hydrogen pressure vessel by acoustic emission

Laser AE system



Nishinoiri S, Enoki M (2004) Development of in-situ monitoring system for sintering of ceramics using laser AE technique. Progress in AE XII:69–76, JSNDI

Embedded sensors



Bertola, N., Schumacher, T., Niederleithinger, E., & Brühwiler, E. (2024). *Early detection of structural damage in UHPFRC structures through the combination of acoustic emission and ultrasonic stress wave monitoring*.

Amplifiers

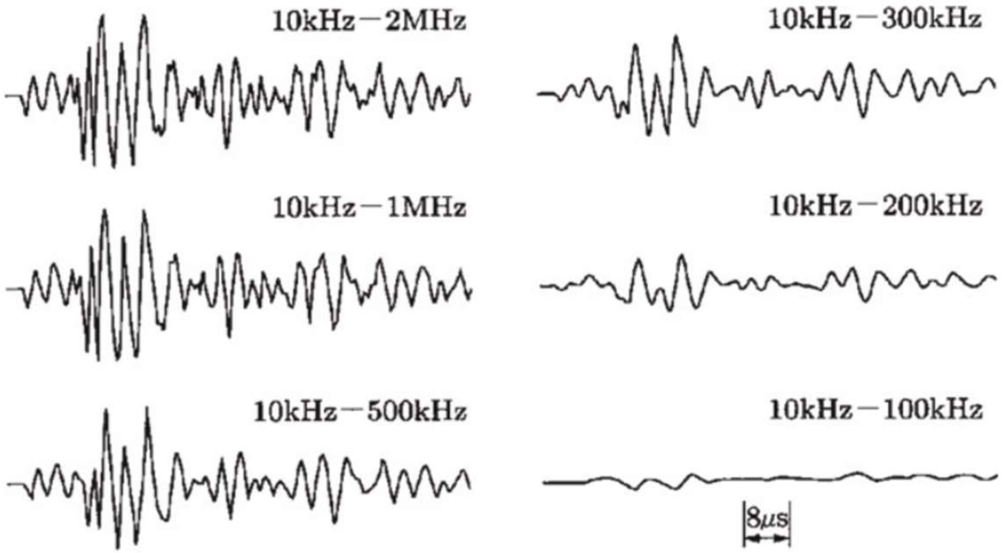
- Magnify AE signals
- Cables from the sensor to the amplifier are subjected to electro-magnetic noise → specially coated cables of short length shall be used
- Preferably with a flat response in the frequency range
- Gain of the amplifier in dB (decibels)
- Preamplifiers with state-of-the-art transistors minimize the electronic noise

https://www.innerspec.com/portable/standard-acoustic-emission-preamplifiers#
https://www.vallen.de/products/preamplifier/

Filters

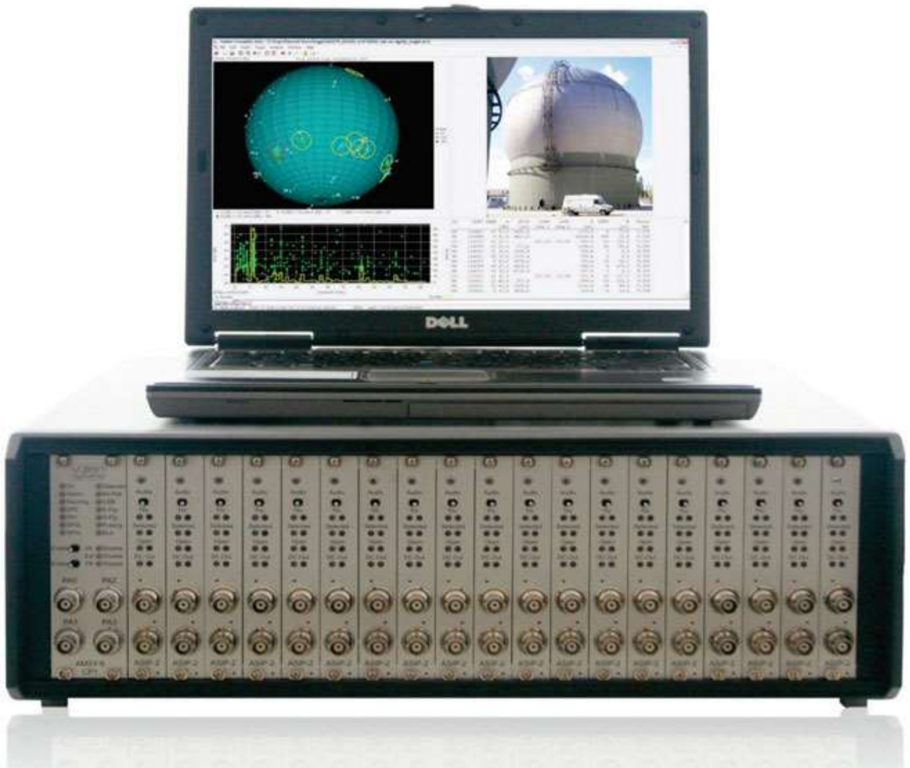
- Variable bandwidth between 1 kHz and 2 MHz
- Choice of the filter depends on:
  - Noise level
  - Attenuation property of the material

Effect of the band-pass filter on AE waveforms



Data acquisition units

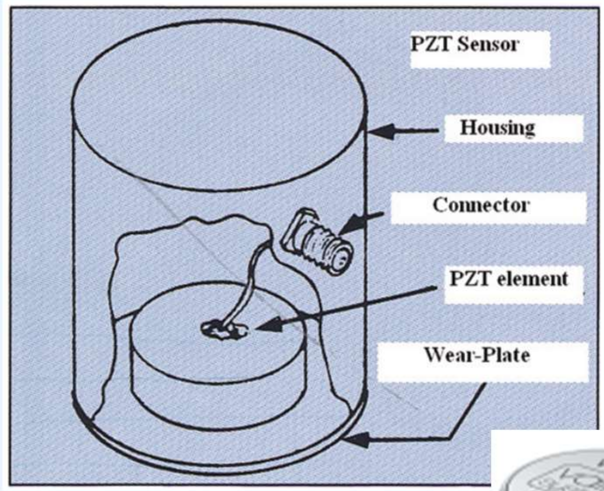
- A/D (analog to digital) conversion
- Triggering
- Data recording
- Anti-aliasing filtering
- Parameter analysis



https://atgndt.com/project/amsy-6/

Key Takeaways
Instruments and measurements

1. Most commonly used AE sensors: contact piezoelectric sensors
2. Two types of sensors: resonant and broadband
3. Proper coupling of the sensors is very important for proper data acquisition
4. Sensors must be always stationary
5. AE signals are weak – to improve signal-to-noise ratio, pre-amplifiers are used
6. DAQ → analog-to-digital conversion



Signal characteristics

Content

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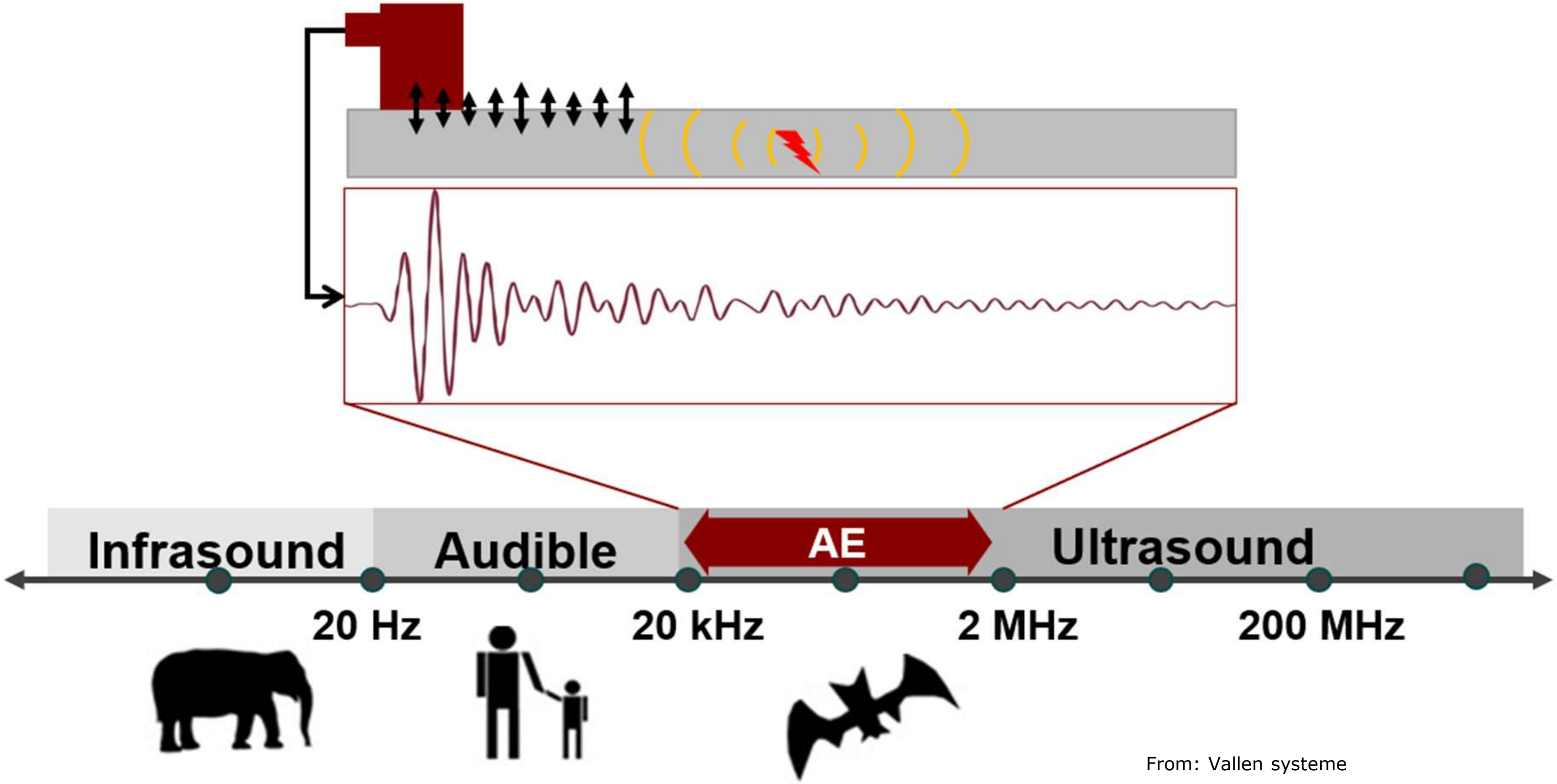
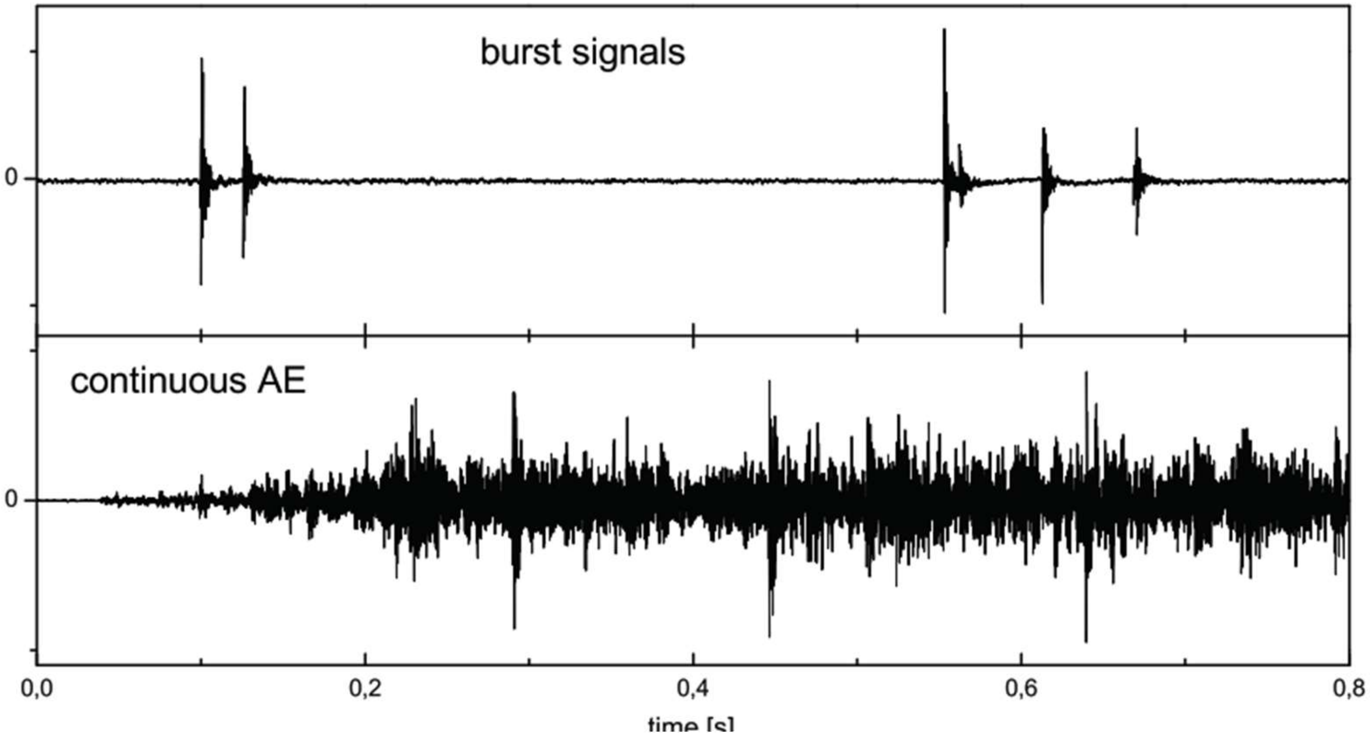
AE – frequency range



From: Vallen systeme

AE signals in time domain



Grosse, C. U., Ohtsu, M., Aggelis, D. G., & Shiotani, T. (2021). *Acoustic Emission Testing Basics for Research-Applications in Engineering Second Edition*.

