Elastic Wave Techniques for Characterization of Advanced Materials and Structures

Dimitrios G. Aggelis
Vrije Universiteit Brussel

29/6/2022

Workshop 3: Design and maintenance of Wind Turbines

27/6/2022-1/7/2022

VUB MeMC MECHANICS OF MATERIALS & CONSTRUCTIONS

DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

KIT Karlsruhe Institute of Technology

UNIVERSITY OF PATRAS

VRIJE UNIVERSITEIT BRUSSEL

Vrije Universiteit Brussel = “Free” University of Brussels (Flemish=Nederlands)

“Vrije” (free) is NOT connected to money

But in thinking and ideas

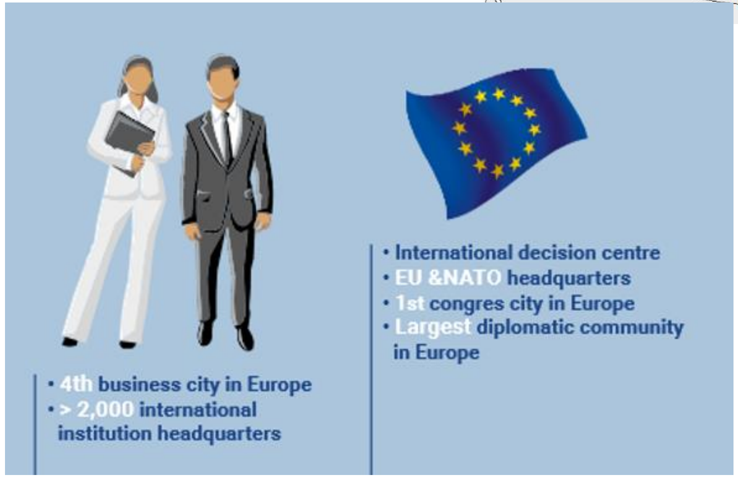
This Photo by Unknown Author is licensed under CC BY-NC-ND

Red thinker
(made by
Inorganic
Phosphate
Cement!
from MEMC)

Introduction to VUB

BRUSSELS, THE HEART OF EUROPE

- 1,2 million inhabitants
- Multicultural capital
  - 104 different languages
  - 33% inhabitants of foreign origin
- EU/NATO headquarters
- **Centre of Scientific Excellence**



Faculty of engineering

- Master programmes in English: 120 ECTS | two years
- All Flemish universities in Belgium, including the VUB, are subsidized by the Flemish government, which ... in relatively **low tuition fees for the bachelors, (initial) masters and PhD programmes.**
- Tuition fees for non-EEA students start from 962EUR/year
  Higher fees of approx. 3250EUR/year apply for our other MSc programmes.

Architectural Engineering — VUB ULB

Chemical and Materials Engineering — VUB ULB

Civil Engineering — VUB ULB

Electromechanical Engineering — VUB ULB

Electrical Engineering — VUB ULB

Biomedical Engineering — VUB Ghent University

Photonics Engineering — VUB Ghent University

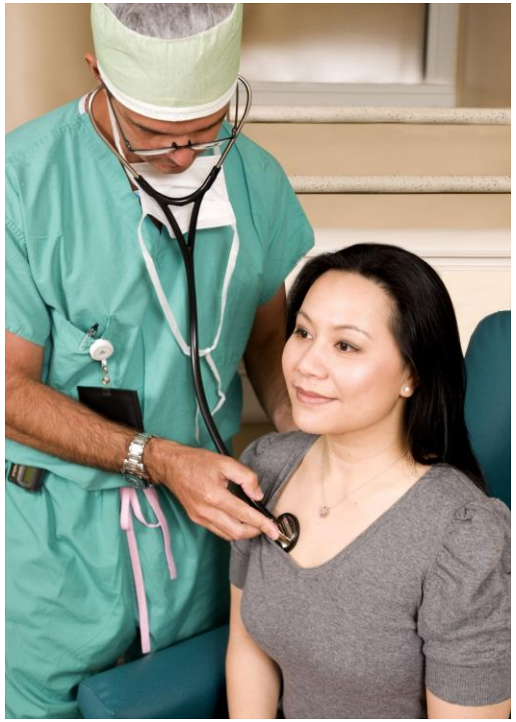
Sustainable Land Management — VUB Ghent University

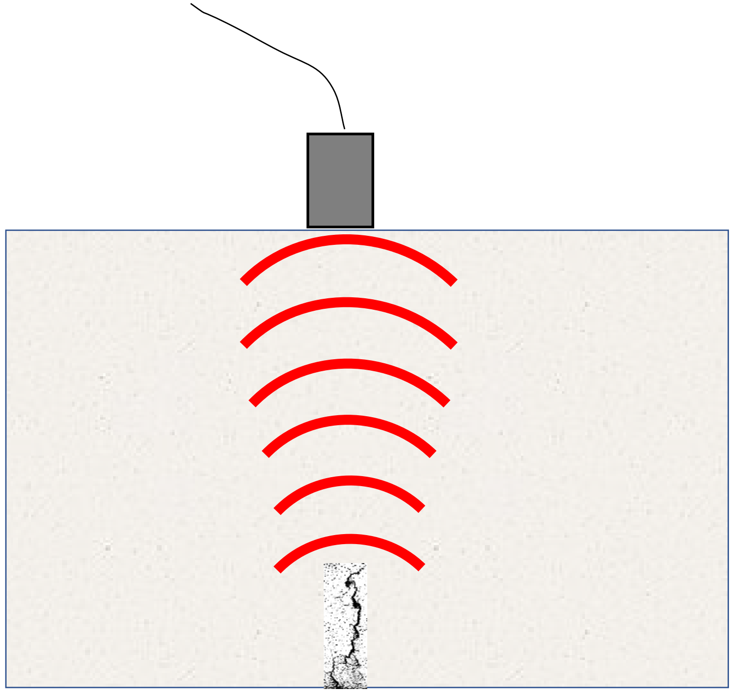
Water Resources Engineering — VUB KU Leuven

Applied Computer Sciences — VUB

Non-destructive Testing

Monitoring of material condition

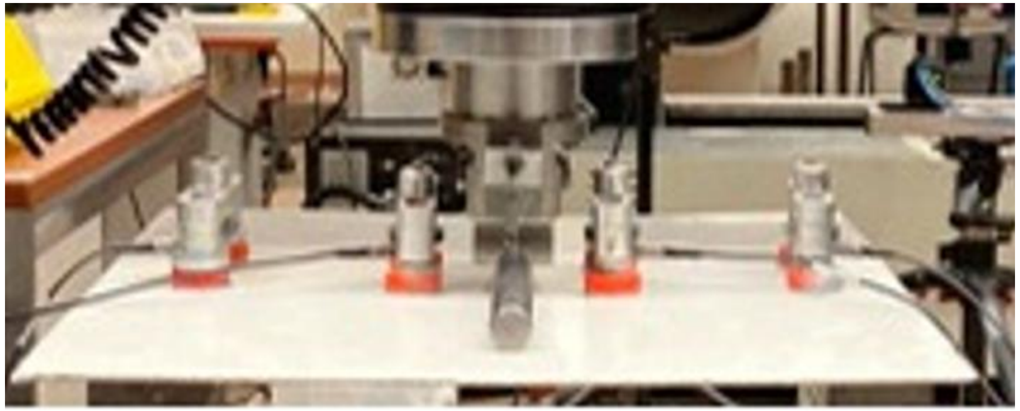


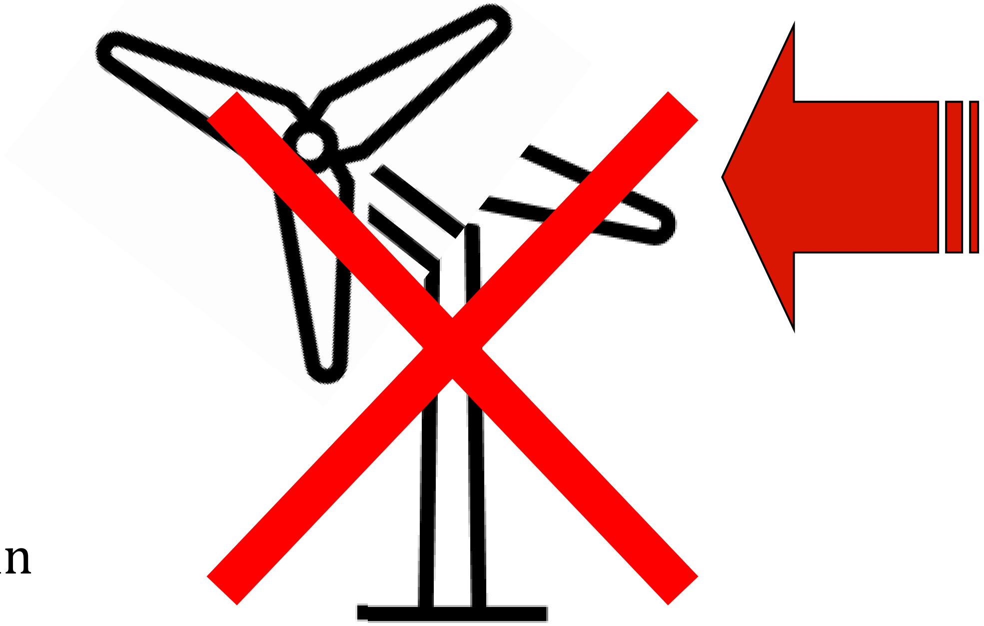


The most important information is the **strength** of the material.

The only way to measure this is by breaking the material in the corresponding mode (bending/compression/tension/fatigue).

This can be done in laboratory and in small samples.



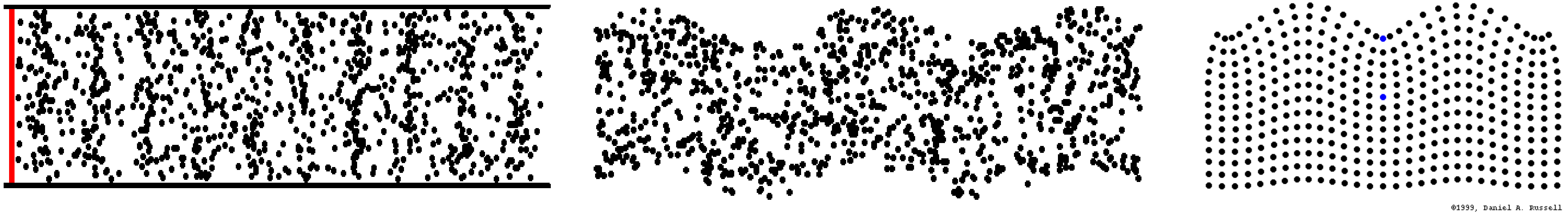


It is understandable that the evaluation of strength of materials in structures should be conducted in a **non-destructive way**!!

Elastic wave methods offer non-destructive nature for inspection

The most well-known application of ultrasound is in medicine

Why use elastic waves for inspection?



•Direct connection of velocity to the elastic properties:

Longitudinal

$$C_p = \sqrt{\frac{E\,(1-v)}{\rho(1+v)(1-2v)}}$$

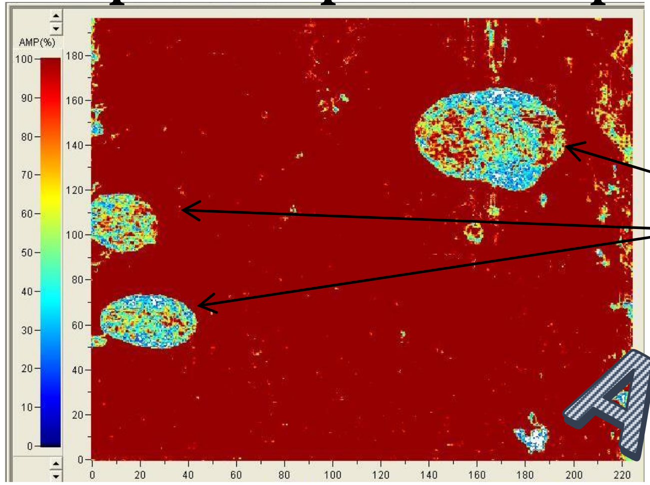
•Pulse velocity measurement exhibits reduced sensitivity on the conditions (coupling, distance, sensors)

•Numerous correlations between material quality, strength and wave velocity

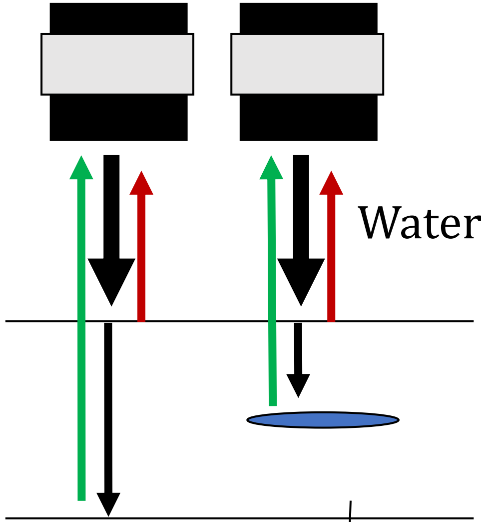
http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/Physics/wavepropagation.htm

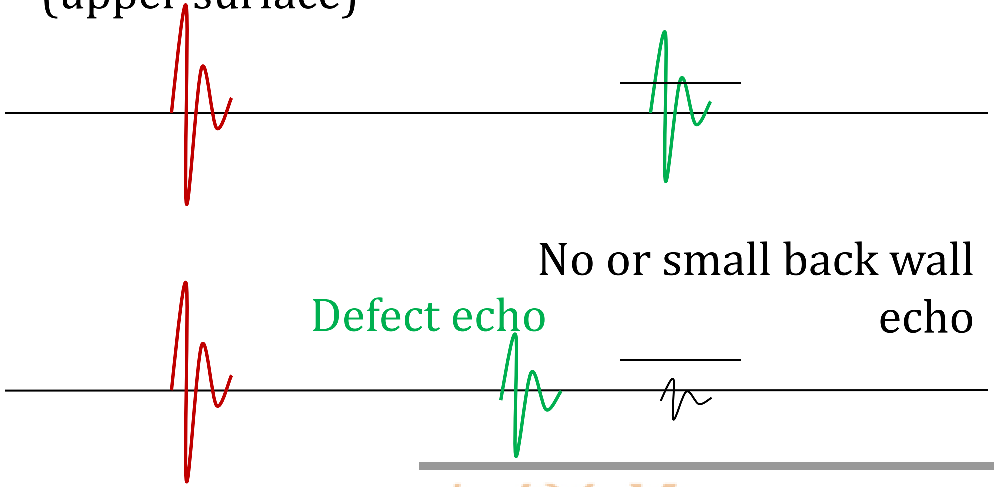
A common application is the "C-scan"

Example of a glass/epoxy composite plate inspected for voids.