Burst signals:

- Sources of emission are non-repeatable and occur discretely
- Independent in time-domain (crack growth, corrosion, local catastrophic yielding, etc.)

Continuous AE:

- Transient bursts are not discriminated
- AE produced by the numerous overlapping AE events (friction processes, leakages, etc.)

Measured units

AE units are voltage (V) or decibels (dB) which are related by:

$$dB = 20 \cdot \log(\frac{A}{A_{ref}})$$

Where:

A - measured voltage

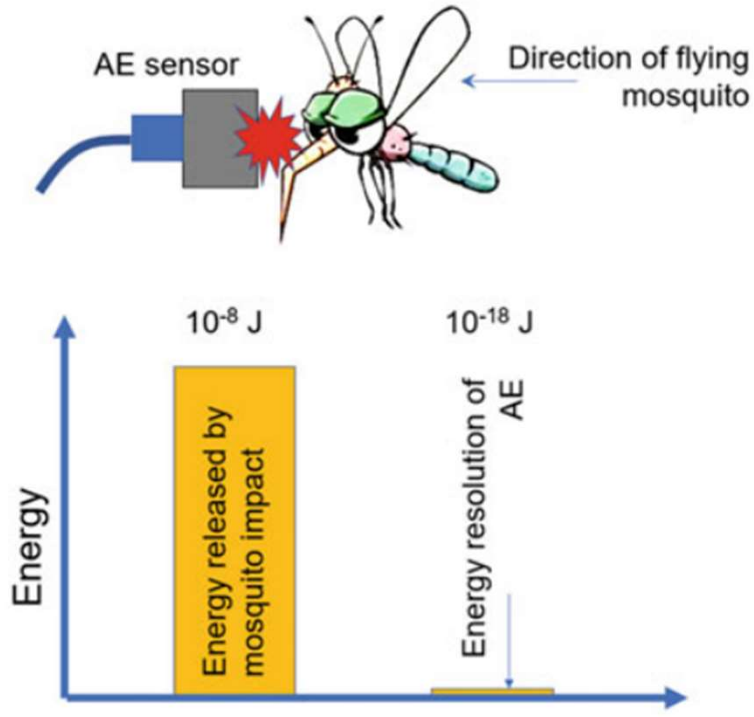
A_{ref} - constant reference value

The energy of the signal is defined as:

$$E_{abs} = \int_0^{t_1} V^2(t)dt$$

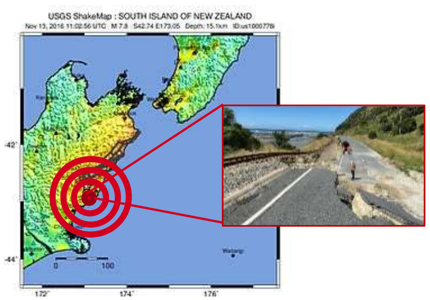
Where:

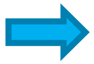
V – rectified waveform envelope

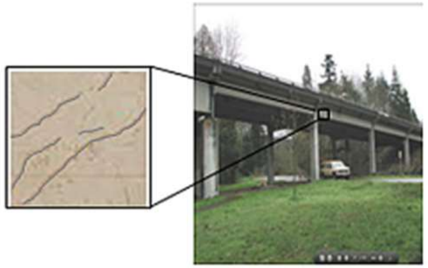


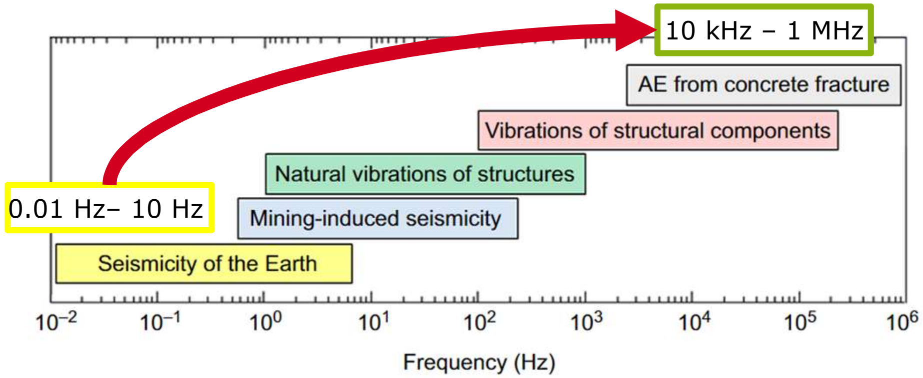
Aggelis, D. G., Sause, M. G. R., Packo, P., Pullin, R., Grigg, S., Kek, T., & Lai, Y.-K. (2021). Acoustic Emission. In *Springer Aerospace Technology* (pp. 175–217). Springer Science and Business Media Deutschland GmbH

Seismology vs Acoustic Emission



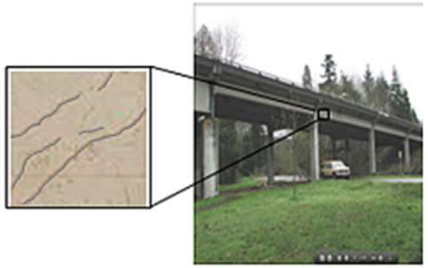


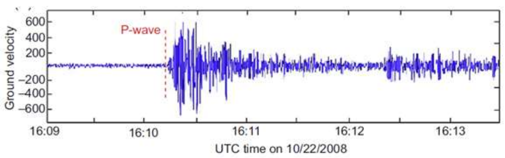




Modified from: Mhamdi, L., Schumacher, T., & Linzer, L. (2015). Seismology-based acoustic emission techniques for the monitoring of fracture processes in concrete structures. In *Acoustic Emission (AE) and Related Non-destructive Evaluation (NDE) Techniques in the Fracture Mechanics of Concrete: Fundamentals and Applications* (pp. 79–111). Elsevier Inc.

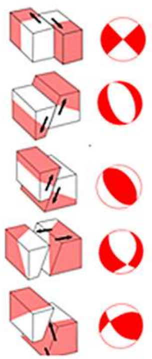
Seismology vs Acoustic Emission





Hypocenter location

Common fault types



Strike-slip

Normal fault

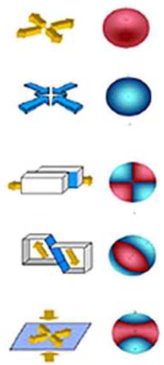
Reverse (thrust) fault

Transtension (Extension + Shear)

Tranpression (Compression + Shear)

Source location

Basic fracture modes



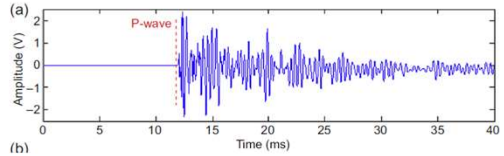
Explosion

Implosion

Shear mode II

Shear mode III

CLVD



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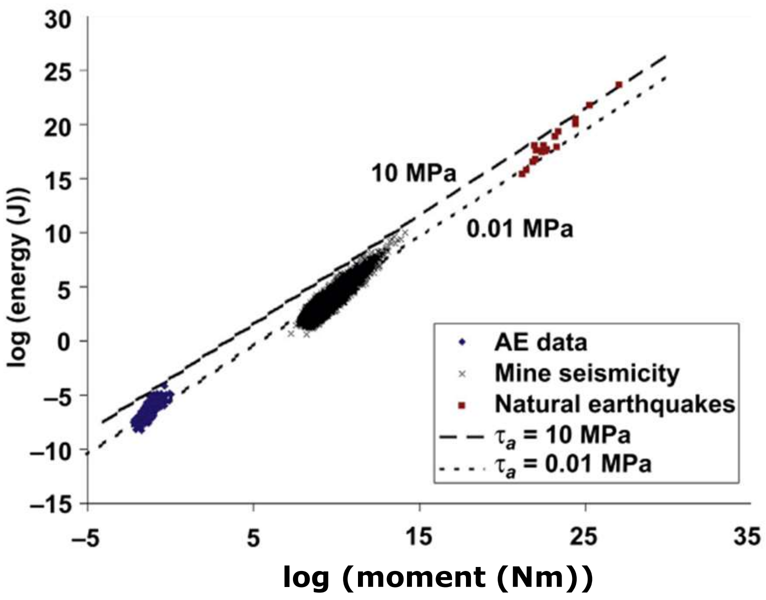
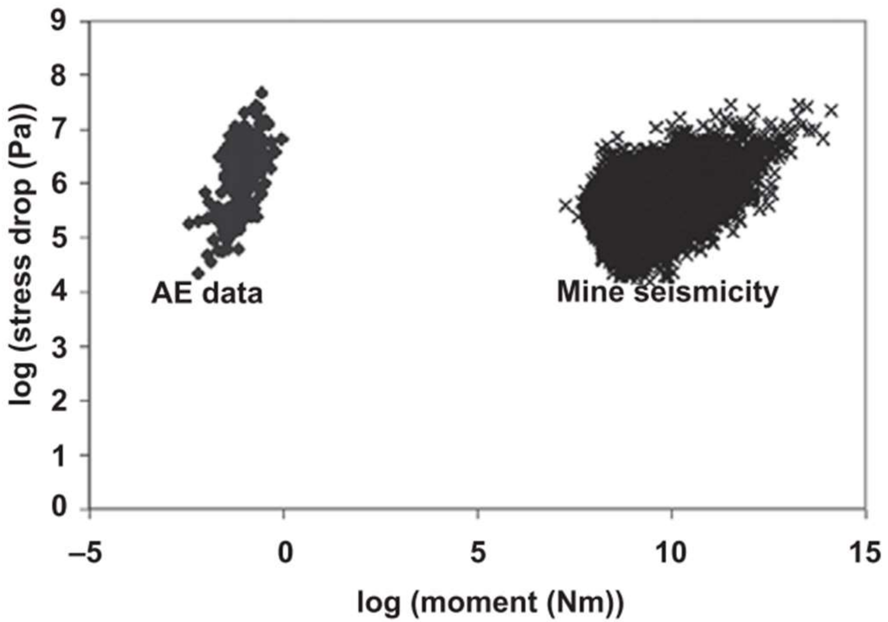
Acoustic emission vs seismology

AE exhibits a similar moment-energy relationship when compared to mine seismicity and natural earthquakes

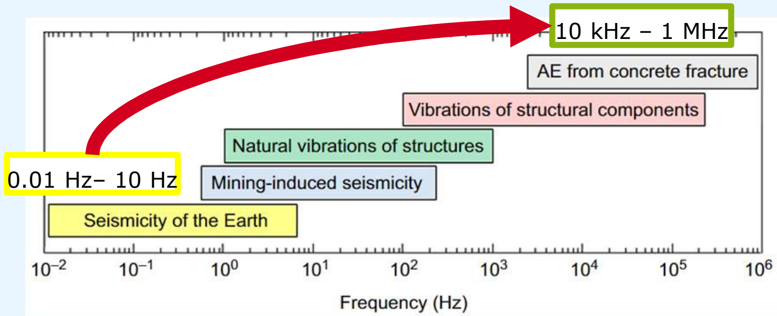


Stress drop independent of the moment – similar to observations from mining-induced earthquakes



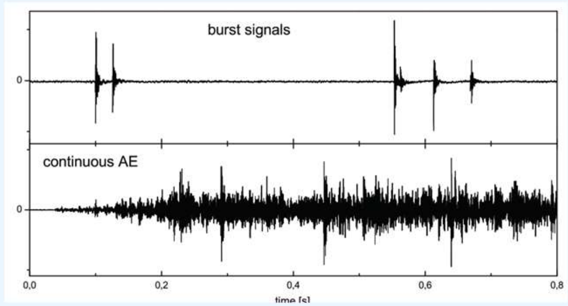
Sellers, E. J., Kataka, M. O., & Linzer, L. M. (2003). Journal of Geophysical Research.

Key Takeaways
AE signal characteristics

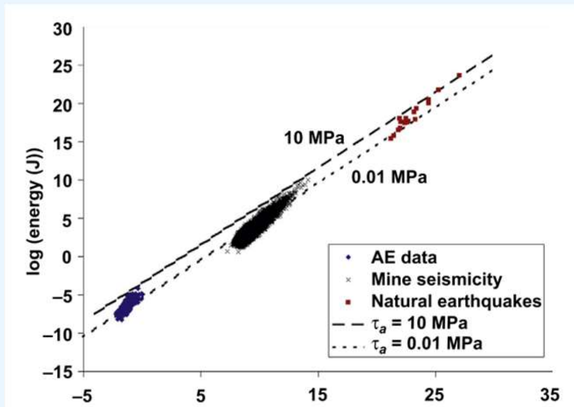


1. AE signals frequency range 20 kHz – 2 MHz
2. Two types of AE signals: burst and continuous
3. Units of AE signals are volts (V) or decibels (dB)

$$dB = 20 \cdot \log(\frac{A}{A_{ref}})$$



4. Although there are differences in scale (space, time), geometry, loading, boundary conditions, and medium, earthquakes, mining-induced seismic events, and AE are similar phenomena



A small break…? (15 min)

Content

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Parameter based AE analysis

Content

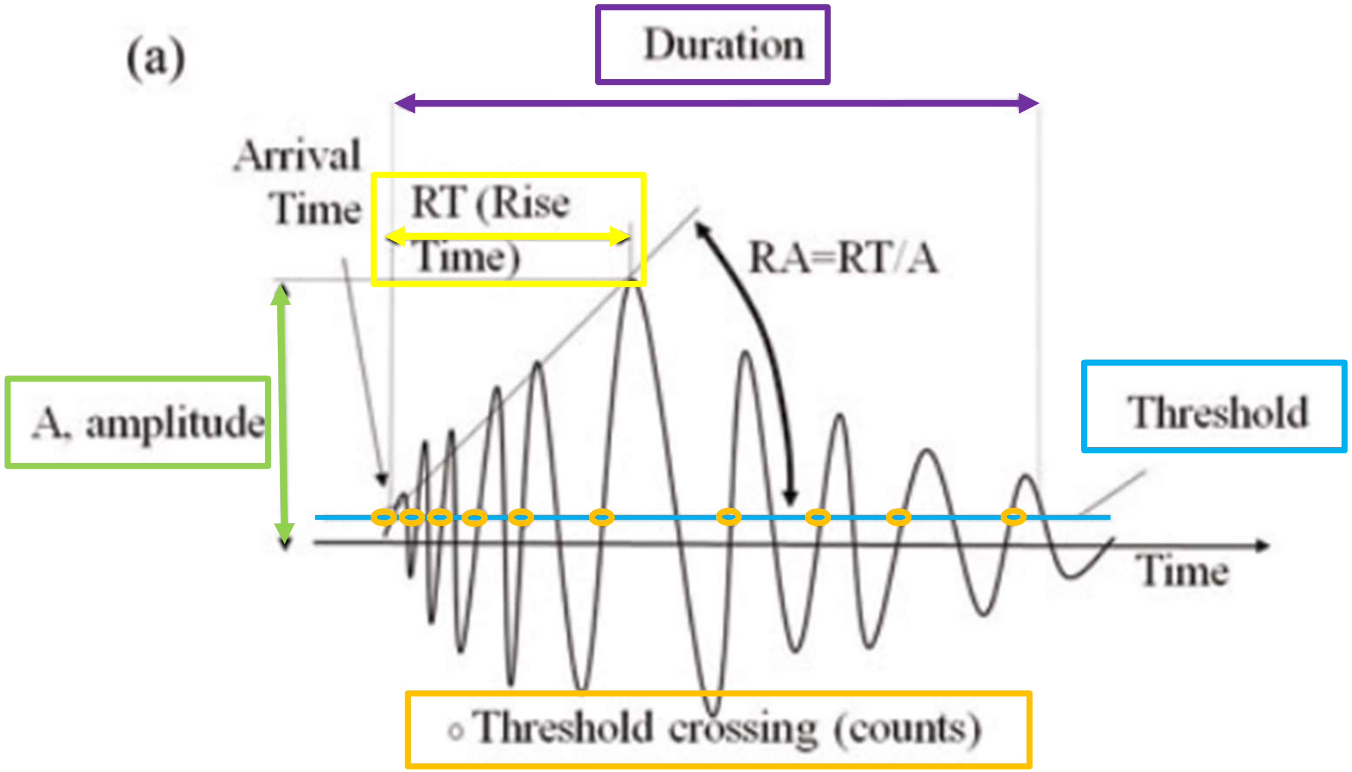
Parameter-based analysis

Idea: the signal can be sufficiently described by the set o characteristic parameters (or features), and storing this relatively small amount of information consumes far less time and storage space

Definitions:

- Hit: a signal that exceeds the threshold and causes a system channel to record data
- Event: hits coming from a common acoustic source

Signal parameters – time domain



- Energy / signal strength

$$E_{abs} = \int_0^{t_1} V^2(t)dt$$

- Average frequency AF: the ratio of the total number of counts over the duration of the waveform [Hz]

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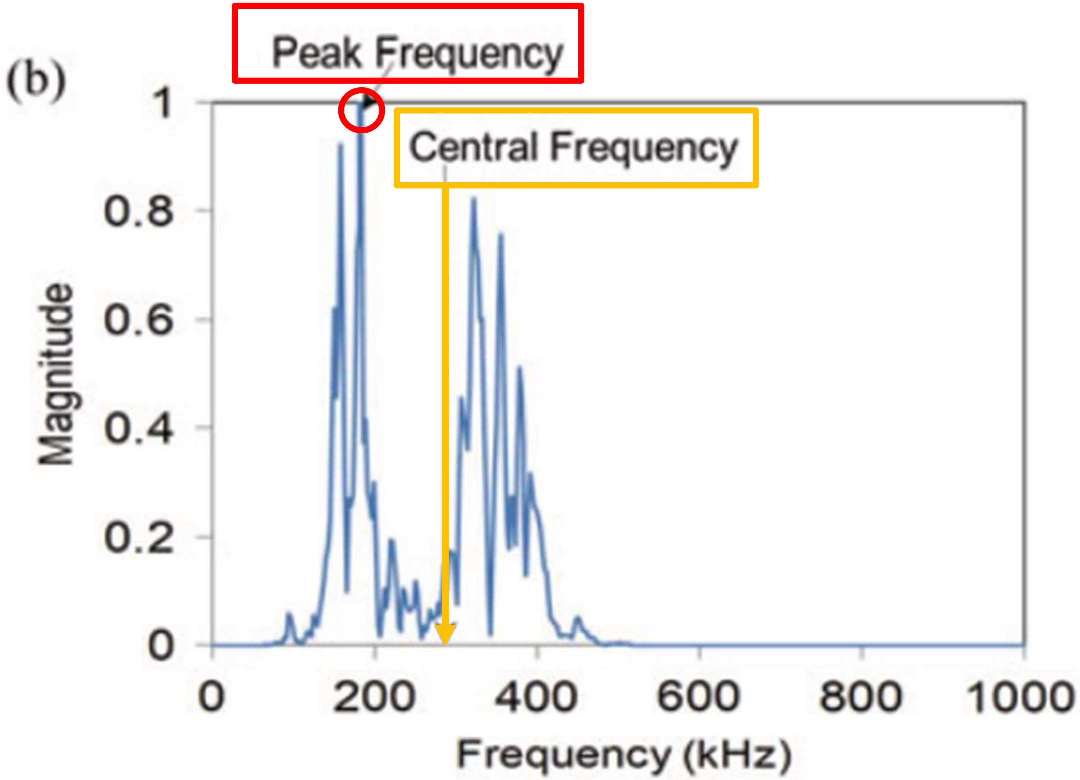
Signal parameters – frequency domain



$$CF = \frac{\int_0^f f H(f) df}{\int_0^f H(f) df}$$

Where:

f - frequency

$H(f)$ - magnitude of the FFT

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Ok, but… so what?

- Quick estimation of the event character
- Example: fracture mode evaluation

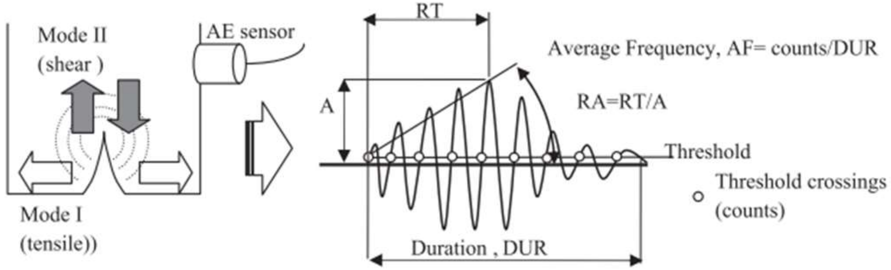
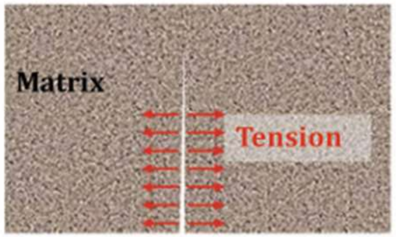
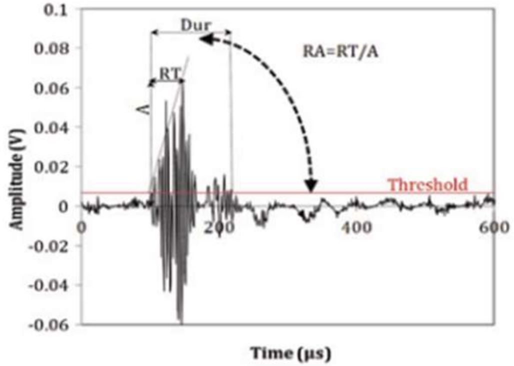


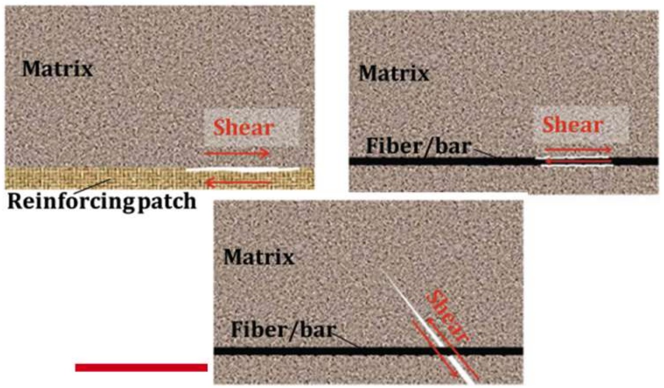
Fig. 1. Crack modes and AE signal.

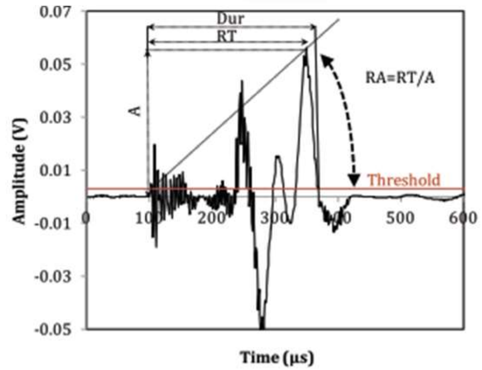
Aggelis DG (2011) Classification of cracking mode in concrete by acoustic emission parameters. Mech Res Commun 38:153–157





Higher proportion of longitudinal waves
→ Shorter duration
→ Shorter rise time





Higher proportion of share waves
→ Slower
→ Arrive later

Classification of AE signals

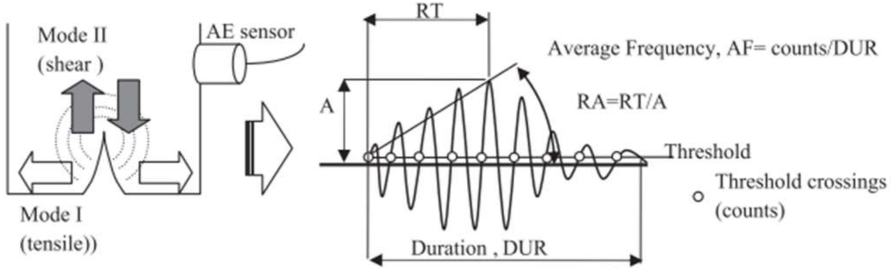
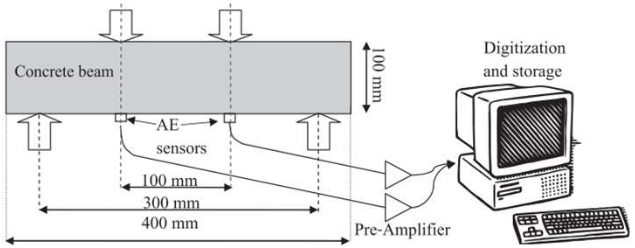
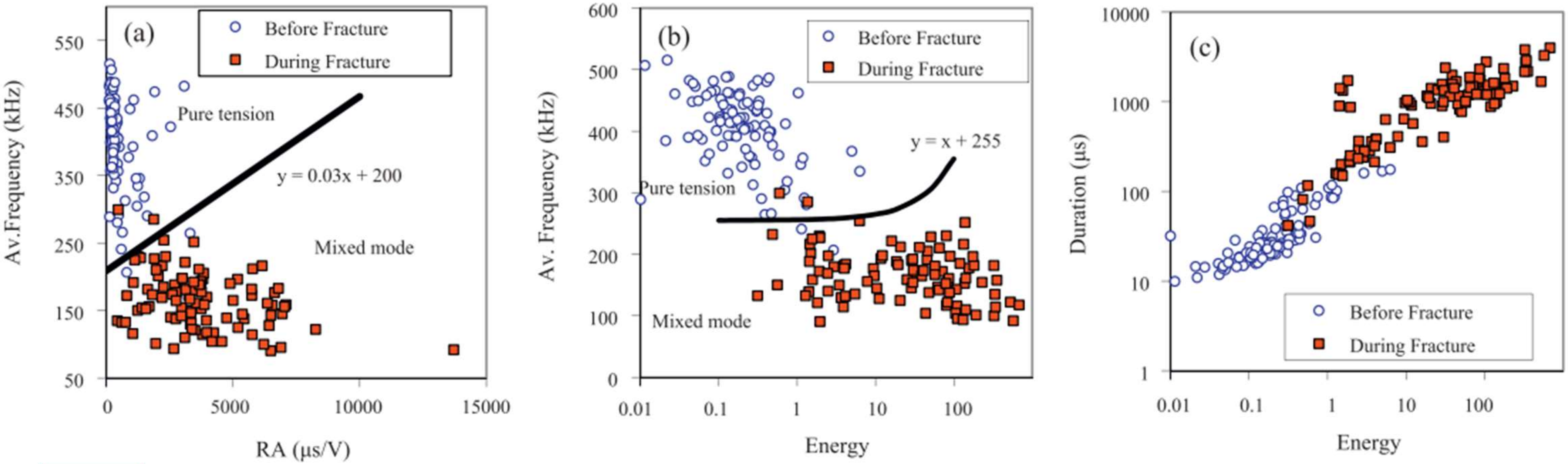


Fig. 1. Crack modes and AE signal.