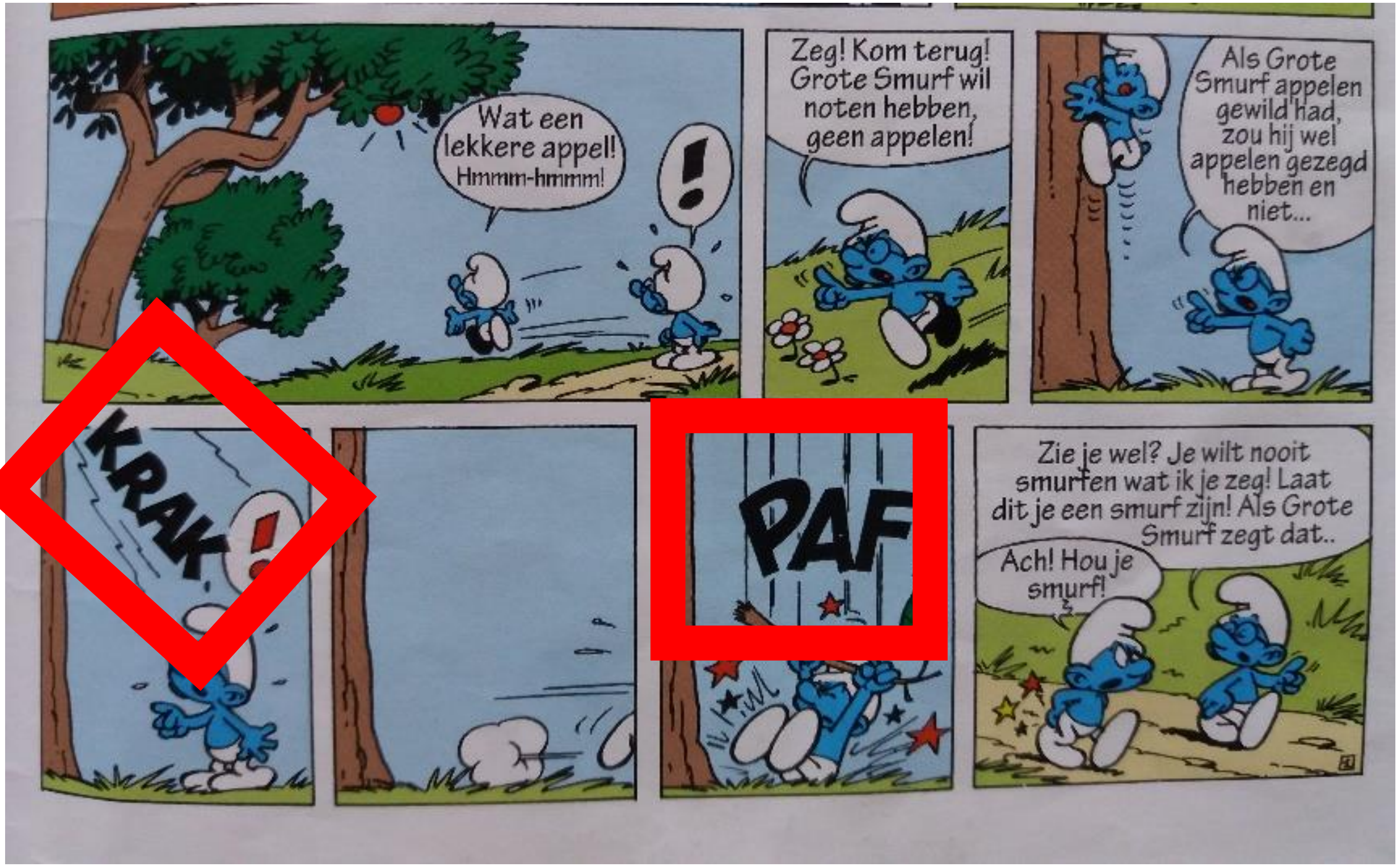


Active method





What is acoustic emission?



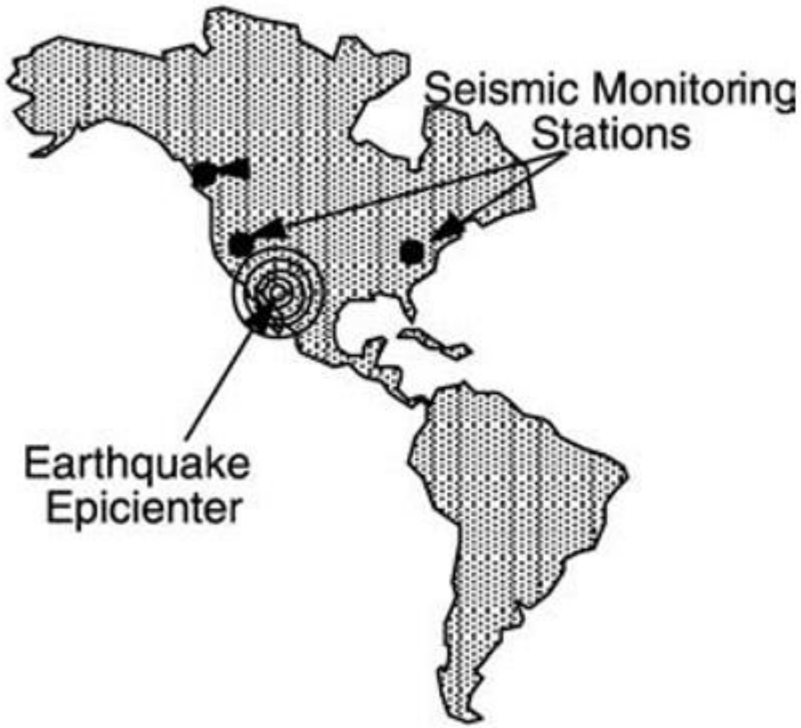
De vliegende smurf

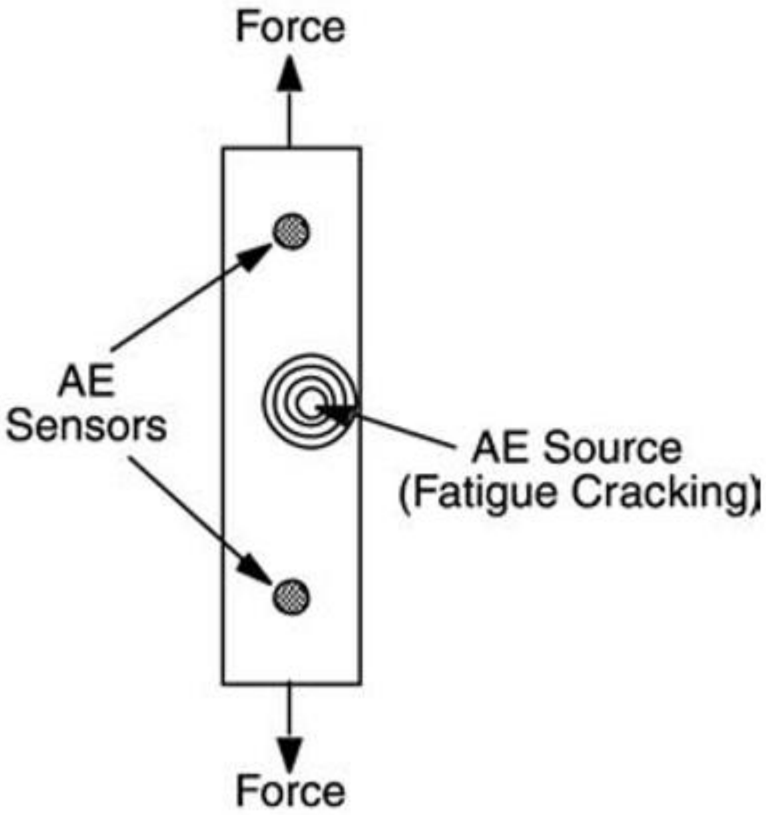
DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

KIT Karlsruhe Institute of Technology

UNIVERSITY OF PATRAS

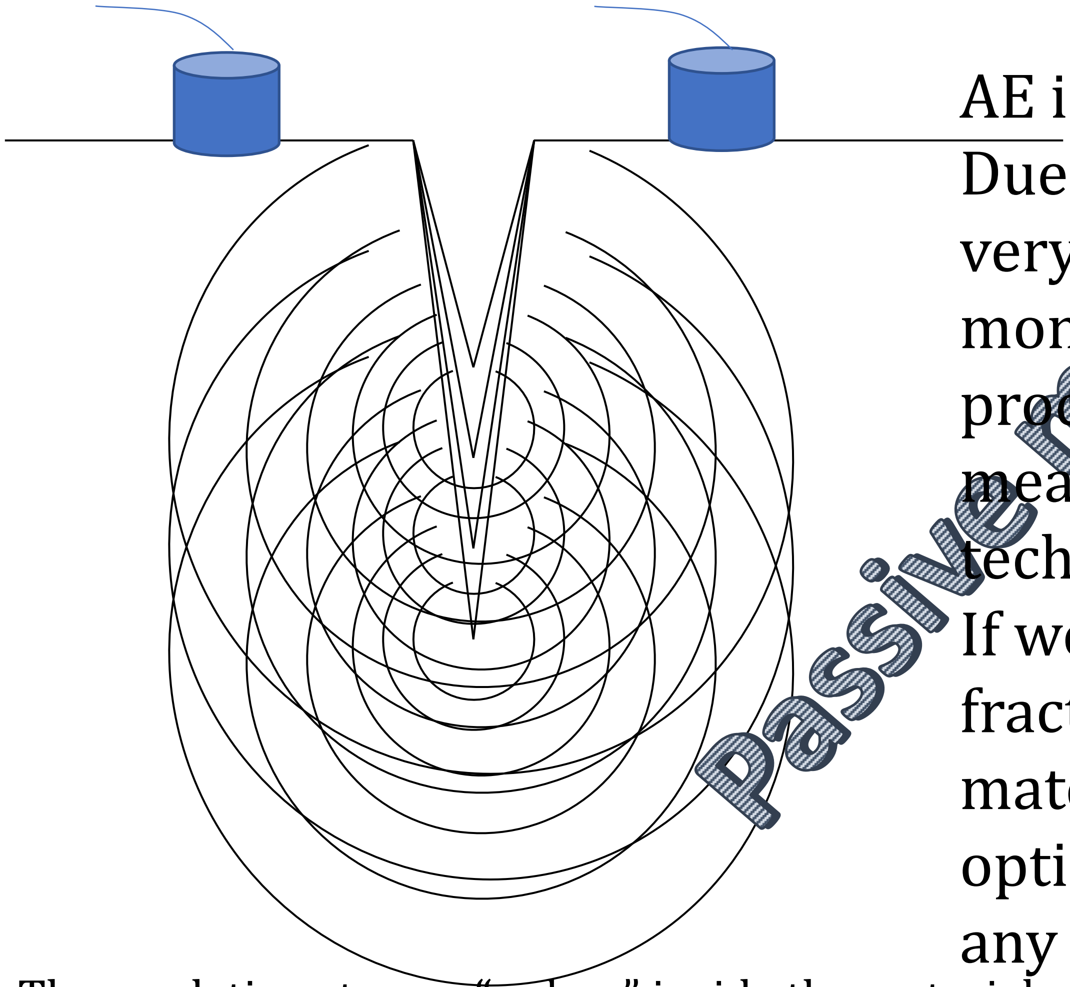
Similarity between seismic waves and acoustic emission





•Nondestructive evaluation, Theory, Techniques and Applications, P. J. Shull (ed.)

Any fracture incident emits transient waves which propagate to any direction like normal elastic waves



The crack tip acts as a "pulser" inside the material

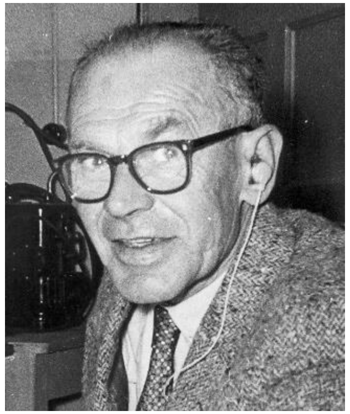
AE is NDT!

Due to its sensitivity AE is very much used in monitoring fracture processes. This does not mean that AE as a technology is destructive! If we wish to study the fracture behavior of materials AE is a good option without causing any intervention.

Passive method

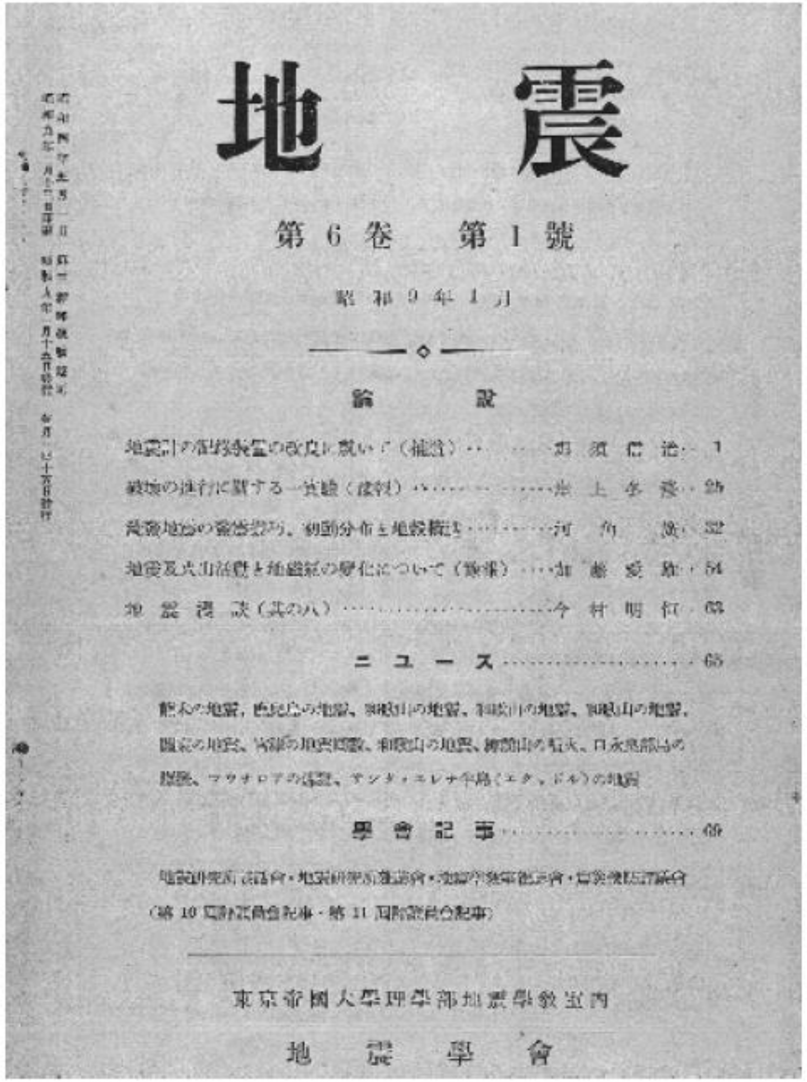
Brief History of AE

- Acoustic emission is as old as fracture (e.g. cracking of wood).
- As a means of quality control its origin is difficult to know.
- Ancient pot manufacturers listened to a cracking noise emitted by clay pots that had been cooled off too quickly. Pots that have given this noise would fail prematurely.
- The father of contemporary AE is considered J. Kaiser who observed "the absence of detectable acoustic emission at a fixed sensitivity level, until previously applied stress levels are exceeded". (J. Kaiser. PhD Thesis, Technische Hochschule Munich; 1950)
- The first published study is the one of Kishinoue in the meeting of the Earthquake Research Institute in the Imperial University of Tokyo 1933. It consisted of a phonograph pick-up with a steel needle inserted into the tension side of wooden beam under bending. (An Experiment on the Progression of Fracture, A Preliminary Report, Jishin, 6:25-31) 1934(in Japanese).



Joseph Kaiser

Grosse C. U., Ohtsu M., 2008. Acoustic Emission Testing, Springer, Heidelberg.