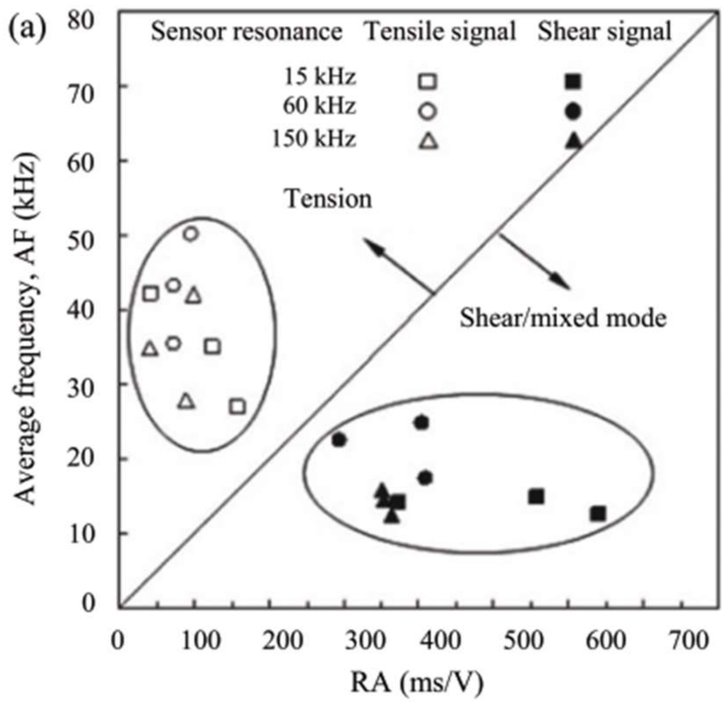


Aggelis DG (2011) Classification of cracking mode in concrete by acoustic emission parameters. Mech Res Commun 38:153–157



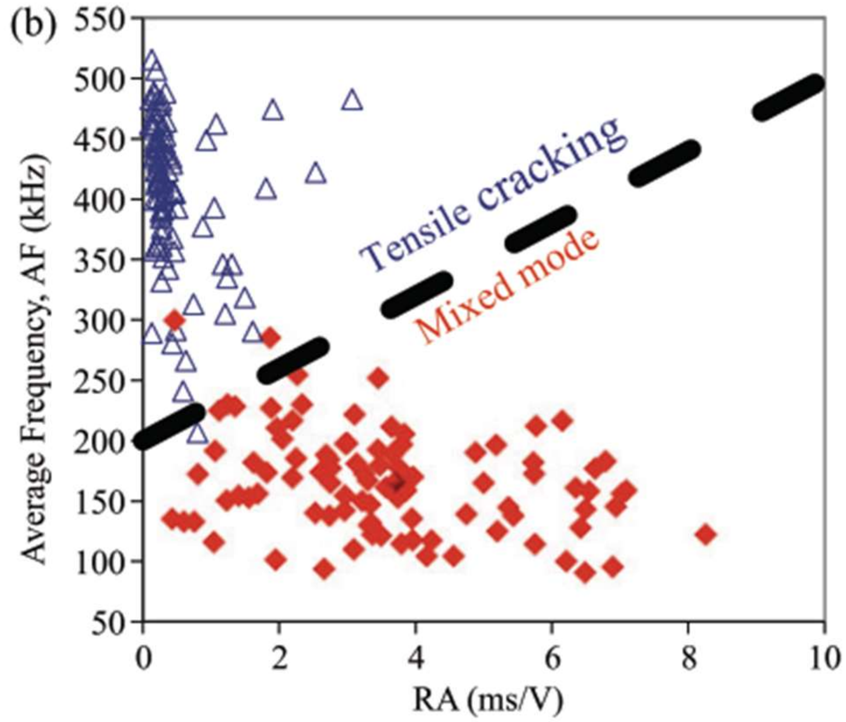
Classification of AE signals

Resonant sensors



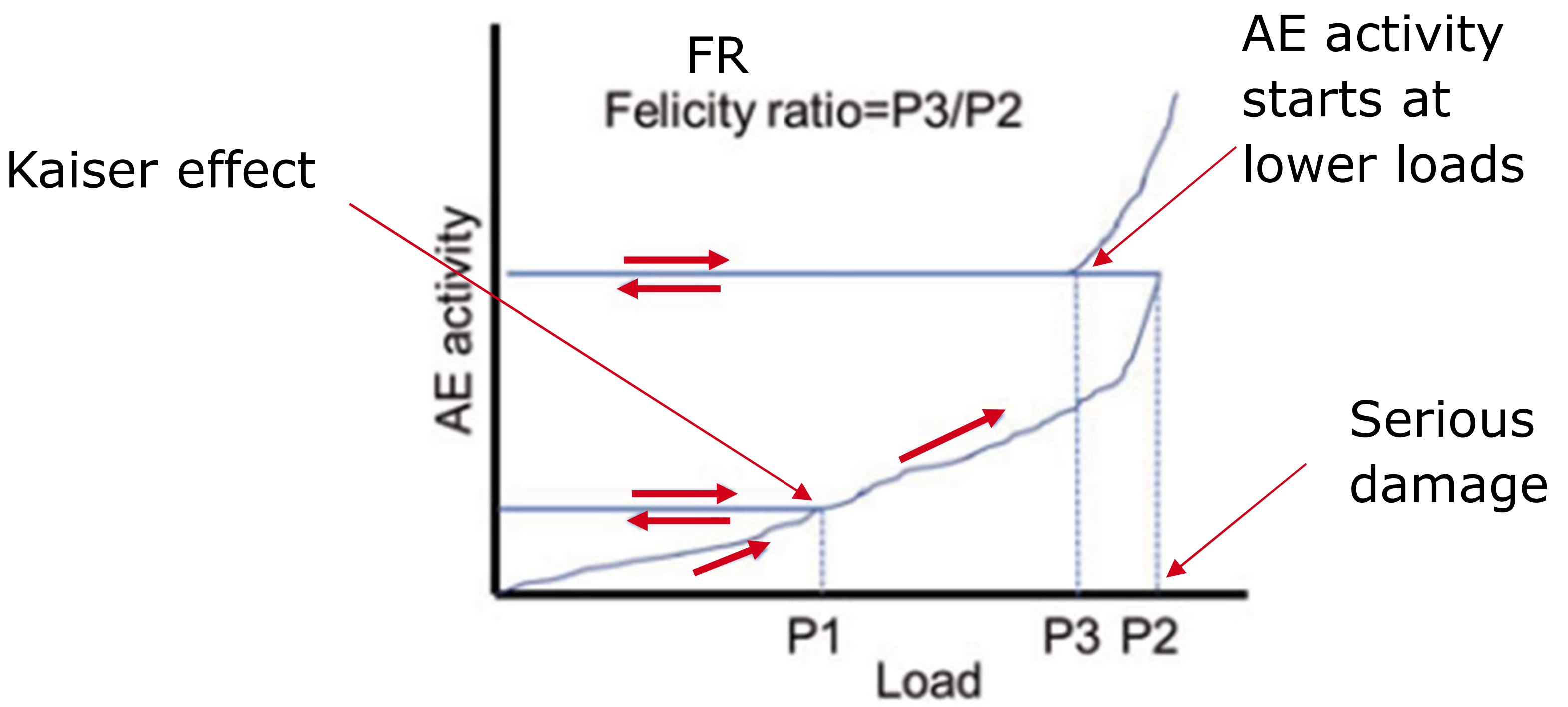
Ohtsu M(2010) Recommendations of RILEM Technical Committee 212-ACD: acoustic emission and related NDE techniques for crack detection and damage evaluation in concrete: test method for classification of active cracks in concrete structures by acoustic emission. Mater Struct 43(9):1187-1189

Broadband sensors



Aggelis DG (2011) Classification of cracking mode in concrete by acoustic emission parameters. Mech Res Commun 38:153–157

Kaiser effect and felicity ratio



If FR ~= 1 – the Kaiser effect is valid, material is intact

The lower the FR gets, the more accumulated damage

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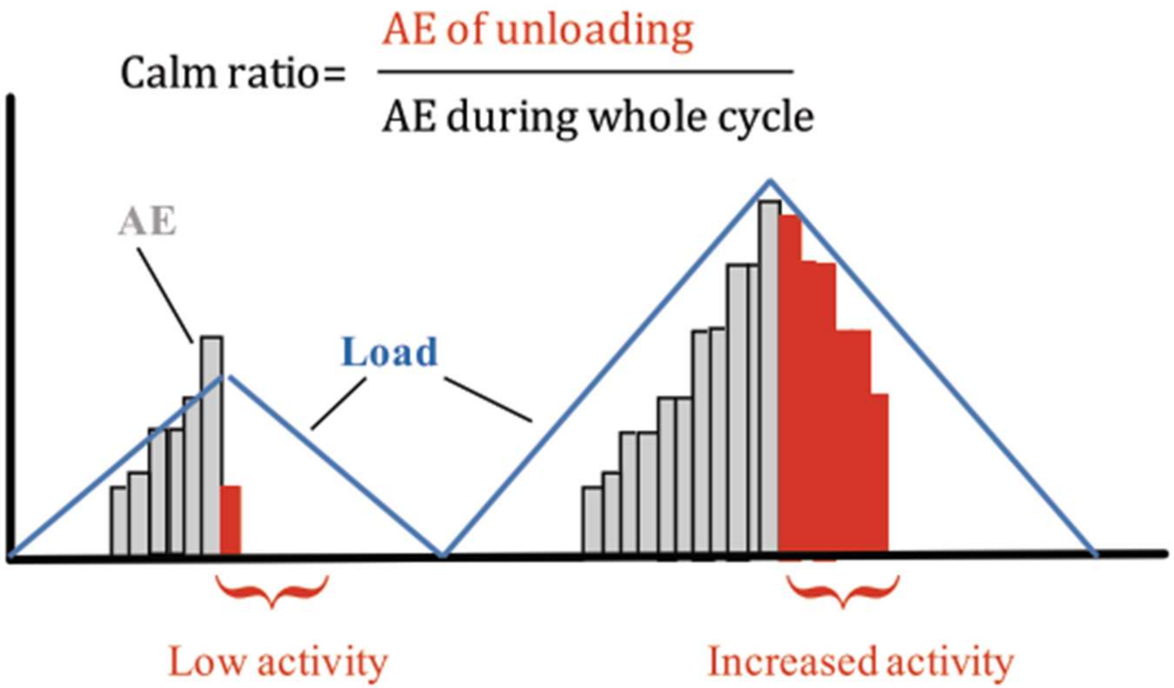
Calm ratio

It is the total activity during unloading over the total activity during the whole cycle (loading and unloading)

- Calm ratio ~= 0: structurally stable material
- Increase of calm ratio: accumulation of damage



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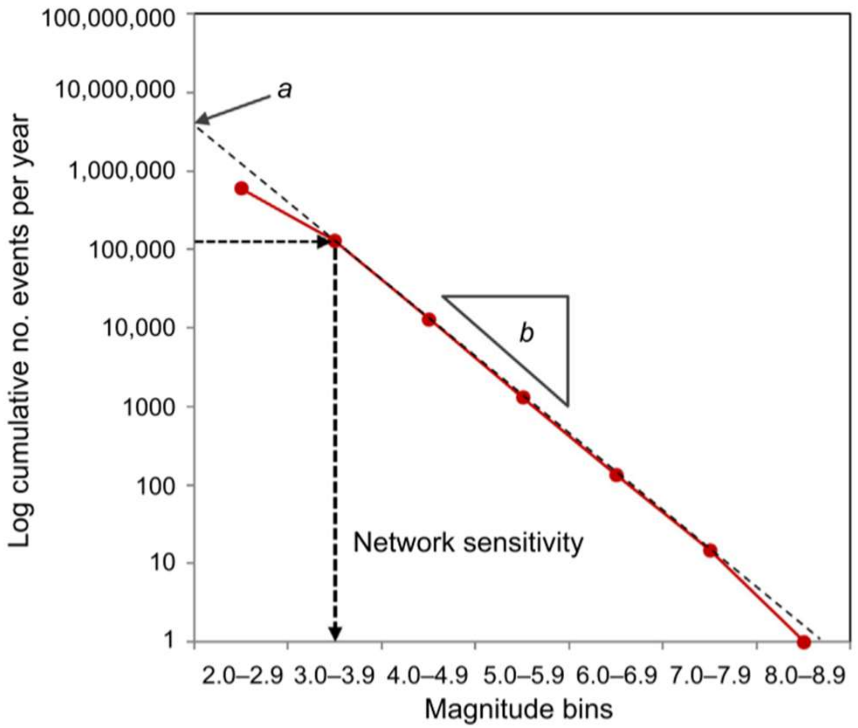
b-value analysis