地震

第 6 巻 第 1 號

昭和 9 年 1 月

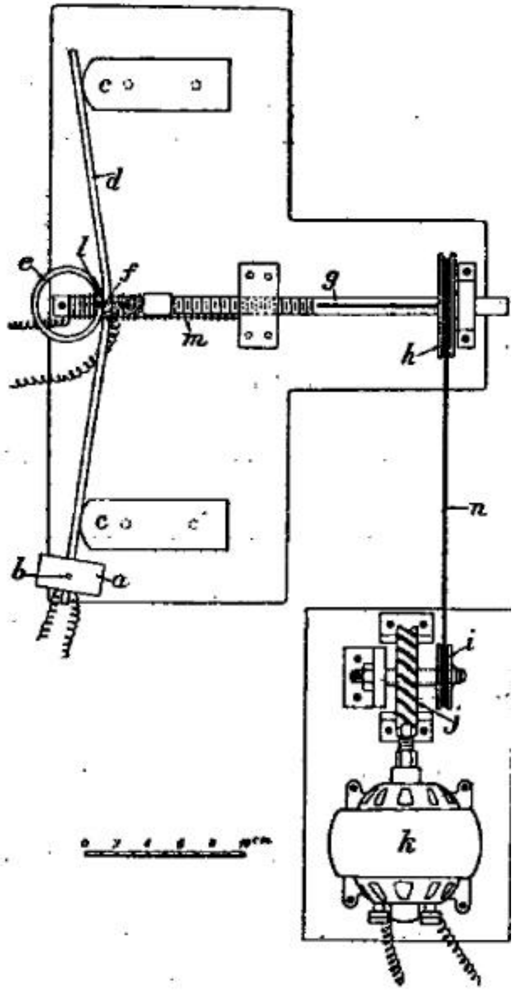
論 説

ニ ユ ー ス

學 會 記 事

東京帝國大學理學部地震學教室內

地 震 學 會

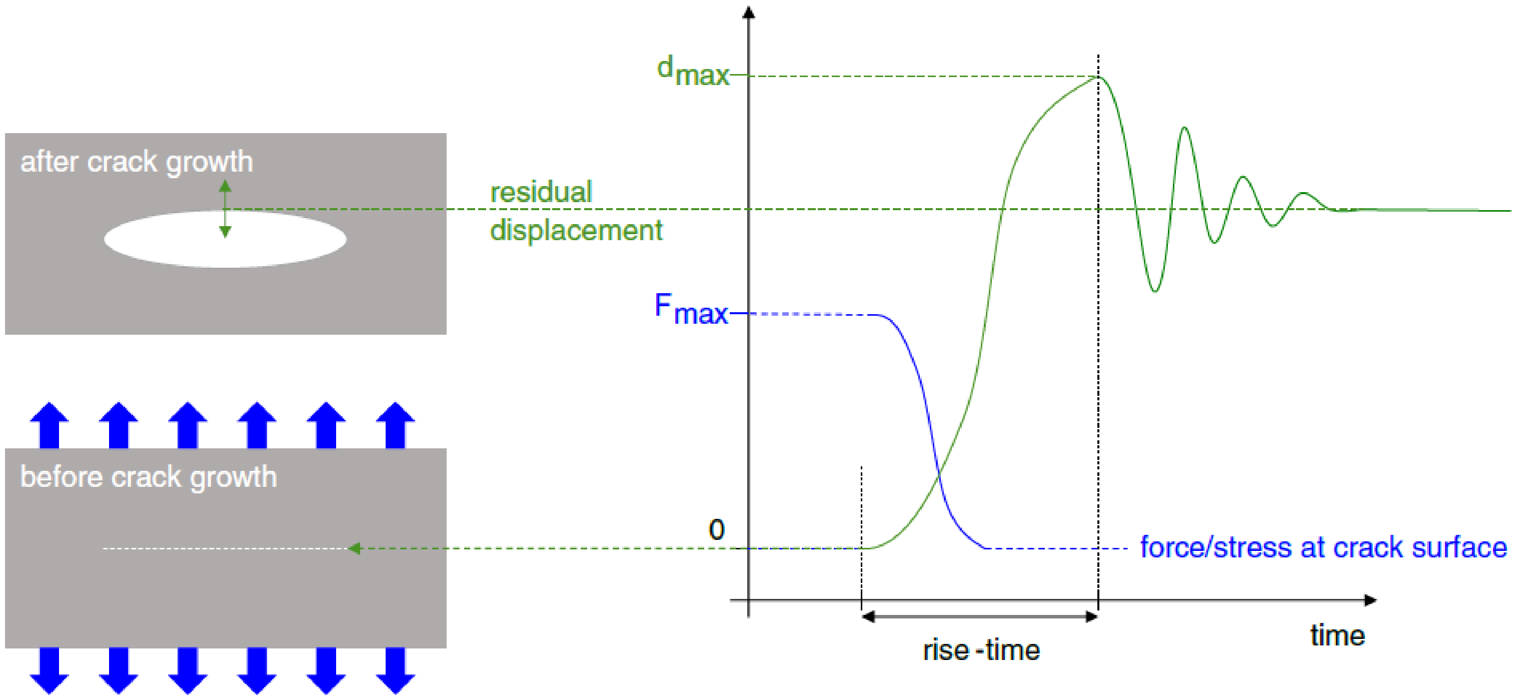


第 4 圖

Top page of "Jisin" report in 1933. Experimental apparatus by Kishinoue.

Grosse C. U., Ohtsu M., 2008. Acoustic Emission Testing, Springer, Heidelberg.

Source of AE is an “Event”



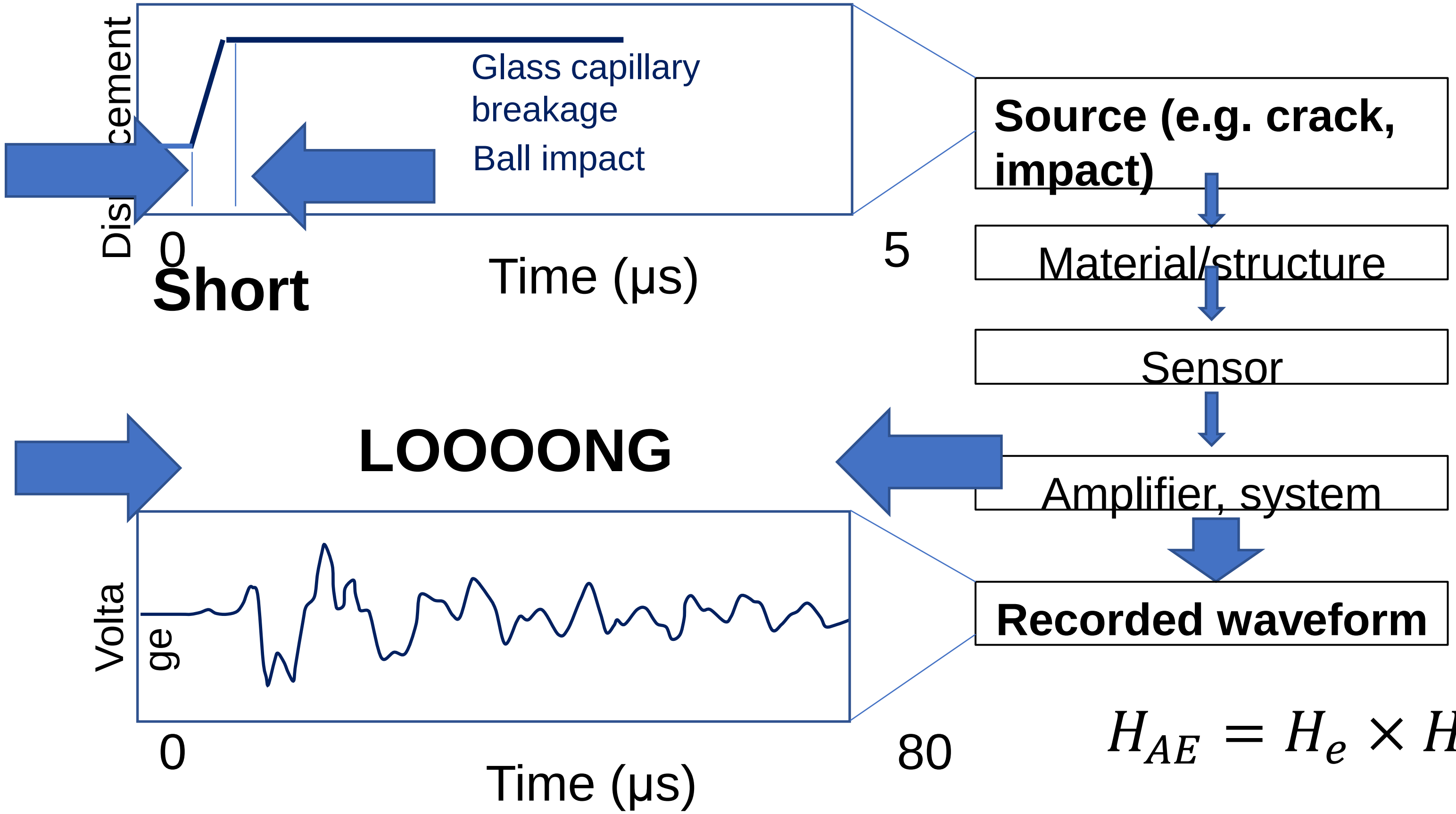
Schematic of crack formation including common definition of rise-time and exaggerated crack-wall oscillation.

Markus Sause, Marvin Hamstad (2018) 7.14 Acoustic Emission Analysis. In: Beaumont, P.W.R. and Zweben, C.H. (eds.), Comprehensive Composite Materials II. vol. 7, pp. 291–326. Oxford: Academic Press.

Opening of the crack is the **primary contribution**

Vibration of the crack sides due to inertia before they arrive to the final position. **(Secondary contribution)**

From the source to receiver



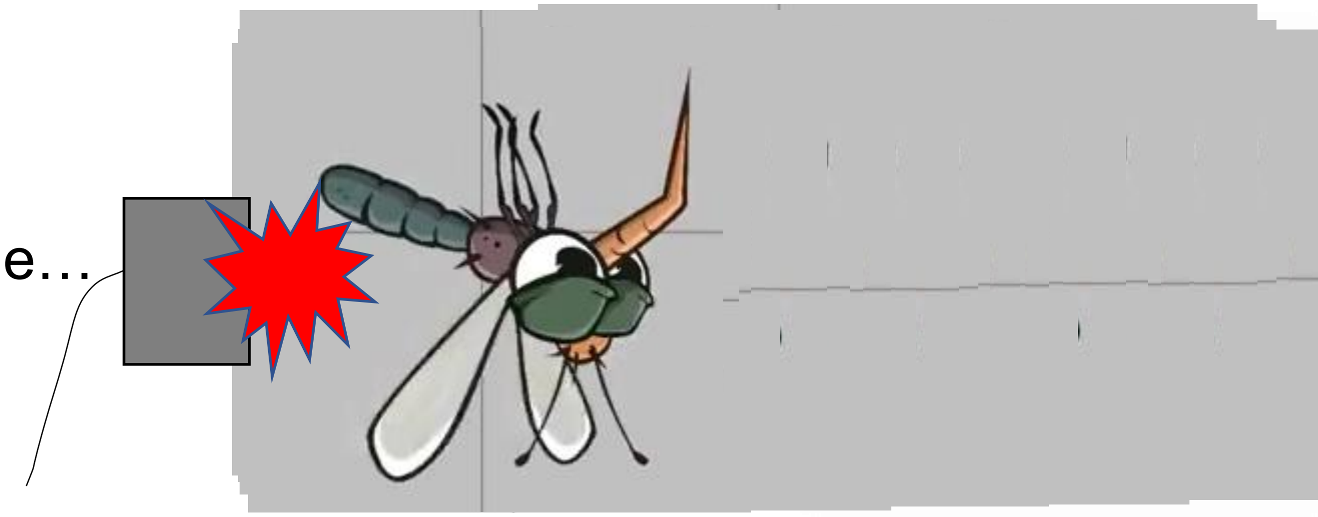
$$H_{AE} = H_e \times H_m \times H_s \times H_a$$

The final waveform is the "convolution" of the individual transfer functions (or the multiplication product of their FFTs)

Key features of Acoustic Emission

High Sensitivity (What?)

We can detect movement of less than nm scale…



Mosquito: mass 2.5 mg

Speed: 0.01 m/s

Kinetic Energy: 125 nanoJoule (10^{-9}J),

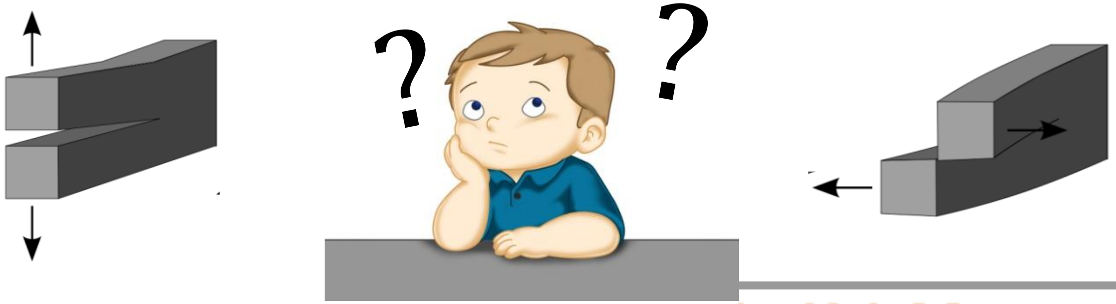
AE sensitivity (10^{-18}J)

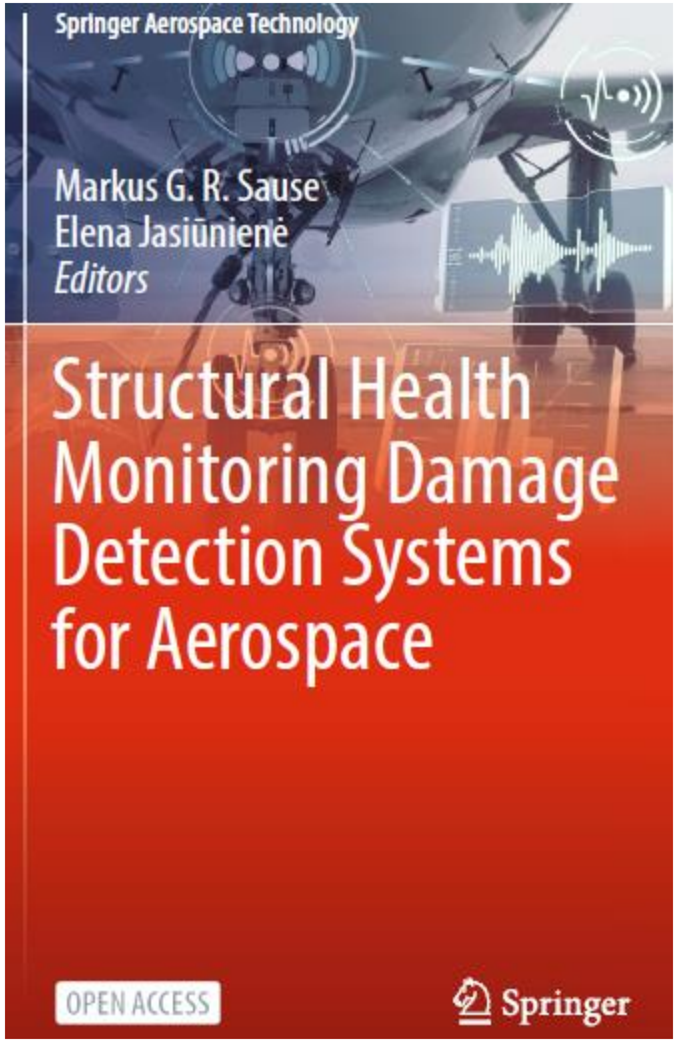
Key features of Acoustic Emission

Damage localization (where?)
Evaluate the position of ongoing damage within mm even if it is not visible