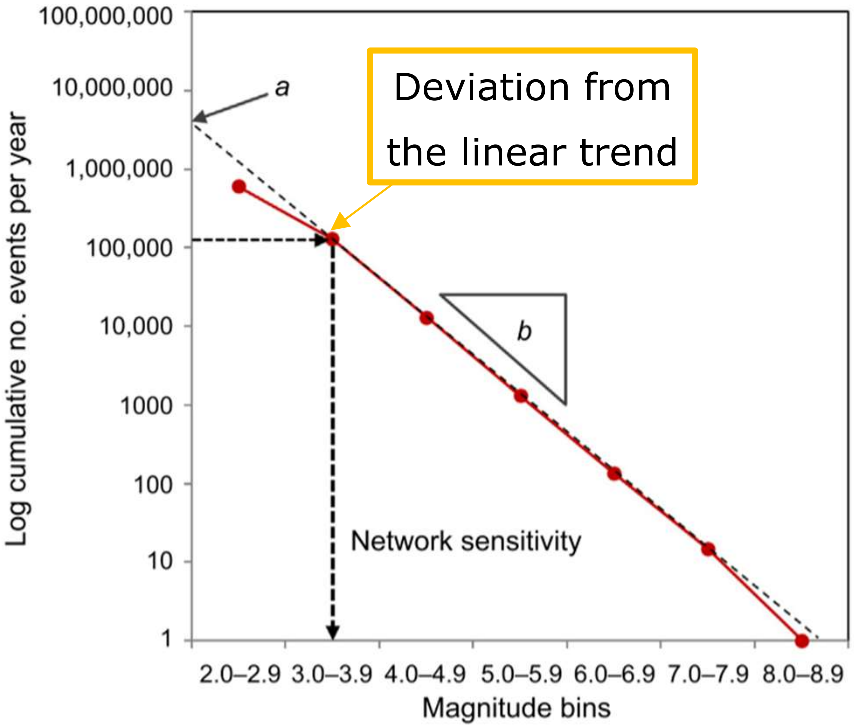


Mhamdi, L., Schumacher, T., & Linzer, L. (2015). Seismology-based acoustic emission techniques for the monitoring of fracture processes in concrete structures. In *Acoustic Emission (AE) and Related Non-destructive Evaluation (NDE) Techniques in the Fracture Mechanics of Concrete: Fundamentals and Applications* (pp. 79–111)

- Assumption: a change in the b-value indicates a change in the concrete's cracking behavior
- Describes overall patterns of large numbers of events statistically
- Characterizes large numbers of events (earthquakes or AE) using an empirical log-linear frequency-magnitude distribution
- Only one sensor is necessary
- The drop in the estimated b-value is a good predictor of the point of maximum applied total force

Gutenberg-Richter frequency-magnitude relation

Example of cumulative frequency-magnitude diagram (or Gutenberg-Richter Distribution)



$$\boxed{log_{10}(N) = a - b \cdot M_L}$$

Where:

M_L - local magnitude – measure of the amount of energy released during an earthquake (strength of the event)

$$M_L = log_{10}A(r) - log_{10}A_0(r)$$

N - the number of earthquakes with magnitude > M_L

a, b - empirical constants

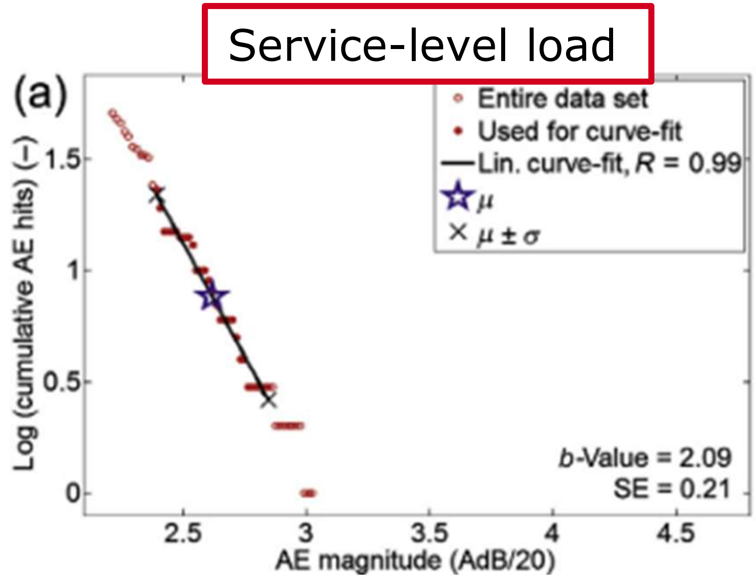
b-value application in material science

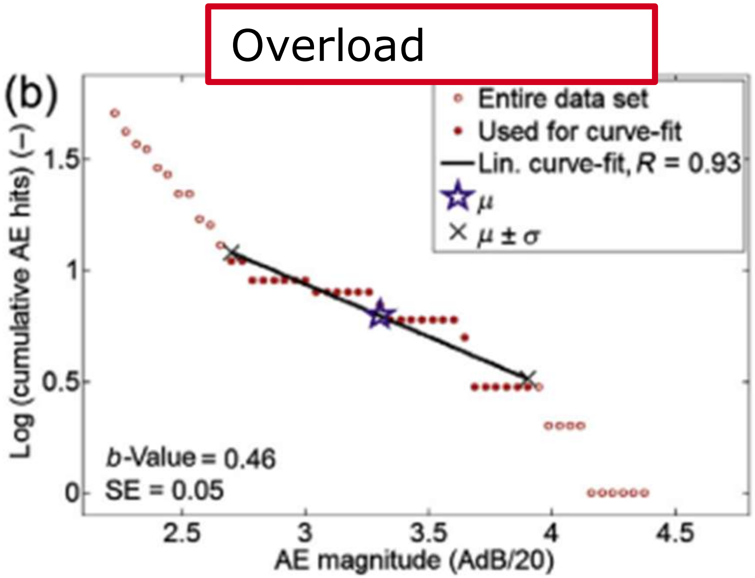
- Max hit amplitude $A(dB)$ is commonly used in b-value analysis for AE applications → amplitude-frequency distribution

$$A(dB) = 20 \cdot log_{10}\big(A(mV)\big) + 60\,dB - G(dB)$$

$A(mV)$, $G(dB)$ - the measured sensor output voltage and the signal gain provided by the preamplifiers, respectively

- Decrease in the b-value (below a value of approximately 1.0) may indicate that stresses are redistributed, and the cracking is more localized





Schumacher, T. (2008). Acoustic emission techniques applied to conventionally reinforced concrete bridge girders. Final Report SPR 633. Salem, OR: Oregon Department of Transportation (ODOT).

Parameter based AE – advantages and disadvantages

Pros:

- Less storage space
- Faster analysis
- Computational inexpensive
- Simplicity
- Not many sensors needed (even just one)
- Real-time analysis
- Cost-effective

Cons:

- Based on "idealized" assumptions
  - Point nature of the source
  - Linear behavior
- Some information is lost – impossible to make elaborated analysis
- Limited view of the physics
- Settings and sensor type affect the results
- Comparison between datasets is difficult

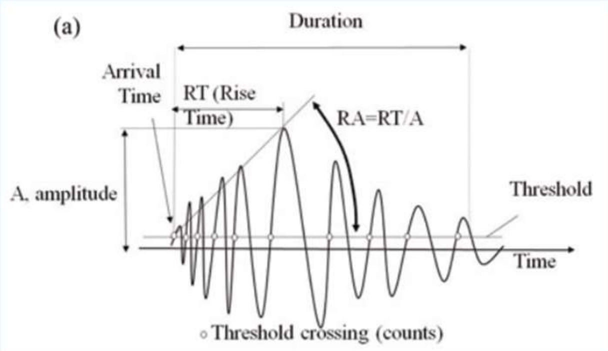
Key Takeaways
Parameter-based analysis

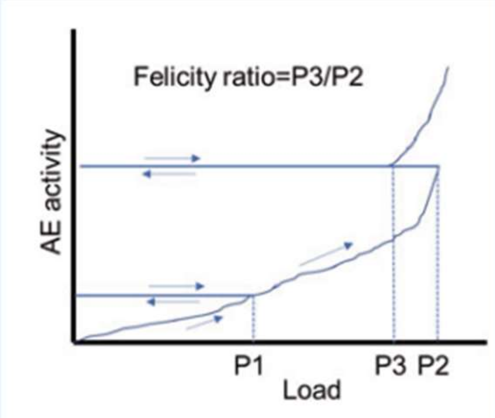
1. Parameter analysis is based on extraction of descriptors that contain most of the waveform information, without the need to store the whole number of points

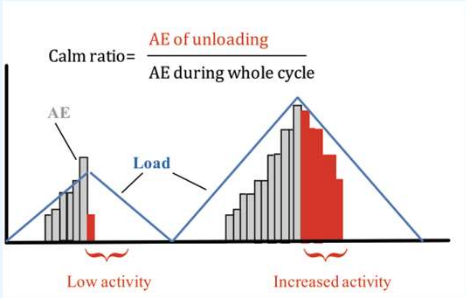
2. Kaiser effect - no new acoustic emissions will occur until the stress surpasses the previous highest level

3. Calm ratio is the total activity during unloading over the total activity during the whole cycle (loading and unloading)

4. A change in the b-value indicates a change in the concrete's cracking behavior







Signal-based approaches

Content

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Signal-based AE techniques

- Use entire transient waveform of AE event
- Contains more information -> improved interpretation of fracture processes
- Two signal-based approaches:
  - Waveform analysis
  - Quantitative analysis (originating from seismology)

- Important:
  - Type of sensor
  - Coupling
  - Recordings synchronization

Waveform analysis

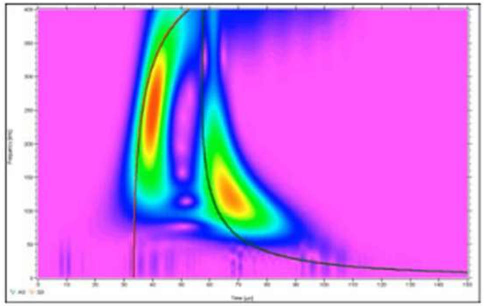
- Changes observable within recorded signals can be associated with changes in the structure being monitored
- Entire waveforms are analyzed and compared
- Suitable for application of machine learning and artificial intelligence techniques
- Does not rely on 3D localization
- In theory, can be performed with a single sensor
- Frequency analysis and waveform correlation

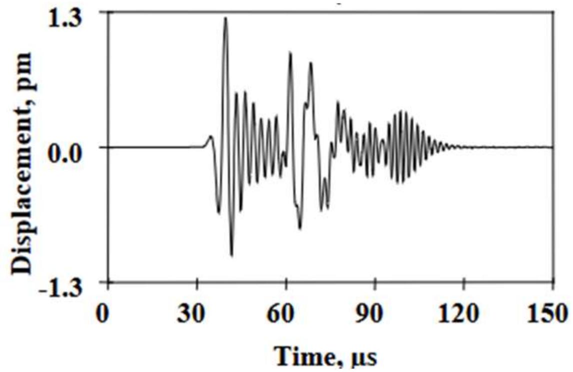
Waveform analysis

1. Waveform correlation

2. Time-frequency analysis, e.g.,:
   – wavelet transform
   – short-time Fourier transform
   – Hilbert-Huang transform

Hamstad, M., O'Gallagher, A., & Gary, J. (2012). A Wavelet Transform Applied to Acoustic Emission Signals: Part 2: Source Location. Journal of Acoustic Emission.