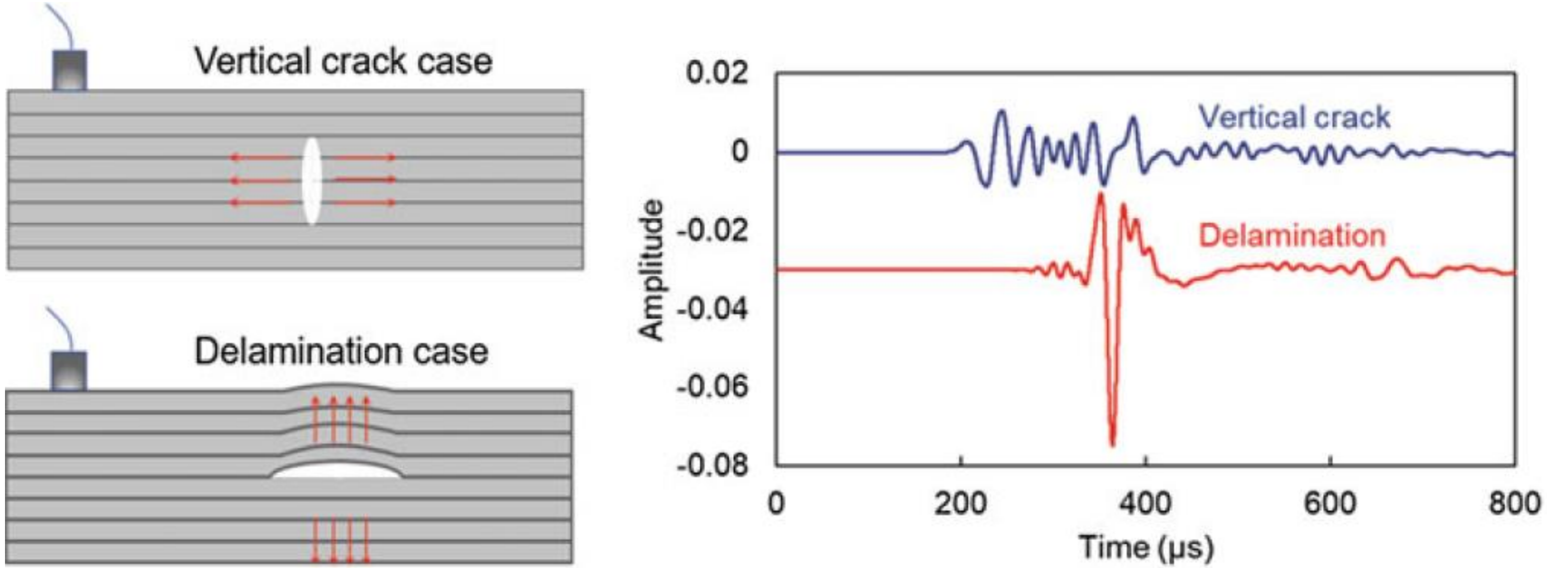
Smurfin

Fracture mode determination (how?)
Helps to characterize the type of damage



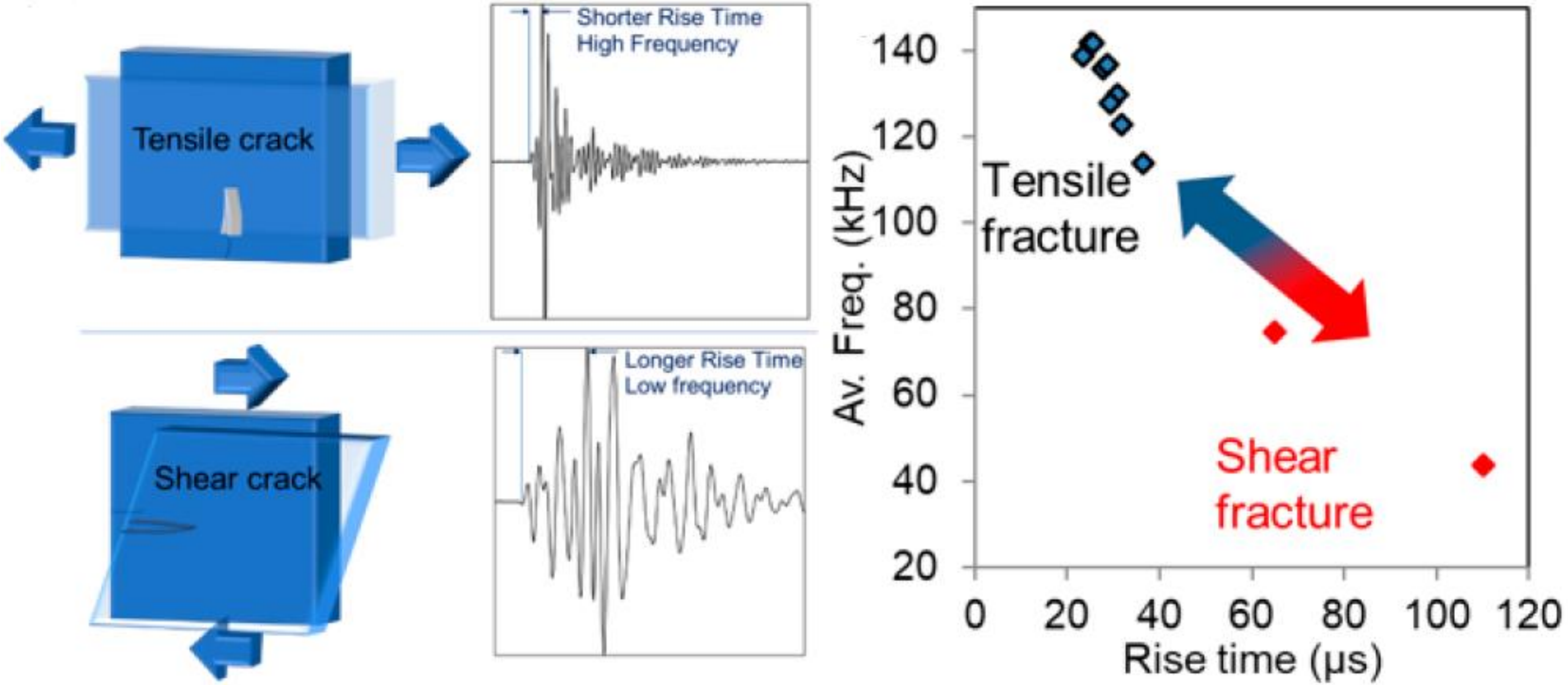


COST ACTION 18203—Optimized Design for Inspection (ODIN)



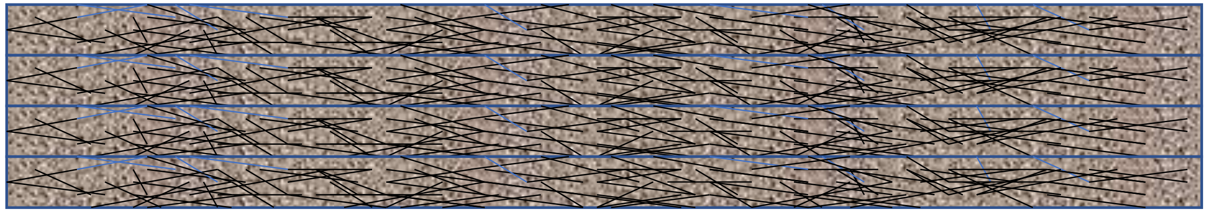
Chapter 7, Acoustic Emission, Dimitrios G. Aggelis, Markus G. R. Sause, Pawel Packo, Rhys Pullin, Steve Grigg, Tomaž Kek, and Yu-Kun Lai

https://doi.org/10.1007/978-3-030-72192-3

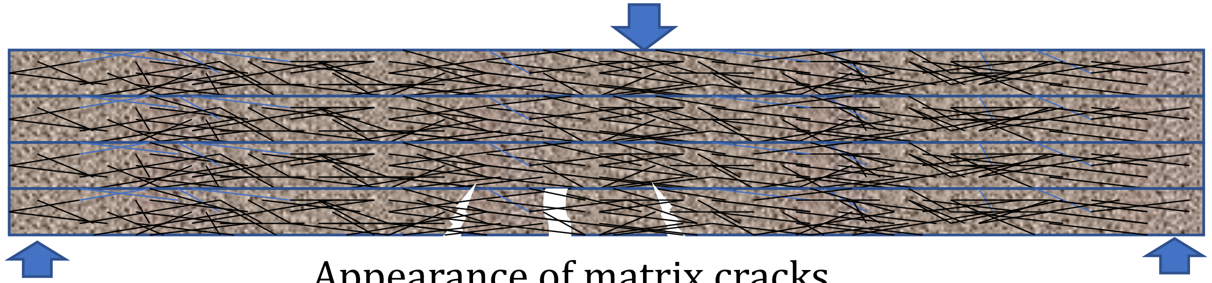

Tensile crack
Shorter Rise Time
High Frequency
Shear crack
Longer Rise Time
Low frequency
140
120
100
80
60
40
20
Av. Freq. (kHz)
0
20
40
60
80
100
120
Rise time (μs)
Tensile fracture
Shear fracture

Fracture composite laminate under bending

No load

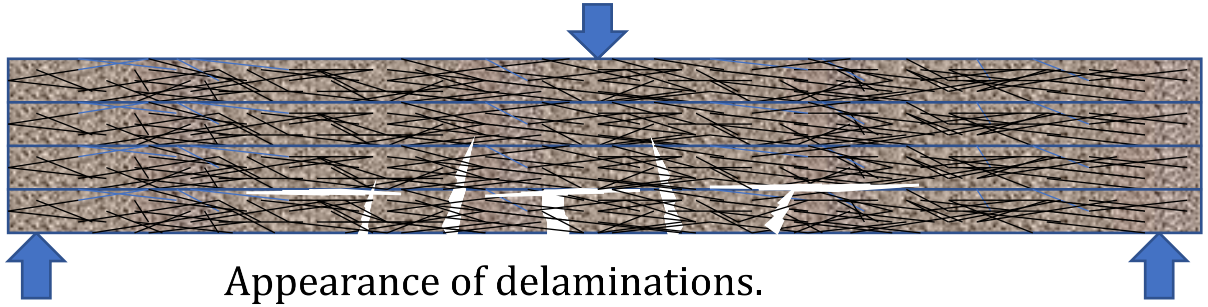


Low load



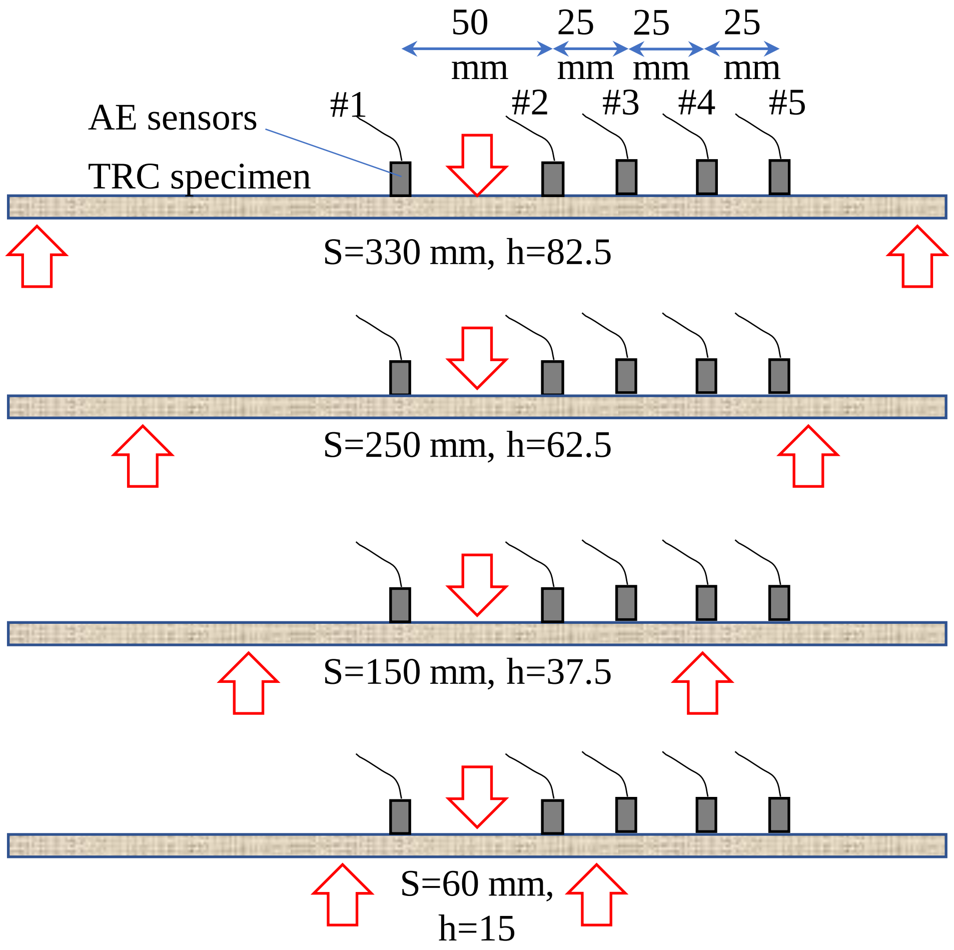
Appearance of matrix cracks.
Pull out of fibers bridging the cracks

Higher load
Matrix cracking
Pull-out
Debonding



Appearance of delaminations.
Extension of pull out and crack widening

Modification of the stress field according to the bending span



3p- bending

Shear/normal stresses=2.9%

Shear?

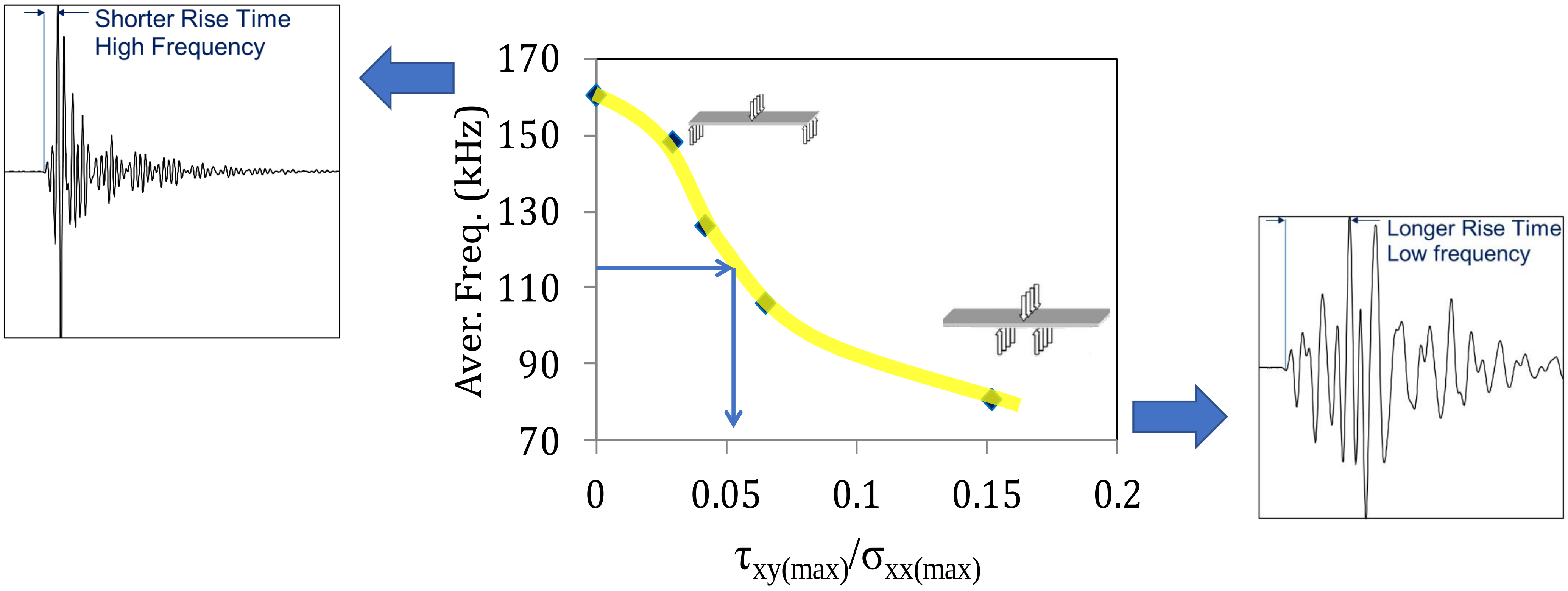
Shear/normal stresses =15%

Pico sensors (broadband, peak at 450 kHz)

5 sensors to check for the plate wave dispersion and attenuation

Acoustic emission

Correlation to stress ratios

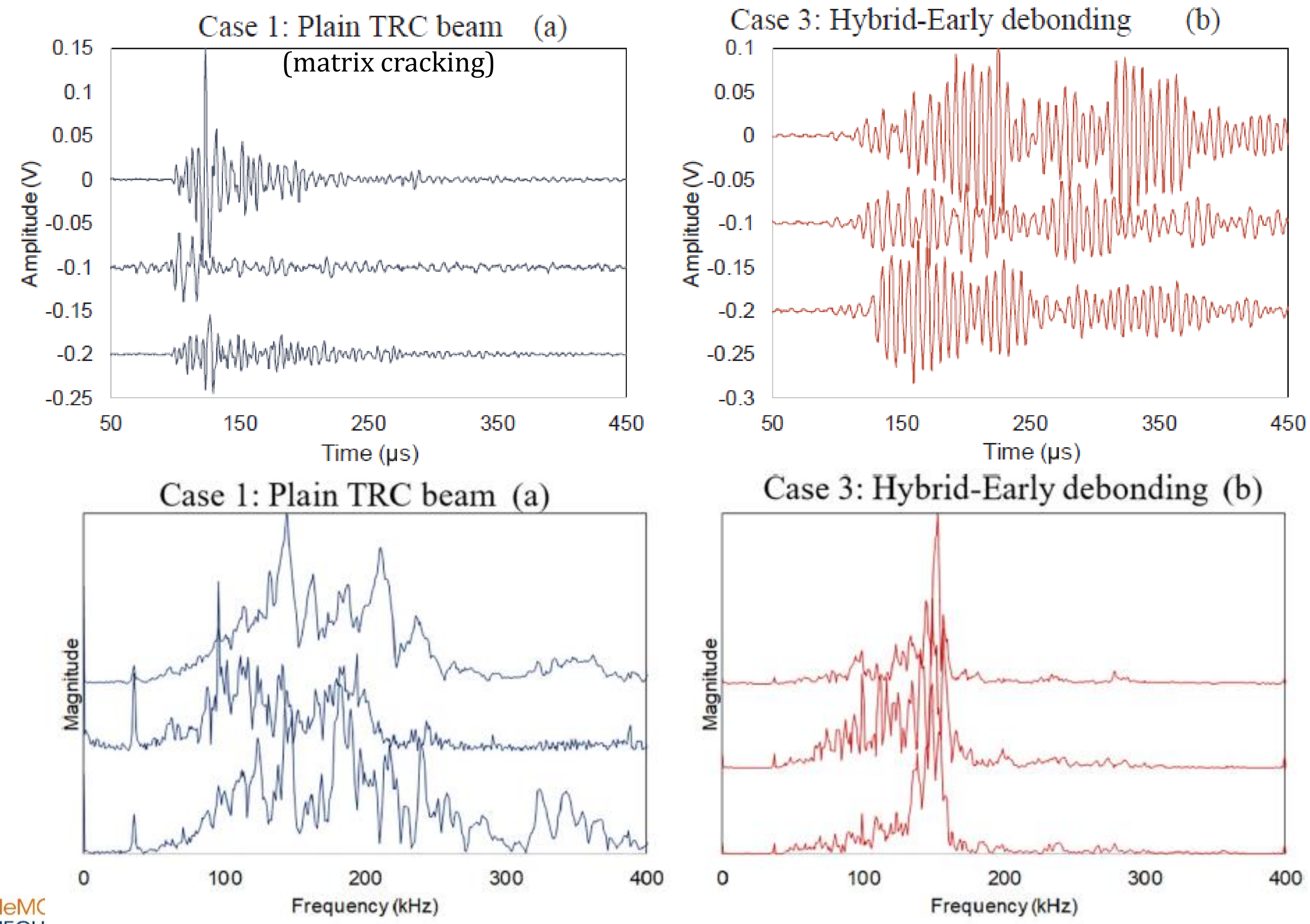


As the shear/normal stress ratio decreases, parameters from the whole AE activity obtain characteristics closer to tensile matrix cracking (high frequency – low RA value).

With passive AE monitoring it is possible to evaluate the stresses ratio even when load is very low!

Construction and Building Materials, 70, 2014, 370-378.

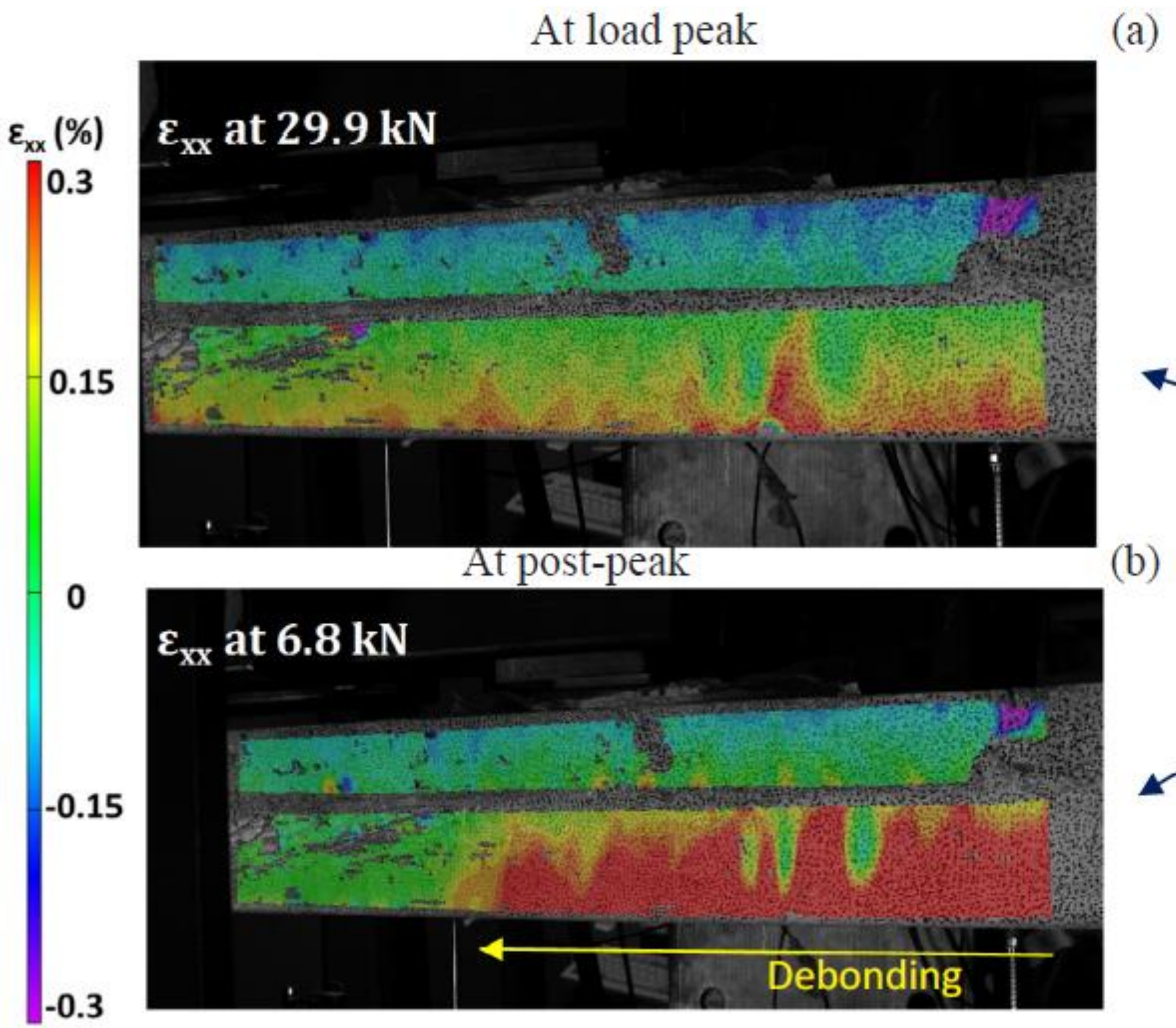
Examples of AE waveforms

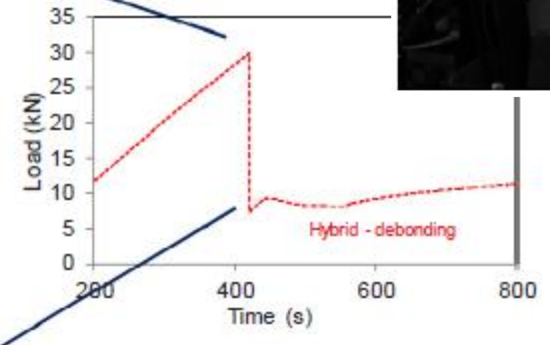


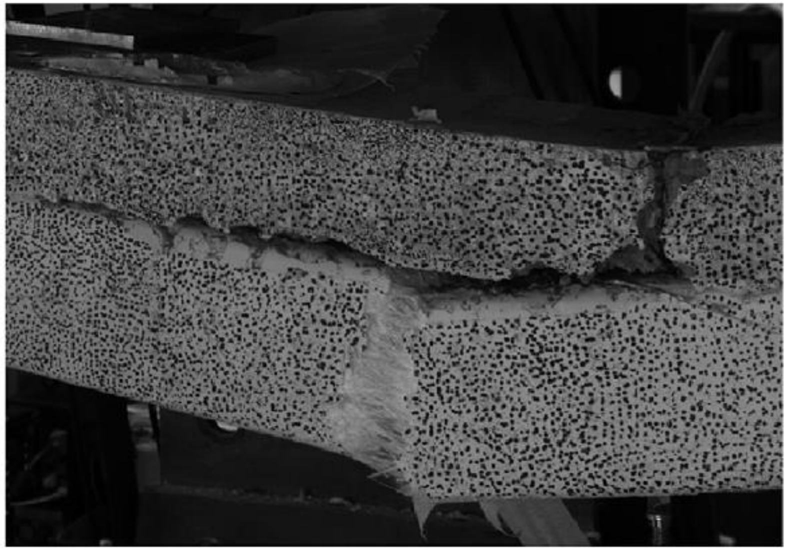
Matrix cracking exhibits shorter waveforms and higher frequencies than debonding of CFRP strip

Engineering Fracture Mechanics 210 (2019) 181–188

How do we confirm the moment of debonding of CFRP strip?