3. Machine Learning-based approaches, e.g.,:
   – Pattern recognition and clustering to discriminate different types of AE events
   – Matrix decomposition techniques (as singular value decomposition, independent component analysis, dictionary learning)
   – Neural networks for AE source localization

Quantitative analysis

- Goal: to describe the nature of each AE source as accurately as possible
- Requires a network of high-fidelity sensors and a sophisticated and time-consuming analysis
- Mostly used in the laboratory – significant requirements on equipment, computation, and interpretation
- Examples:
  - **Source localization**
  - Source inversion techniques:
    - First motion technique
    - **Moment tensor inversion (MTI)**

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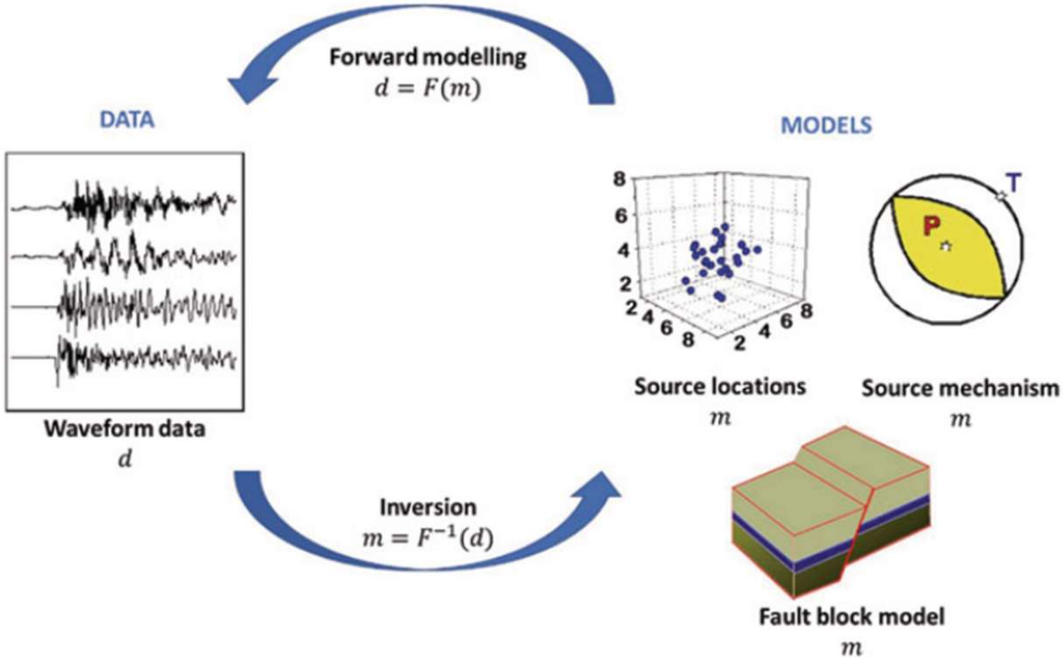
Quantitative analysis

Relies on inversion methods

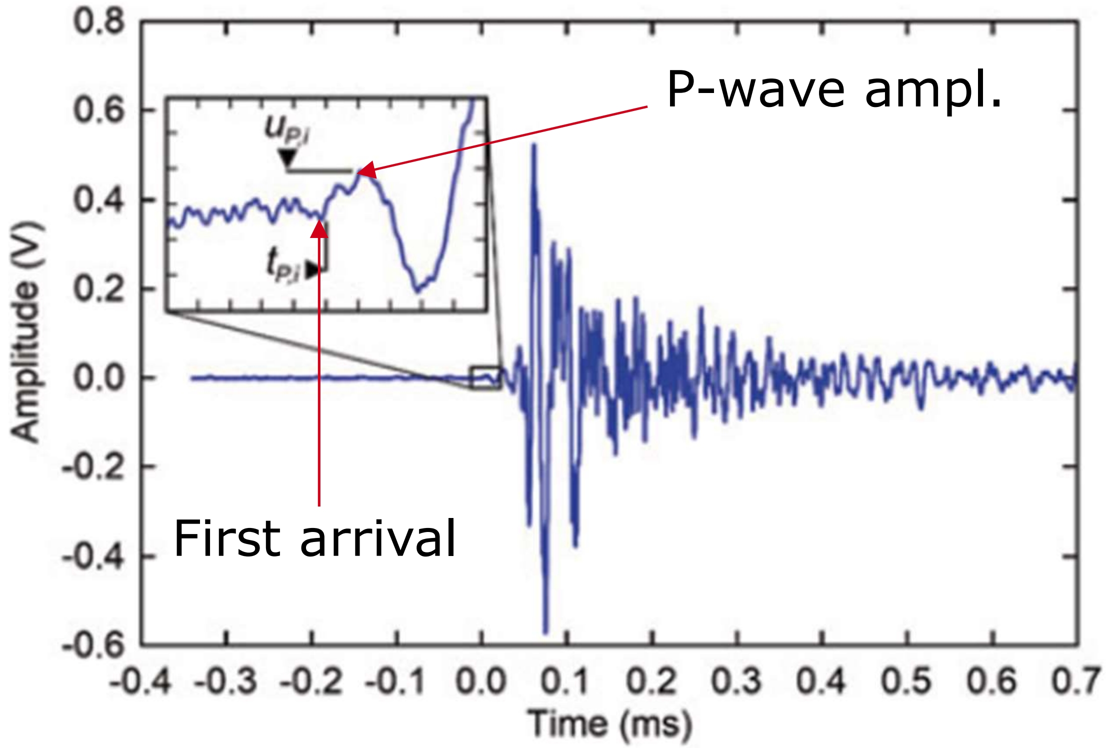
$$d = F(m) \quad \rightarrow \quad m = F^{-1}(d)$$

Where:
d - numerical modeling data
m - set of model parameters
F - operator representing the governing equations relating the model and data



Grosse, C. U., Ohtsu, M., Aggelis, D. G., & Shiotani, T. (2021). *Acoustic Emission Testing Basics for Research-Applications in Engineering Second Edition*. http://www.springer.com/series/15088

Quantitative analysis – First arrival



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Akaike Information Criterion (AIC) (Akaike, 1974)

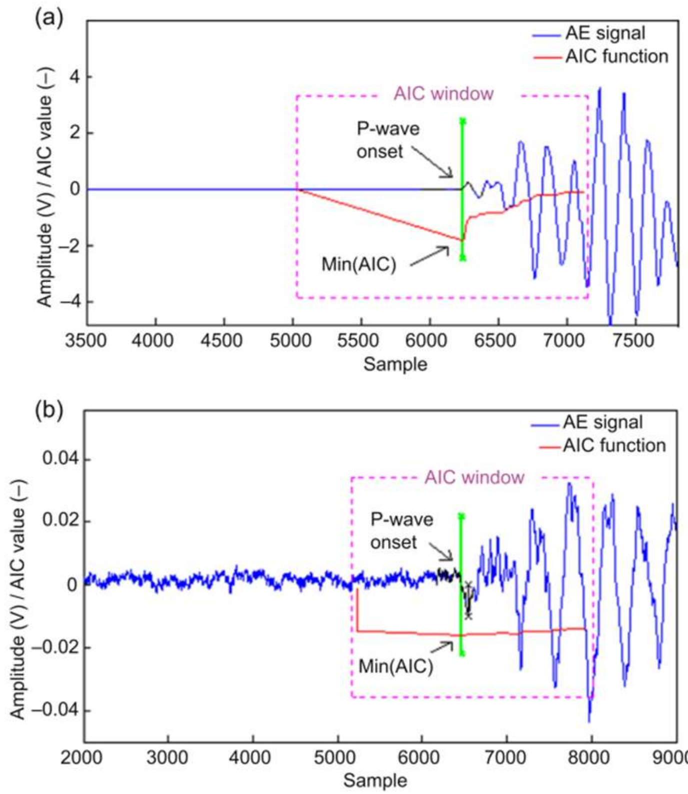
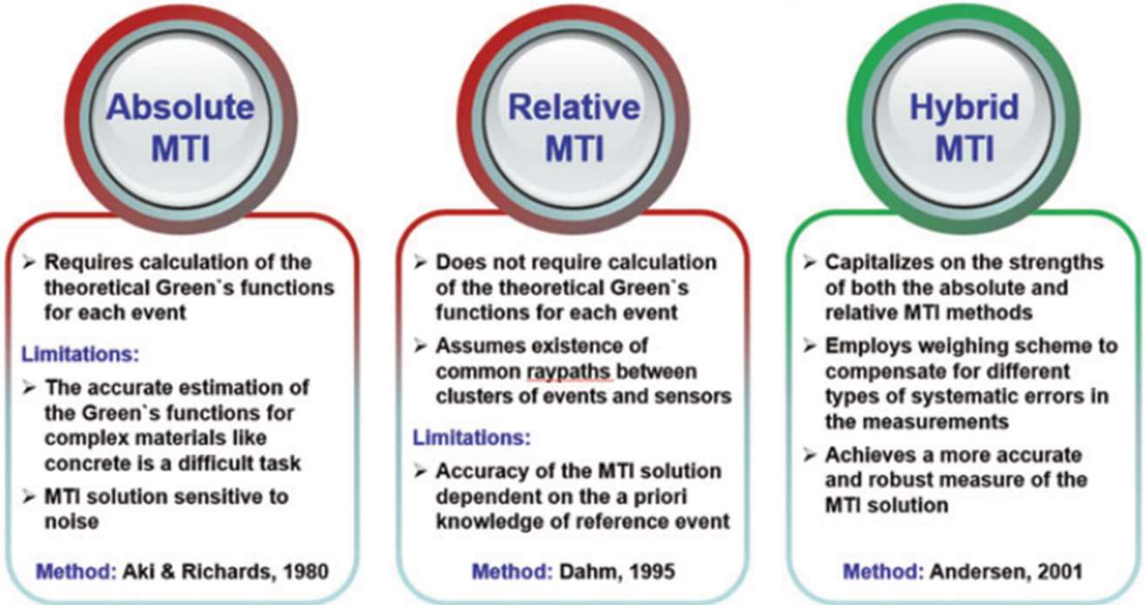


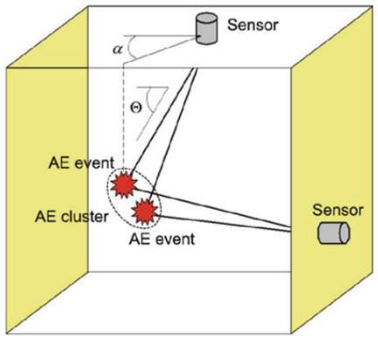
Figure 5.18 P-wave arrival estimation for signals with (a) high and (b) low signal-to-noise ratios.

Moment Tensor Inversion - overview

- Goal: to use observed values of (ground) displacement to infer properties of the source
- Methods differ greatly according to the available data and purpose of study
- “absolute”, “relative”, and “hybrid” methods
- Based on methods used to estimate the Green’s functions, which describe the wave propagation between a source and a receiver (sensor)



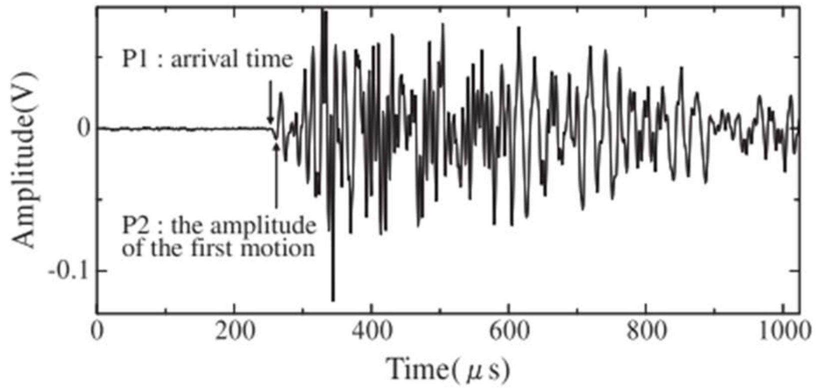
Mhamdi L. (2015) Seismology-based approaches for the quantitative Acoustic emission monitoring of concrete Structures

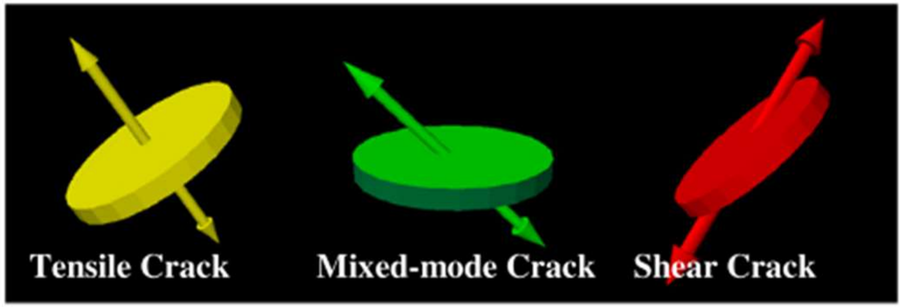


Grosse CU,Weiler B, Reinhardt HW (1997a) Relative moment tensor inversion applied to concrete fracture tests. J Acoust Emiss 14(3–4):64–87

Moment tensor inversion (MTI) in concrete AE

1. Simplified Green's functions for moment tensor analysis (SiGMA)
2. Concrete cracking is categorized as either tensile, shear, or mixed-mode
3. Absolute method
4. Uses only P-wave arrival time and amplitudes in time domain
5. At least six AE signals are needed to perform MTI to obtain stable and reliable results (with high noise level – more signals are needed)

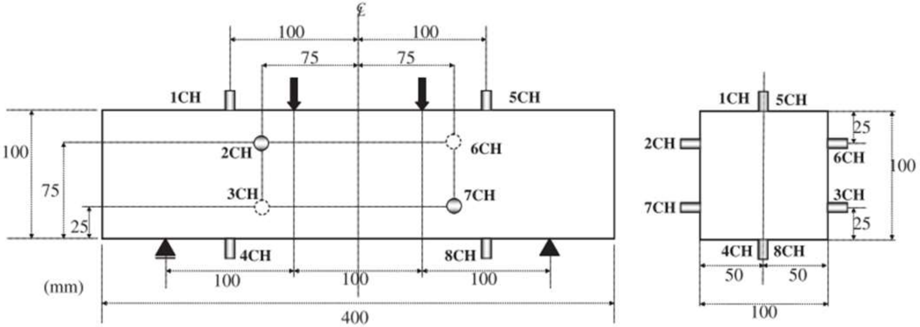


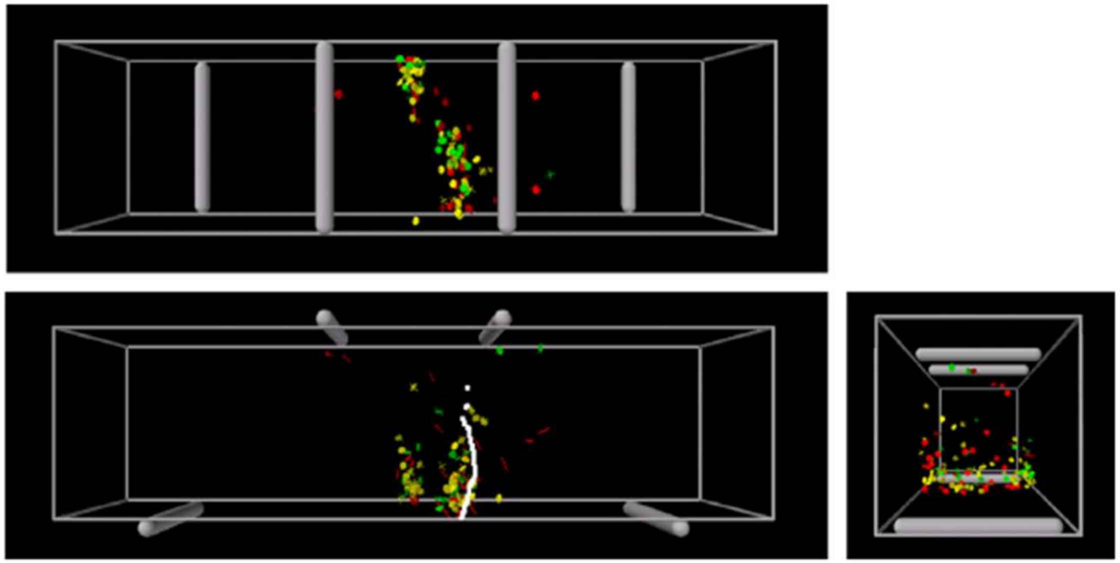


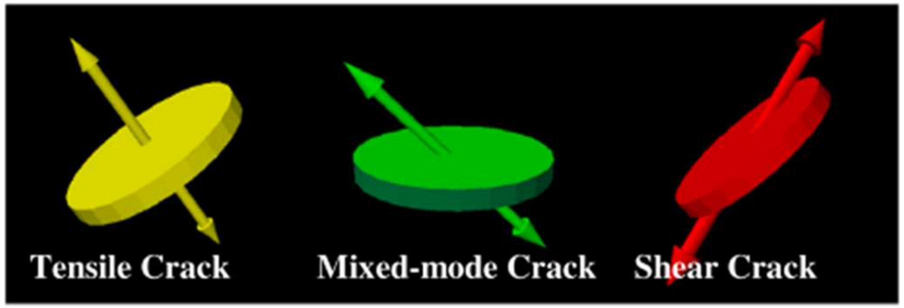
Ohno, K., & Ohtsu, M. (2010). Crack classification in concrete based on acoustic emission. *Construction and Building Materials*, *24*(12), 2339–2346.

Moment tensor inversion (MTI) in concrete AE example

SiGMA analysis in four-point bending test







Ohno, K., & Ohtsu, M. (2010). Crack classification in concrete based on acoustic emission. *Construction and Building Materials*, *24*(12), 2339–2346.

So which one is better??

Parameter-based

- Faster, computationally cheaper
- Less data
- Good for statistical analysis
- No signal stored?

Signal-based

- Require more sensors
- Big data problem
- Time consuming
- More available due to the technology development

Different application!

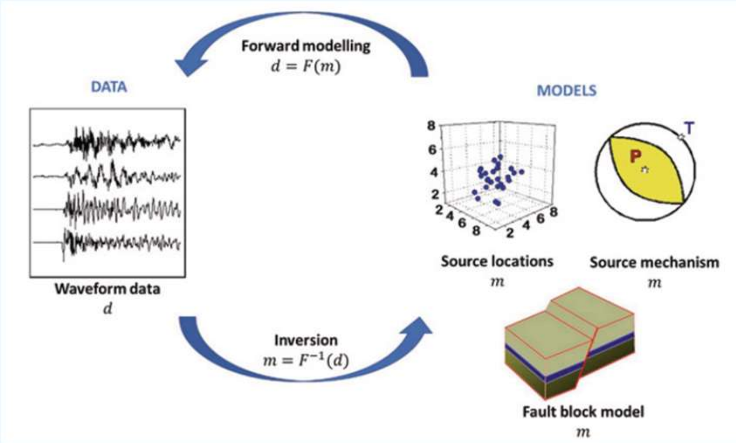
Key Takeaways
Signal-based analysis

1. Signal-based AE techniques Use entire transient waveform of AE event

2. Two signal-based approaches:
    - Waveform analysis
    - Quantitative analysis (source location and Moment Tensor Inversion MTI)

3. Important:
    - Type of sensor
    - Coupling
    - Recordings synchronization

4. In concrete, cracking is categorized as either tensile, shear, or mixed-mode



Source localization

Content

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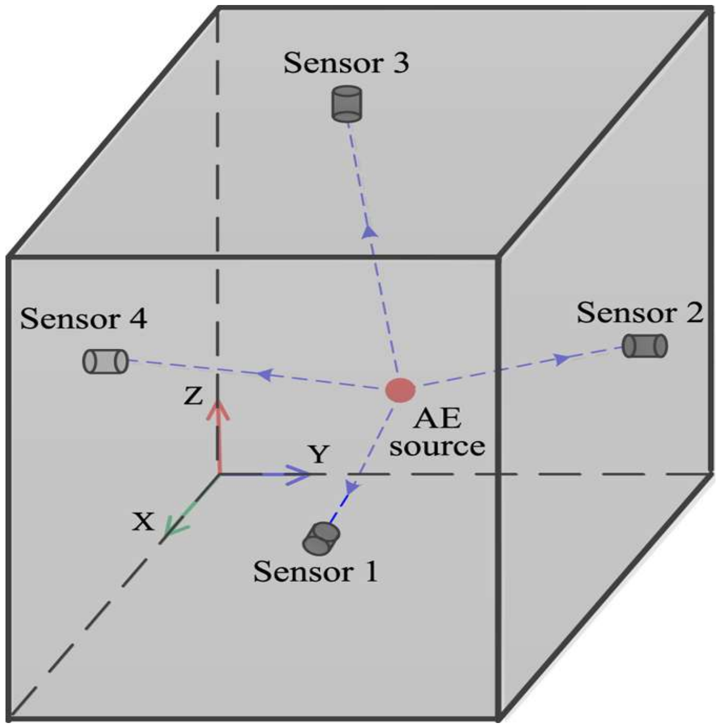
Source location techniques

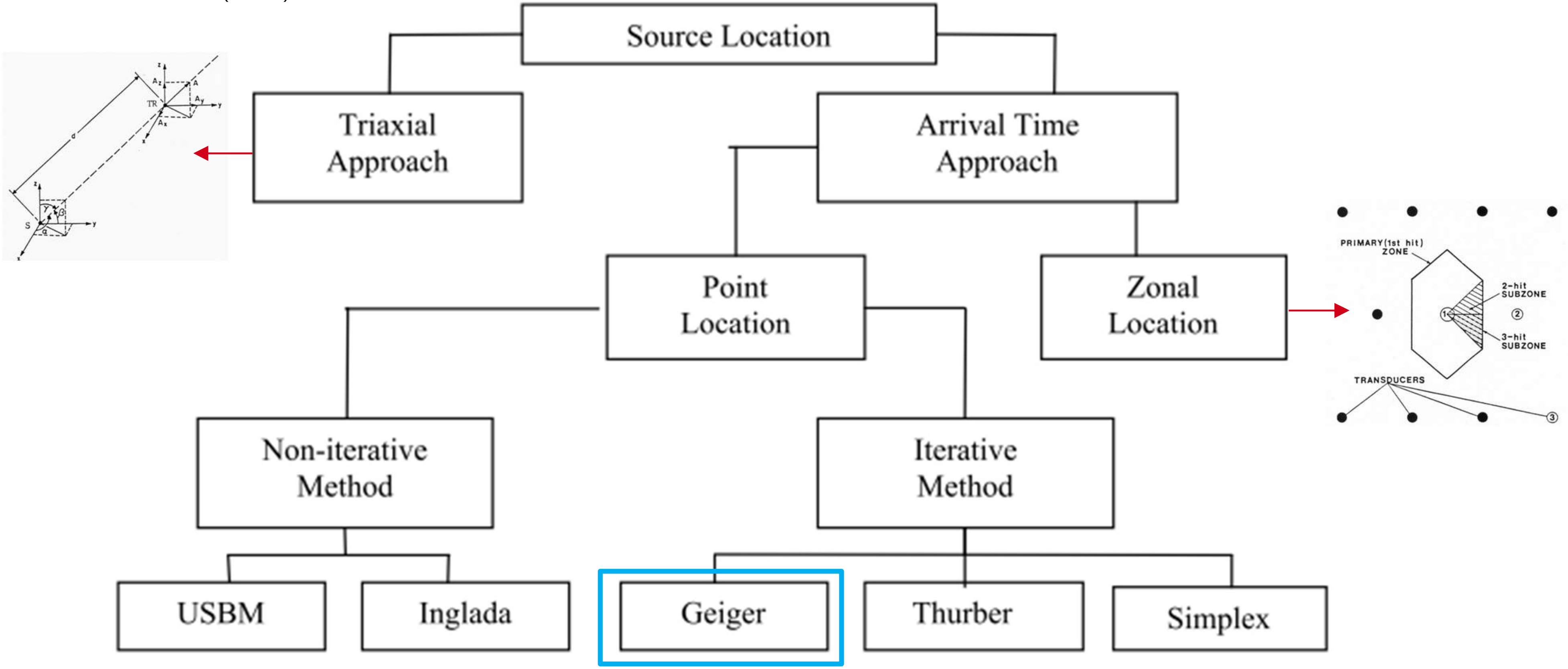
- Goal: to associate an AE event, formed from a collection of AE signals that arrive within a certain time window, with a physical cause
- Seismology-based localization techniques can be applied with minor modifications
- Inverse problem
- Crucial: accurate onset time determination



hou ZL, Zhou J, Dong LJ, et al. Experimental study on the location of an acoustic emission source considering refraction in different media. Scientific Reports. 2017 Aug;7(1):7472.

Classification of AE source location methods

Ge, M. (2003). ANALYSIS OF SOURCE LOCATION ALGORITHMS Part I: Overview and non-iterative methods. In *J. Acoustic Emission* (Vol. 21).



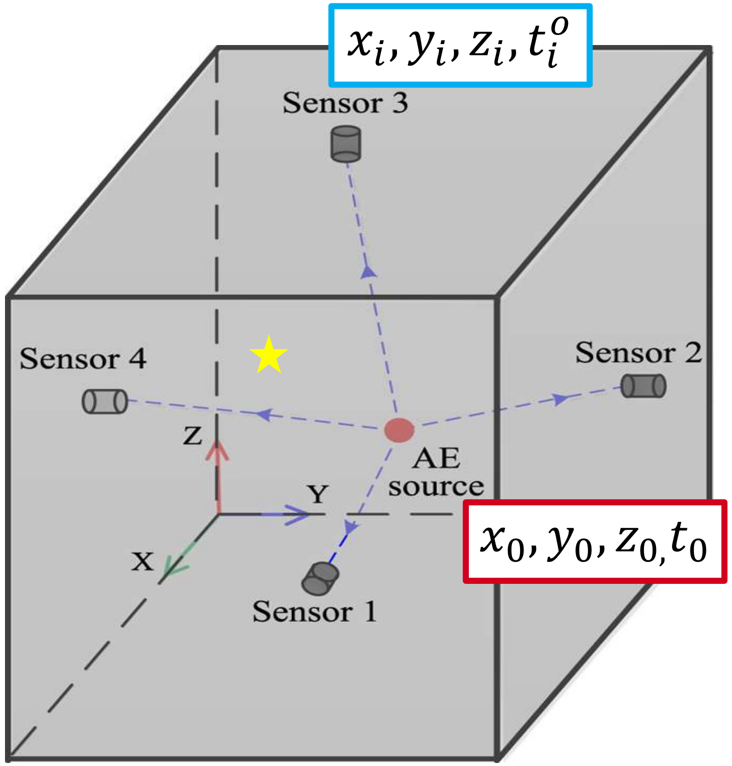
Geiger’s method - principle

Goal: to minimize the residuals (*r*) between calculated *c* and observed *o* arrival time at each sensor

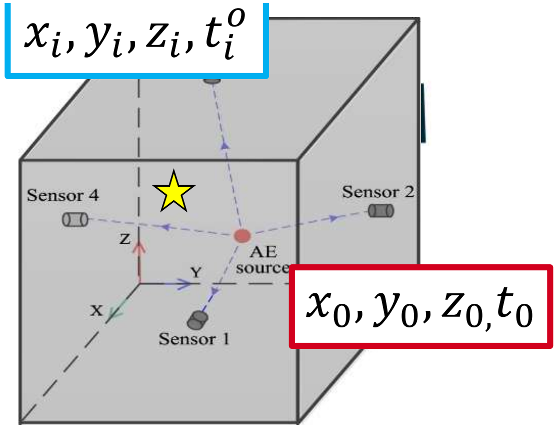
$$t_c^i = t(x_i, y_i, z_i, x_0, y_0, z_0) + t_0$$

$$r_i = t_i^0 - t_i^c \rightarrow min$$

Geiger's method relies on:
1. Sensors: x_i, y_i, z_i detect the waves at different locations.
2. Arrival Times: t_i^0 the time at which each sensor detects the wave.
3. Wave Speed: v the speed at which the wave travels through the material.



Geiger's method – how it works?



1. Initial Guess: ☆
   Start with an initial guess for the event's location and time. This could be a random point or based on rough calculations.

2. Calculate Predicted Times:
   Using the guessed location, calculate how long it would take the wave to reach each sensor, assuming you know the wave speed.

3. Compare Predicted and Actual Times:
   For each sensor, compare the predicted arrival time to the actual arrival time detected by the sensor.

4. Adjust the Guess:
   Adjust the guessed location and time to minimize the difference (errors) between the predicted and actual times.