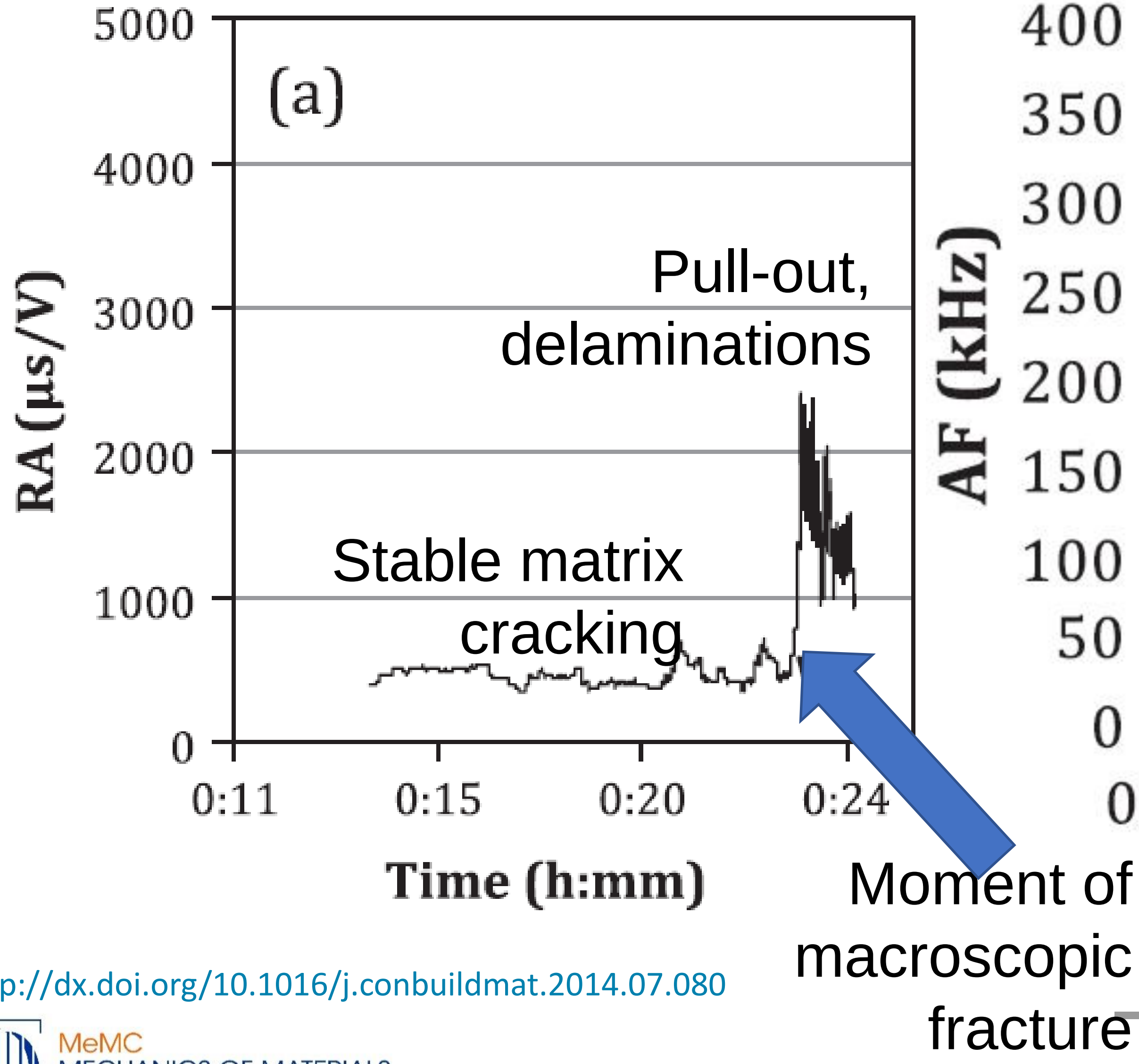


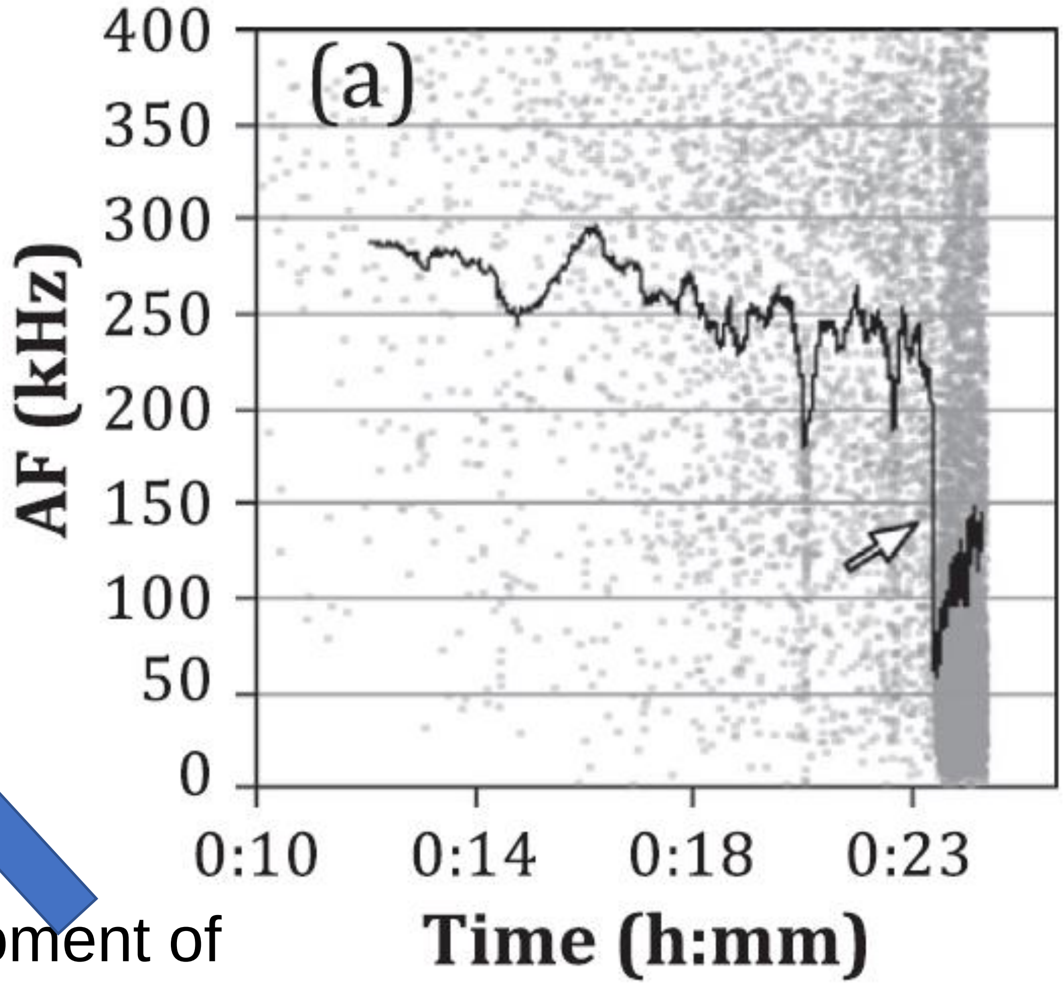


By comparing the strain before and after the event as given by DIC

Engineering Fracture Mechanics 210 (2019) 181–188

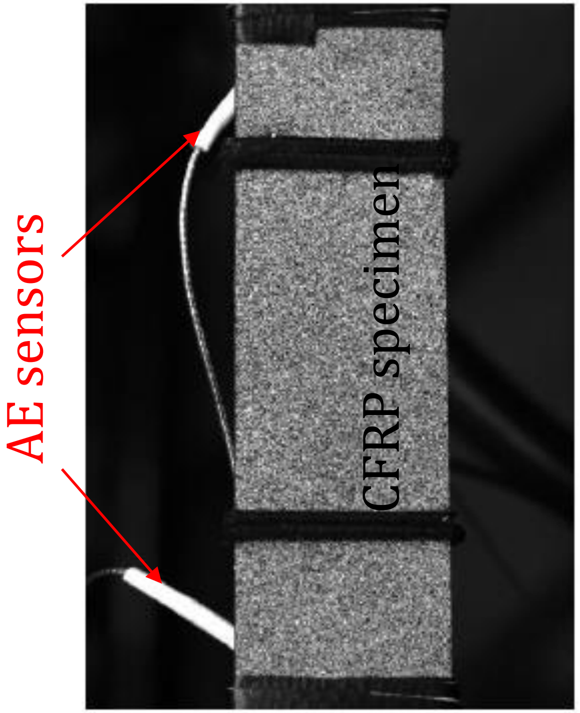
Changes in the AE parameters during the fracture process

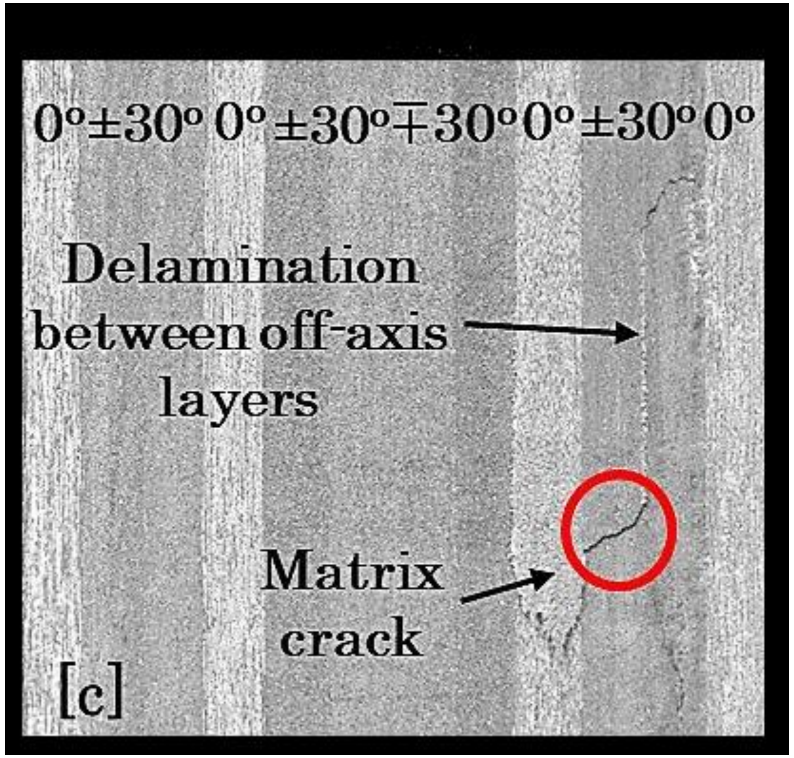




http://dx.doi.org/10.1016/j.conbuildmat.2014.07.080

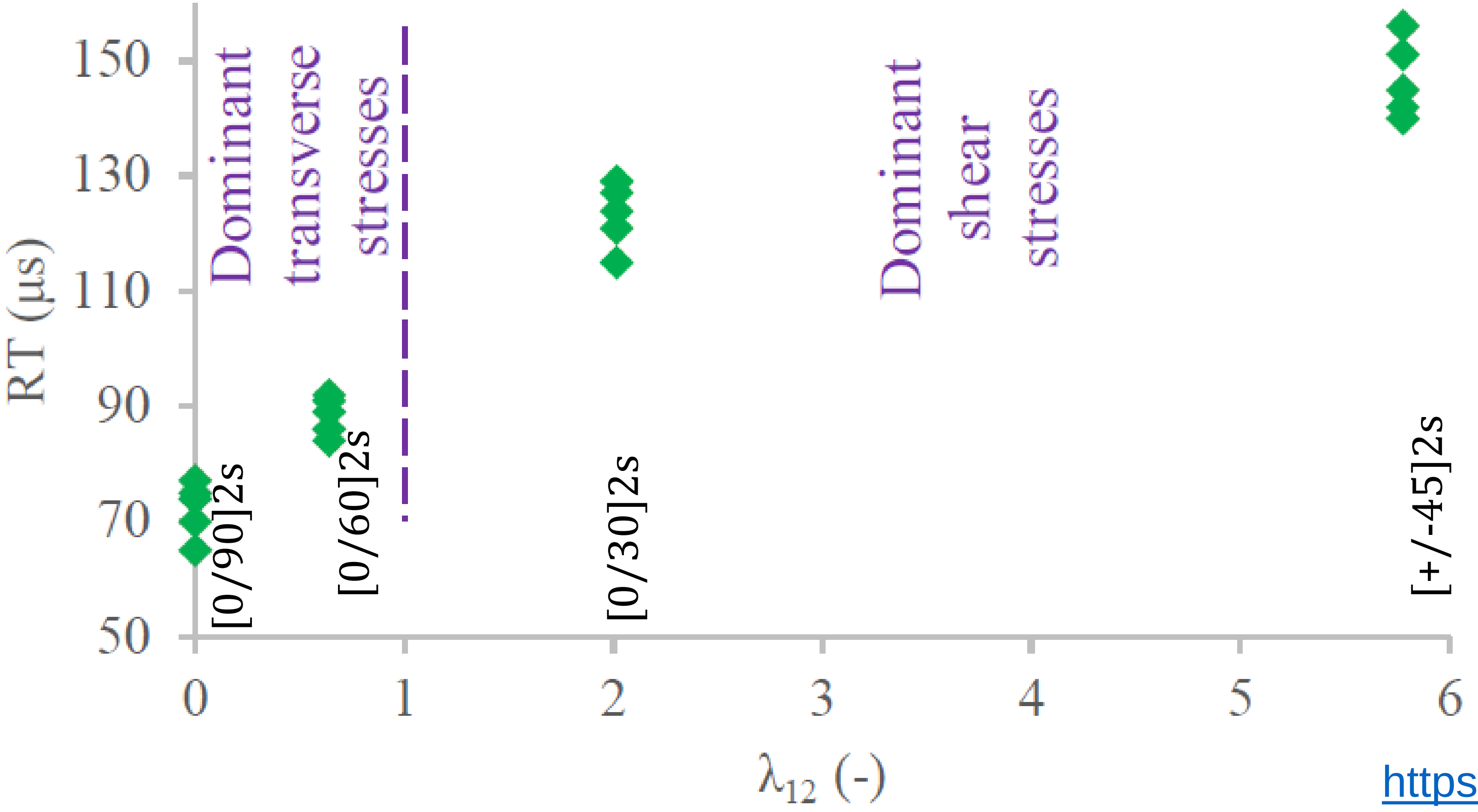
Similar conclusions in a great variety of structural materials
Example from CFRP





Kalliopi-Artemi Kalteremidou, AN INTEGRATED NDT APPROACH FOR DAMAGE ASSESSMENT OF CFRP COMPOSITES UNDER COMPLEX STATIC AND FATIGUE LOADS, PhD Thesis, VUB, Brussels, 2020

Similar conclusions in a great variety of structural materials
Example from CFRP

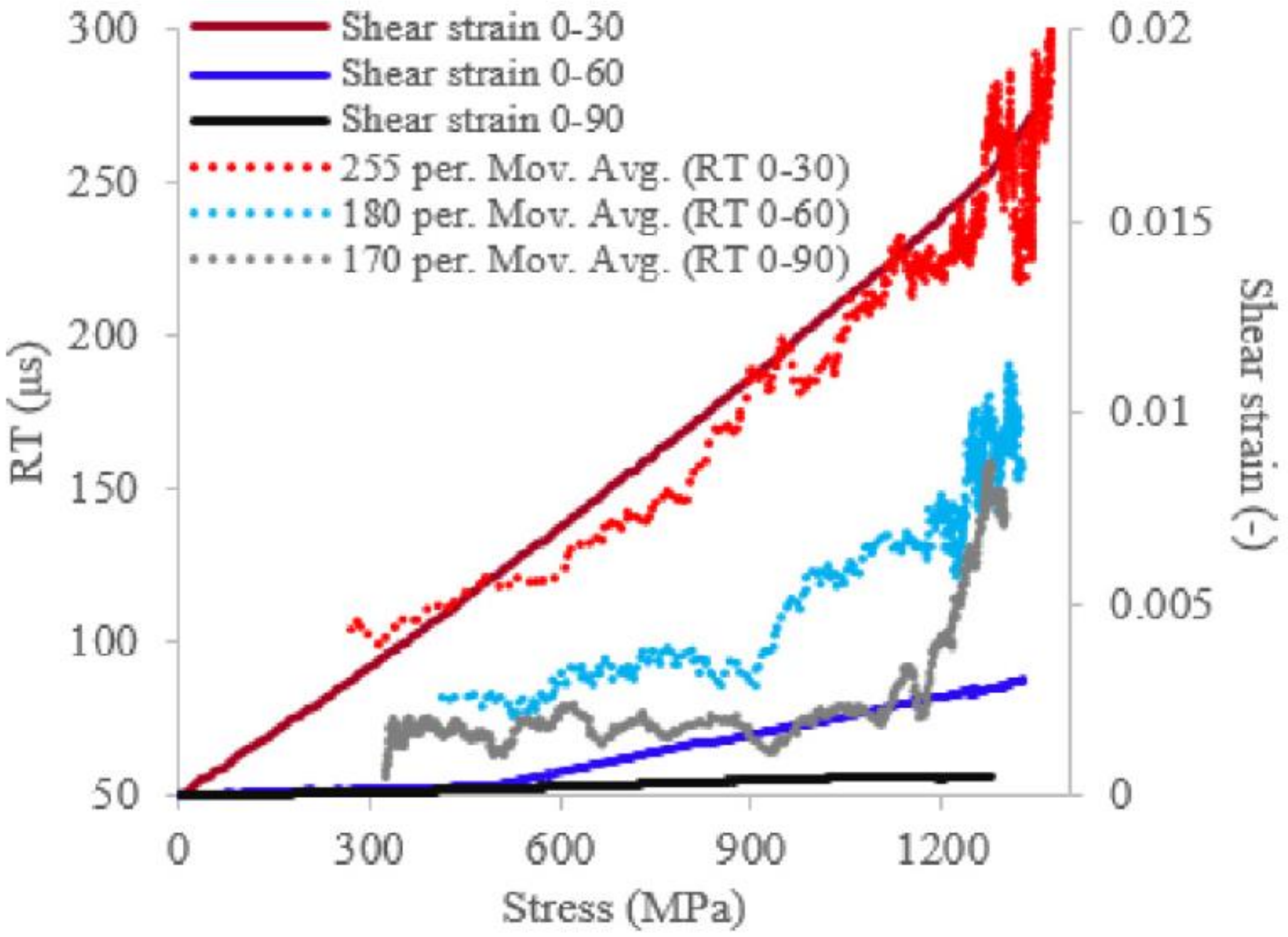


The multiaxiality ratio (λ) expresses the shear over the tensile stress σ2 on the off-axis layer. Depending on the angles this changes

https://doi.org/10.3390/app8112021

This is evident from the early AE parameters (less than 40% of the maximum load). The RT follows the increase of the shear stresses.

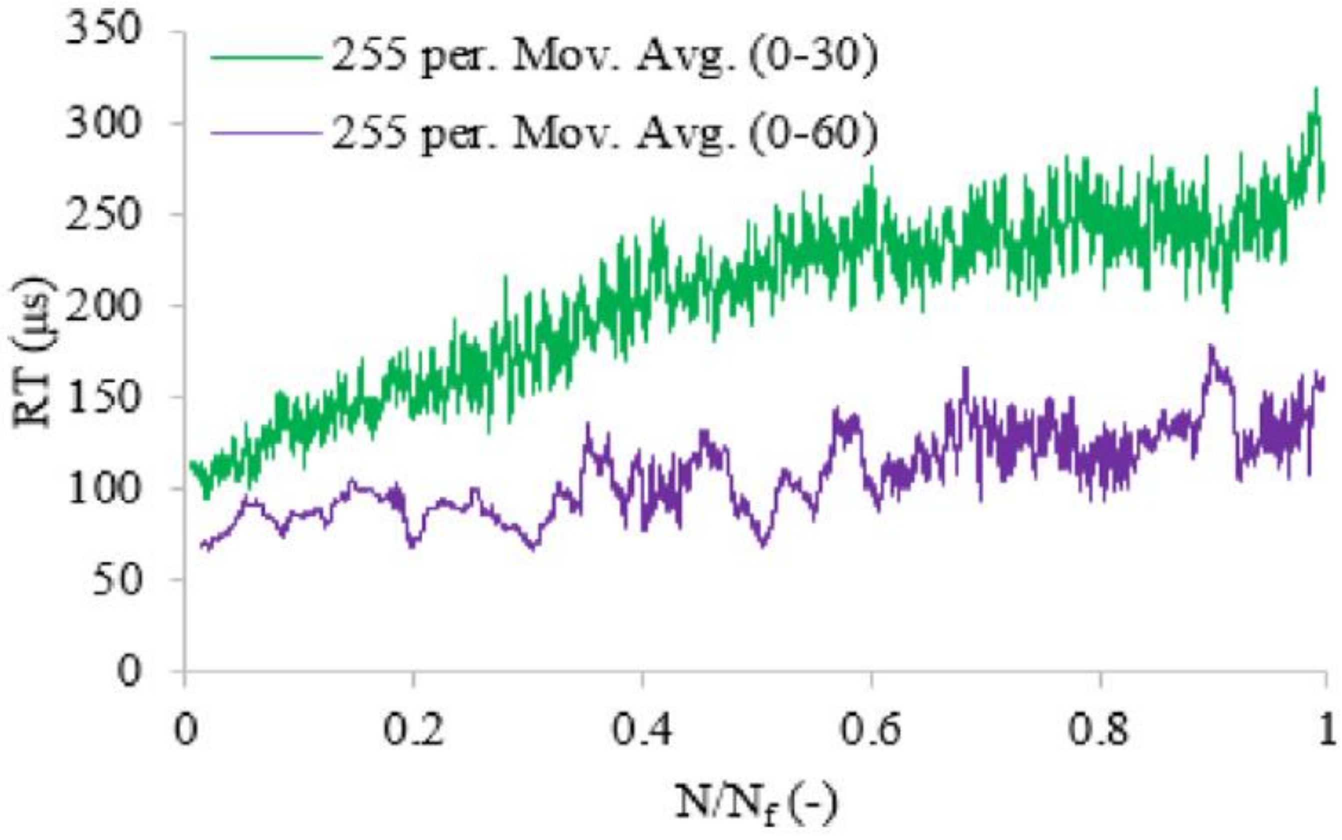
Quasi-static loading



Laminates that develop stronger shear stresses exhibit higher RT and in general longer AE signals.