5. Iterate:
   Repeat the calculation and adjustment process until the errors are as small as possible.

$$D_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2}$$

$$i = 1, 2, 3, \dots, n$$

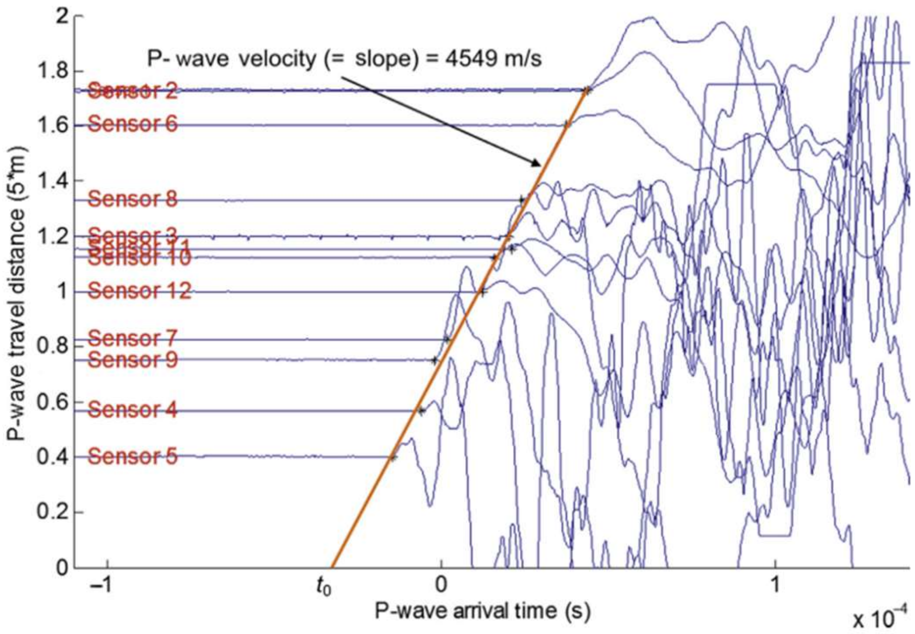
$$t_i = \frac{1}{v} D_i + t$$

$$\Delta t_i = t_{i,obs} - t_{i,calc}$$

$$r_i = t_i^0 - t_i^c \rightarrow min$$

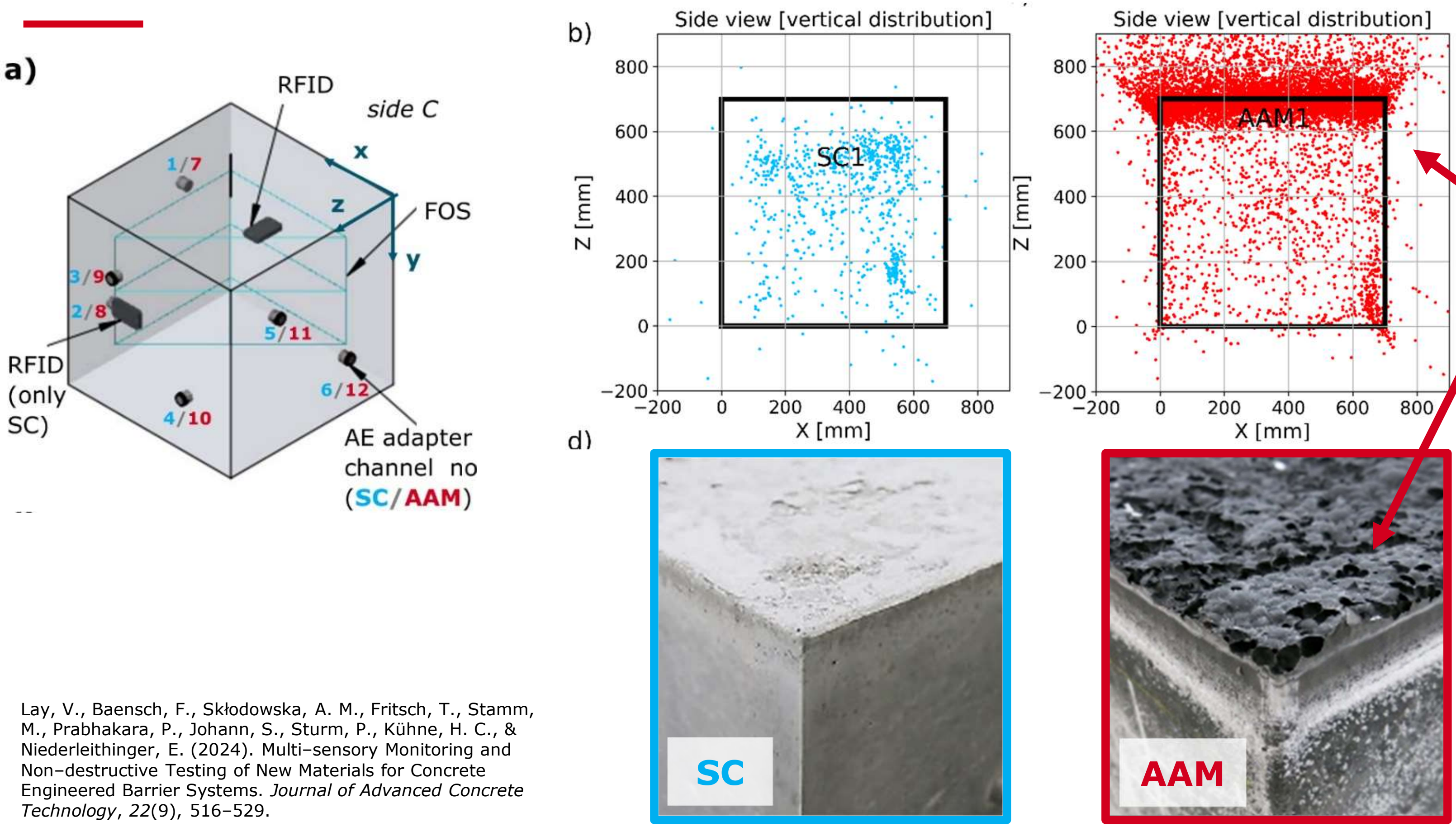
Source of uncertainties

1. Errors in the picking of the arrival times
2. P-wave velocity
3. Travel paths in cracked heterogeneous and anisotropic materials
4. Number of sensors
5. Signal-to-noise ratio
6. The equations used generally assume that the material is homogeneous and isotropic, and that the AE source can be modeled as a point source.



Linzer, Mhamdi, & Schumacher, (2015). Application of a moment tensor inversion code developed for mining-induced seismicity to fracture monitoring of civil engineering materials. Journal of Applied Geophysics, 112, 256e267.

Geiger’s method - example



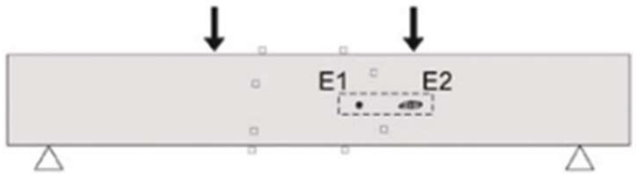
Low localization accuracy due to surface effects

slow reaction kinetics, air bubbles get caught in the top layer of the AAM

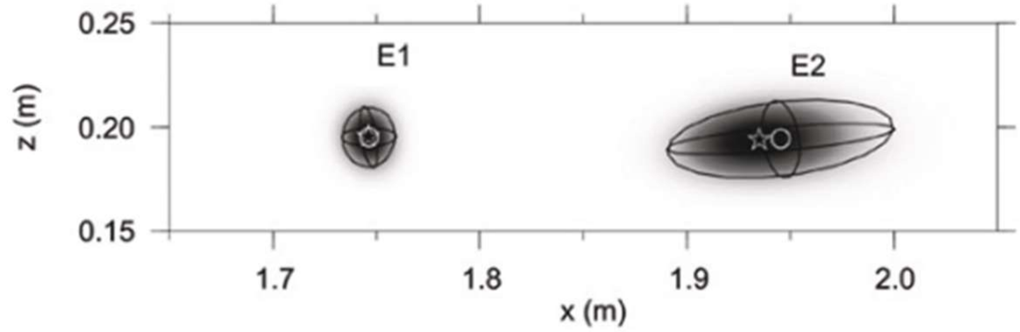
Lay, V., Baensch, F., Skłodowska, A. M., Fritsch, T., Stamm, M., Prabhakara, P., Johann, S., Sturm, P., Kühne, H. C., & Niederleithinger, E. (2024). Multi–sensory Monitoring and Non–destructive Testing of New Materials for Concrete Engineered Barrier Systems. *Journal of Advanced Concrete Technology*, *22*(9), 516–529.

Other methods

1. Neural networks
2. Probabilistic approaches (e.g. *NonLinLoc*, Lomax et al. 2000)
3. Direct algebraic methods from GPS technology
4. Time Reversal Methods
5. …

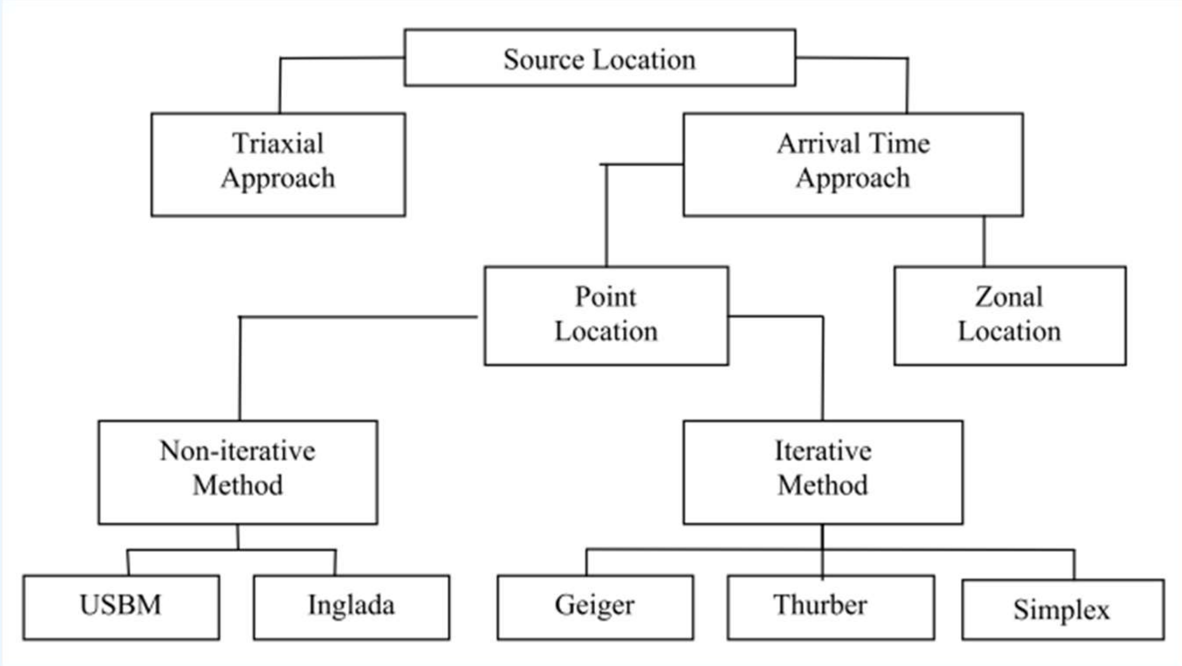


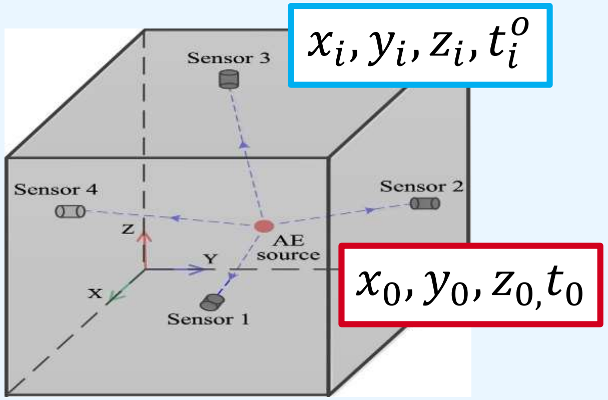
Nonlinear localization results (using NonLinLoc)



Key Takeaways
Source localization

1. Proper source localization is necessary for quantitative methods in AE
2. Most AE localization methods were developed in the framework of earthquake seismology
3. Many sources of uncertainties (first arrival picking, velocity estimation, travel paths…)





Summary, conclusions, outlook

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To sum-up: advantages/disadvantages

BAM

Why AE is great?

+ Passive and non-invasive
+ Damage process can be observed during the entire load history
+ Detecting new cracks and propagation of old ones
+ Can detect cracks at a very early stage
+ Fracture mode characterization
+ Source localization
+ Very sensitive
+ Relative position sensor-defect not critical

But...

- Method only capable to detect new cracks, progression of existing cracks or friction process
- Not perfectly reproducible
- Big datasets
- Very sensitive to noise and signal attenuation
- Low energy released
- Preferably combined with other methods

New Developments in AE techniques

1. "Big data" science – machine learning and artificial intelligence necessary for progress
2. ML and AI can be applied to localization or discrimination between AE and noise or the determination of different types of fractures
3. AE in structural health monitoring (SHM) – to evaluate the aging of a structure or component and to detect defects at an early stage
4. Digital twin technologies – for structures as bridges, tunnels, machines, wind turbines

Thanks a lot for attention!

Any questions?

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