Mechanics Research Communications 111 (2021) 103663

Fatigue of CFRP



Laminates that develop stronger shear stresses exhibit higher RT and in general longer AE signals during the whole duration of fatigue.

Mechanics Research Communications 111 (2021) 103663

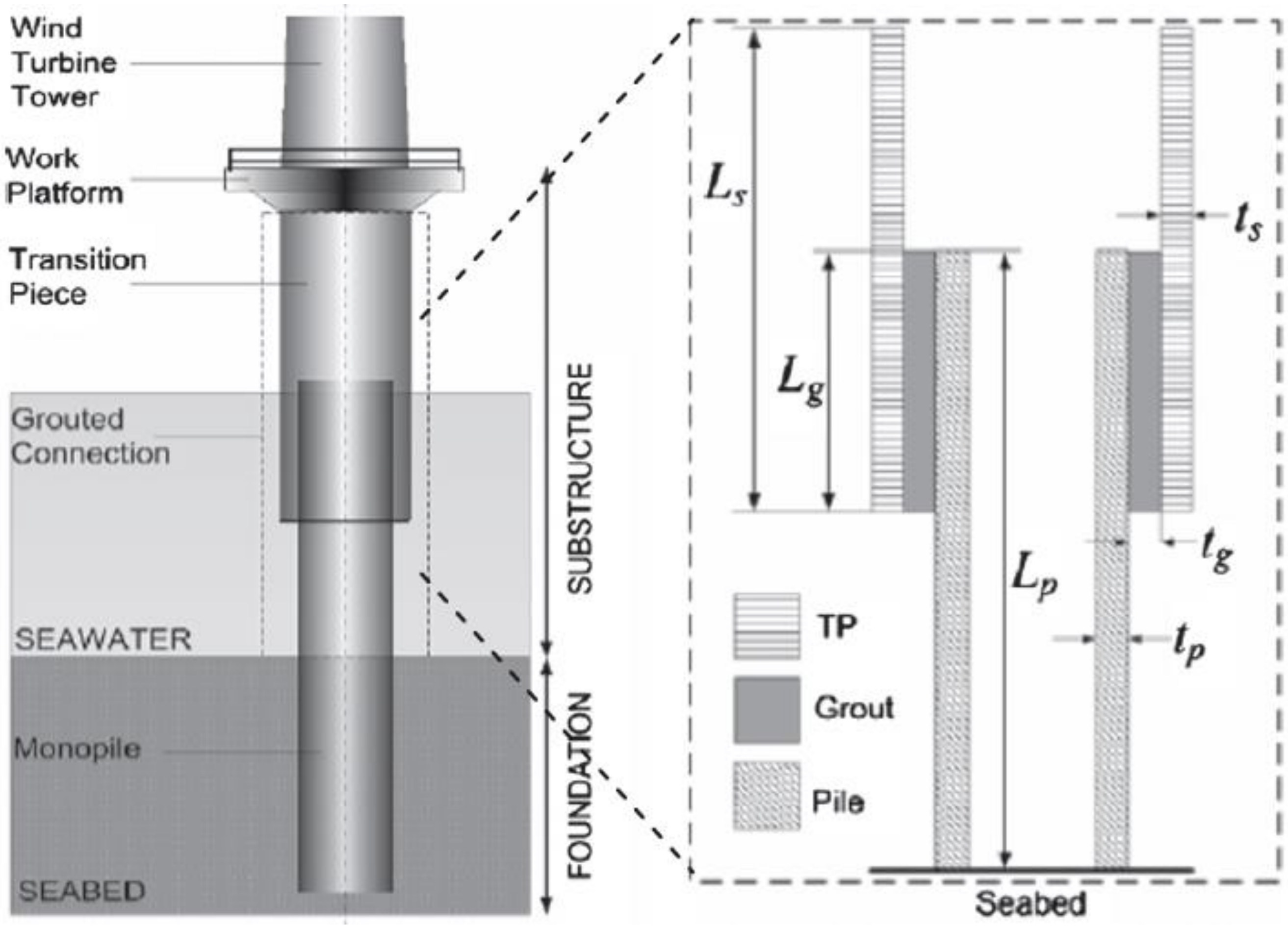
Basic message from fracture studies with AE

Strong correlation between AE parameters and fracture mode but furthermore with the stress field that will eventually dominate!
AE can reveal the dominant stresses in the material even at low load.

Global trend, examined in
- Concrete (and cementitious materials in general)
- Composites like textile reinforced materials
- Polymer Composites
- Masonry (bricks)

Do not pay attention to the absolute values!!! These change a lot according to geometry, propagation distance, sensors. The importance is in the relative trends and the transient shifts during loading.

Assessment of grouted samples from monopile wind turbine foundations

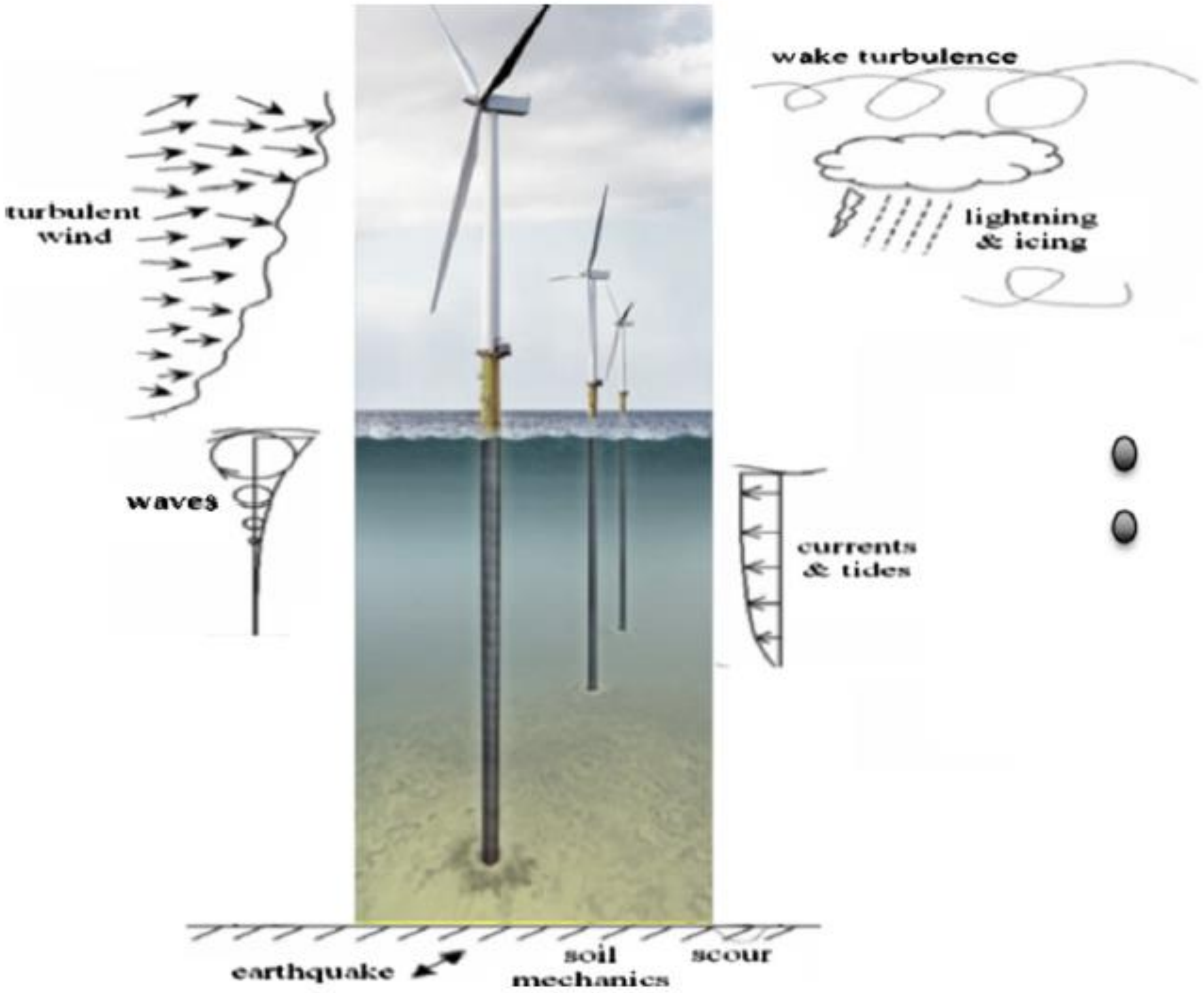


http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047

Nearly 80% of the installed substructures

Two concentric steel pipes

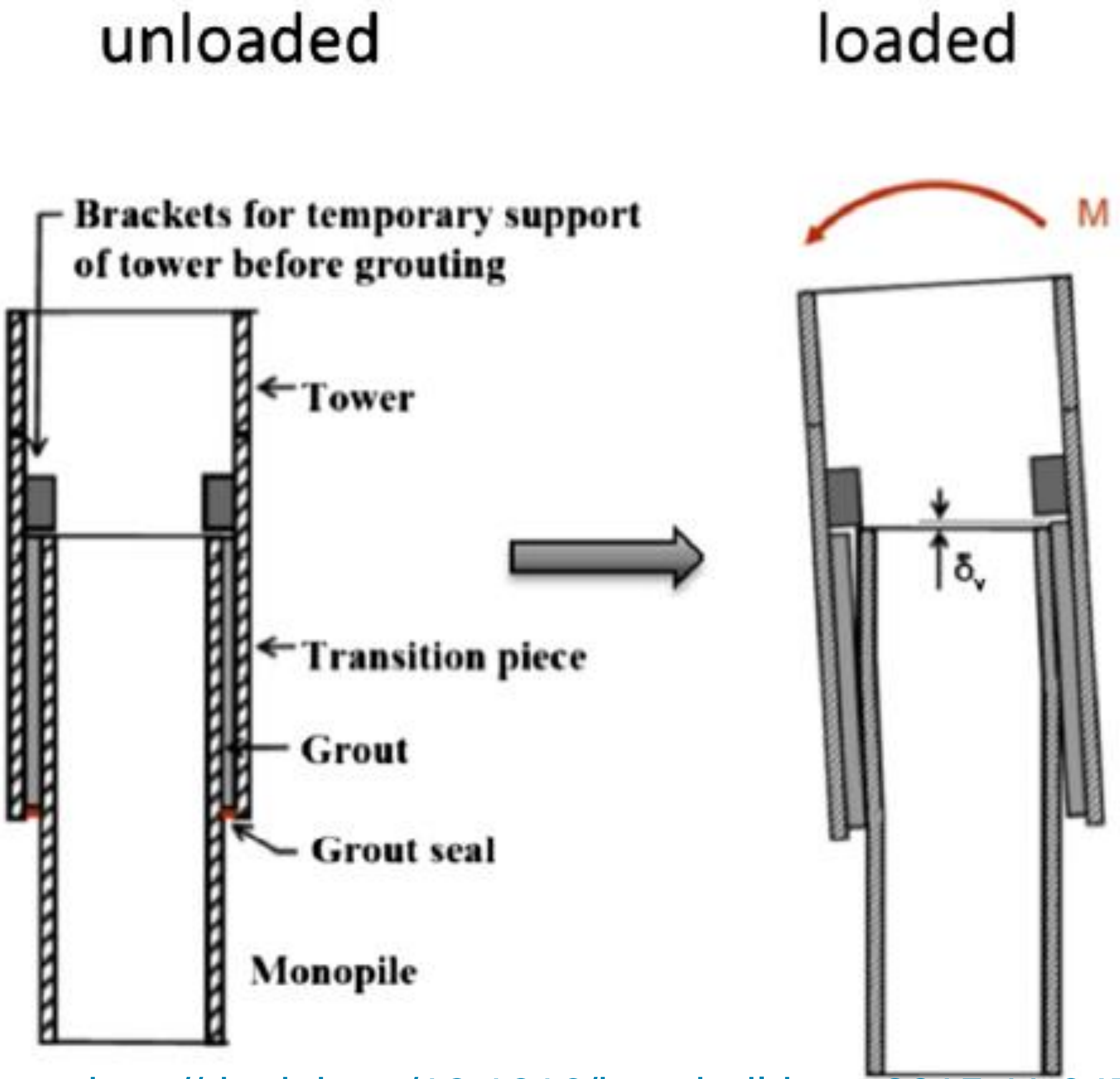
High strength cementitious grout that fills the annulus



http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047

Dynamic operational loads jeopardize the durability.

Alternating moment loading may lead to wear on the sliding surfaces and reduction in axial load bearing capacity.

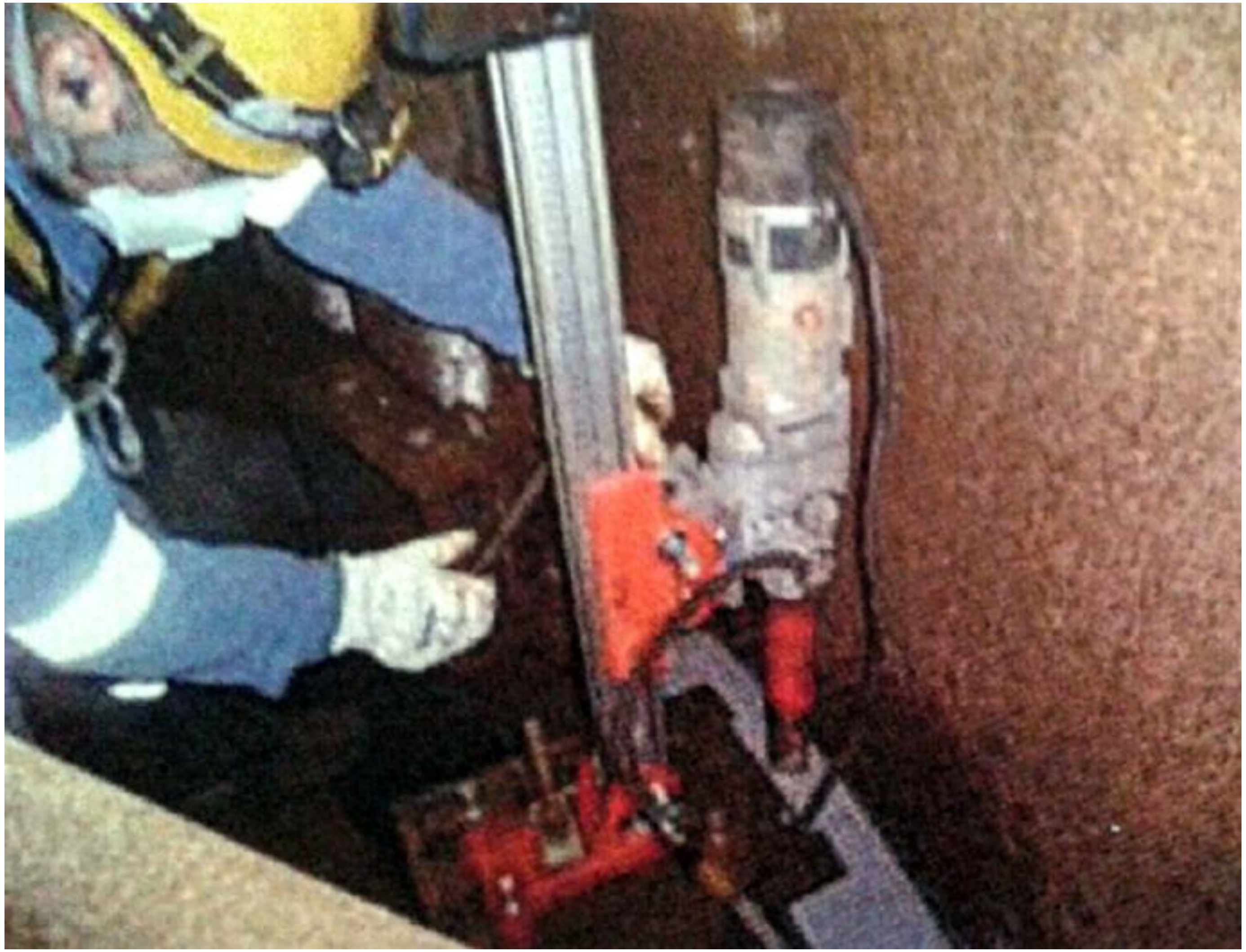


http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047

Operation and maintenance cost is estimated at about 1/3 of the costs of electricity.

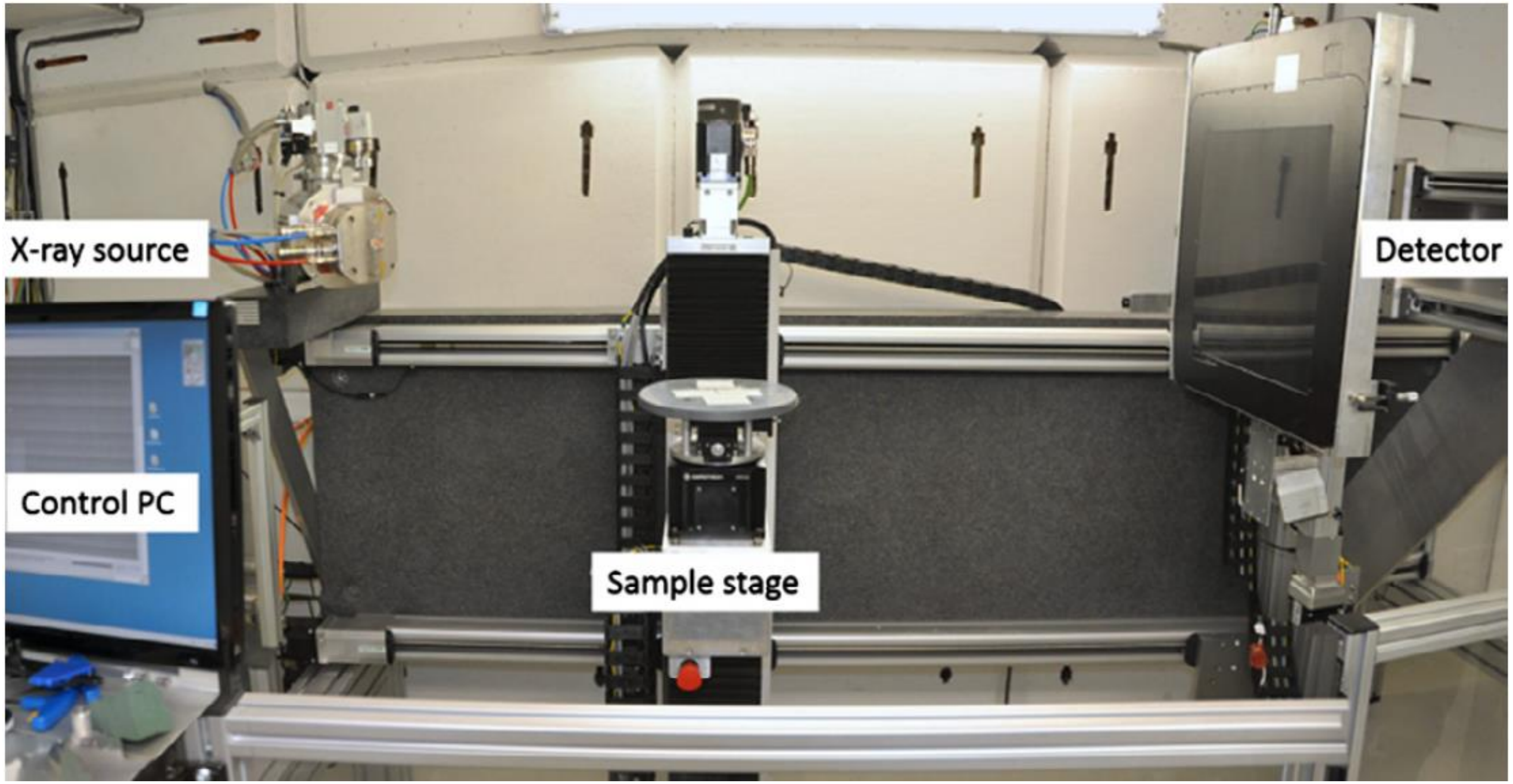
Out of this 30% is preventive and 70% is corrective maintenance.

Early indication of structural problem allows better planning of maintenance.



Core drilling

http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047



X-ray computed tomography.

“Hector”, UGENT.

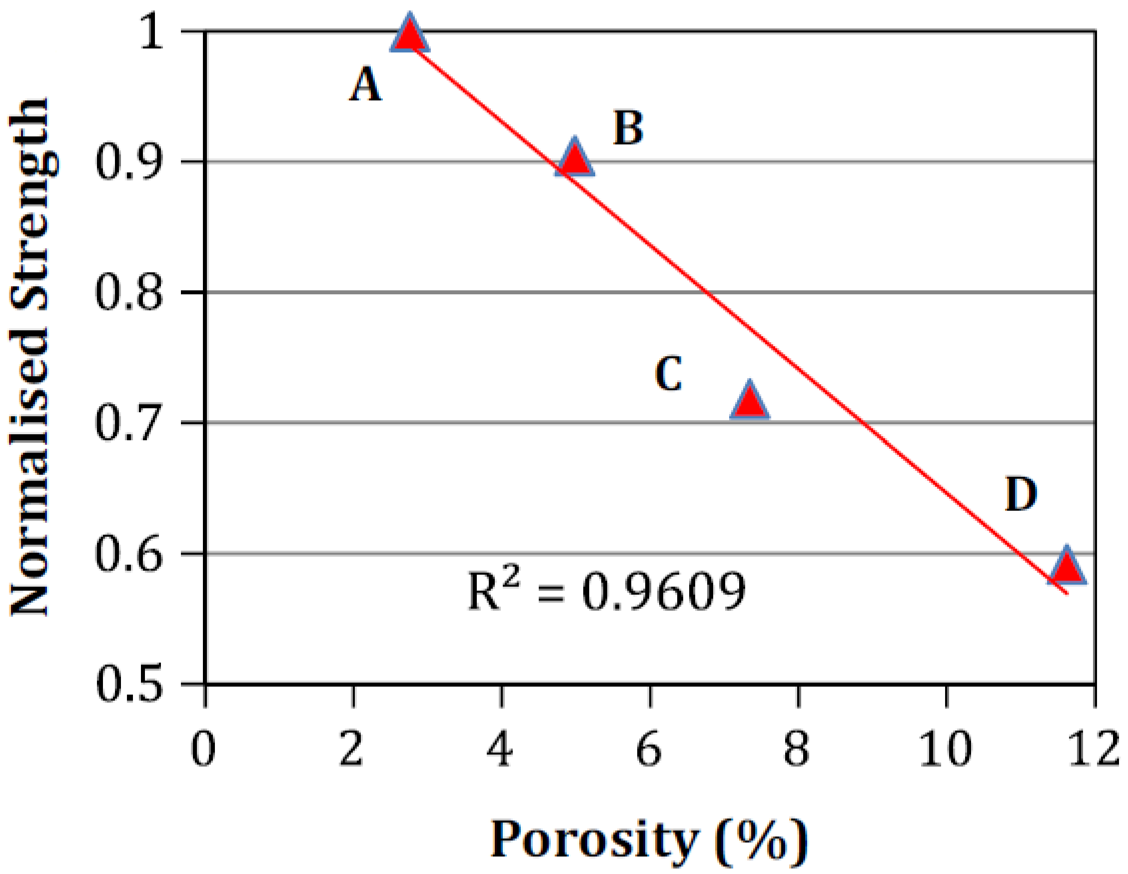
Resolution (voxel) 100 μm.

3000 projections were taken while the sample was rotating over 360º.

http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047

Photographs of the compression test of mortar samples (a) before and (b) after final fracture.

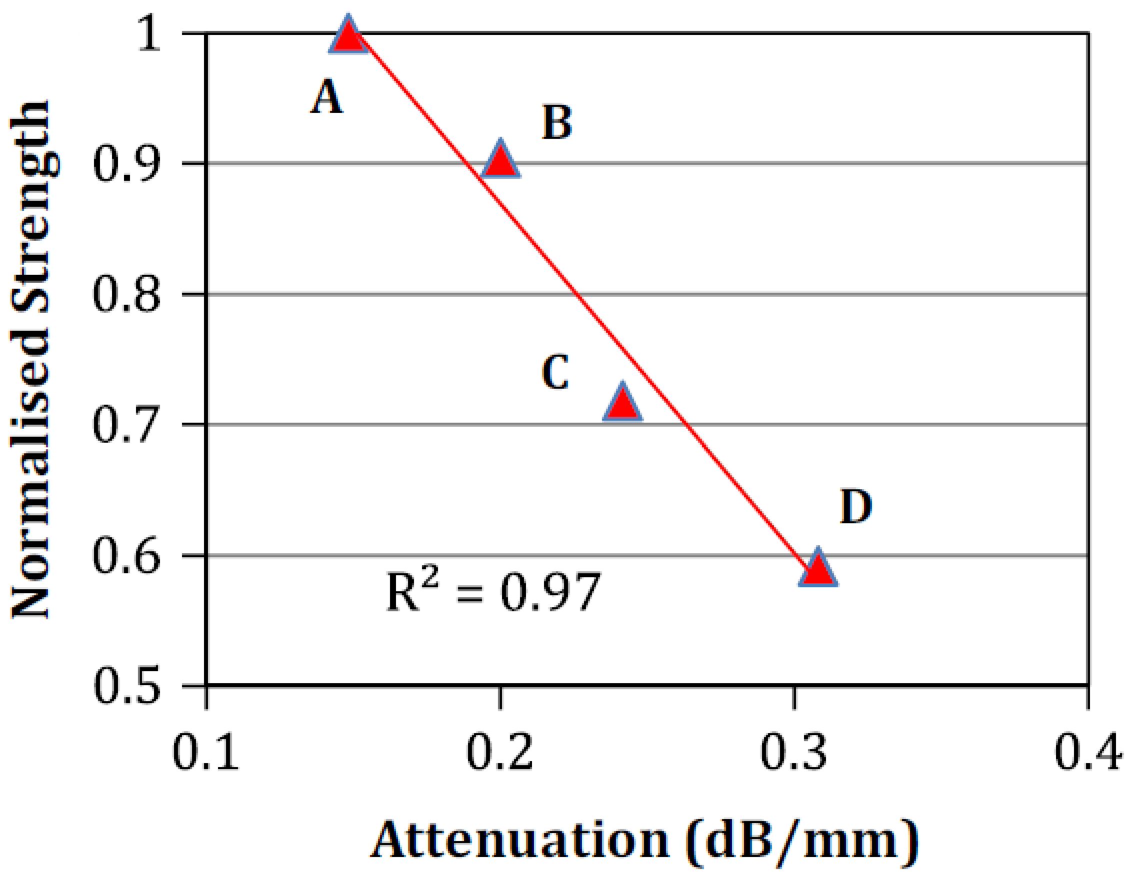
http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047



Maximum strength is approximately 120 MPa

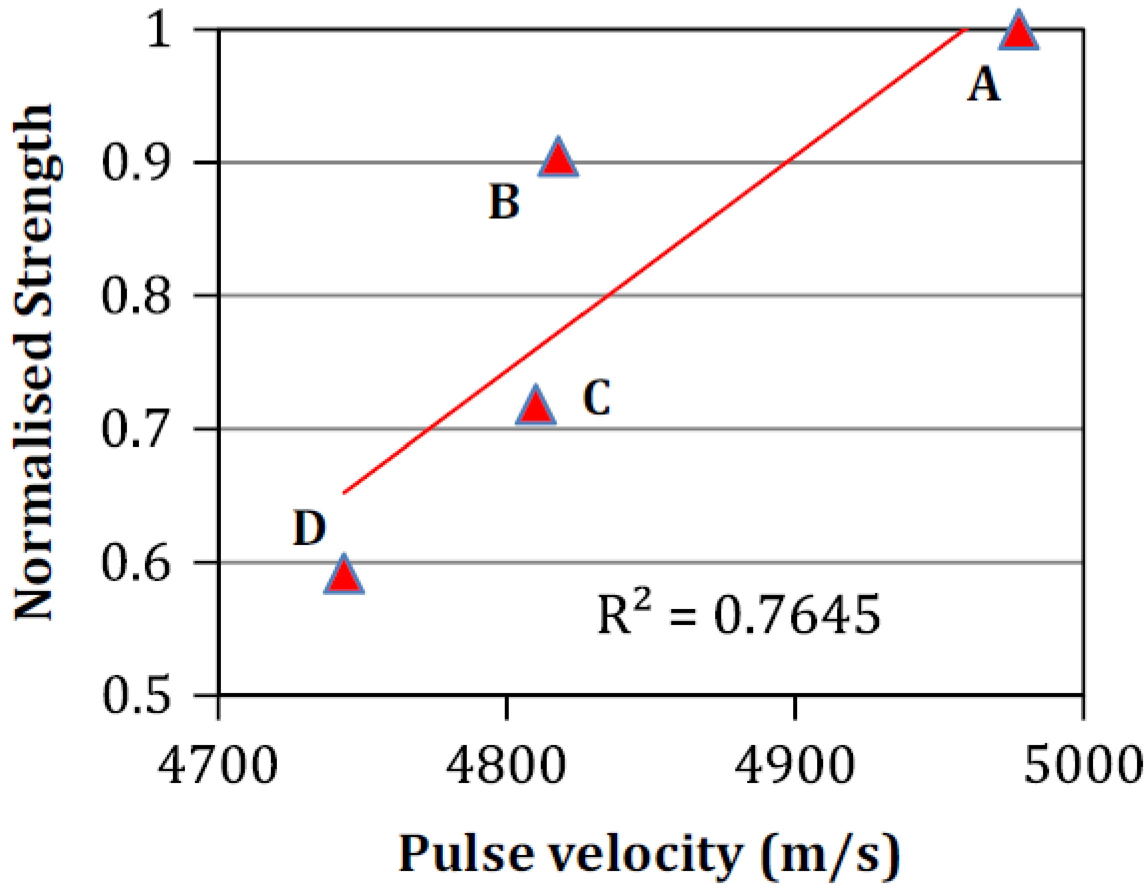
Strength decreases with porosity

http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047



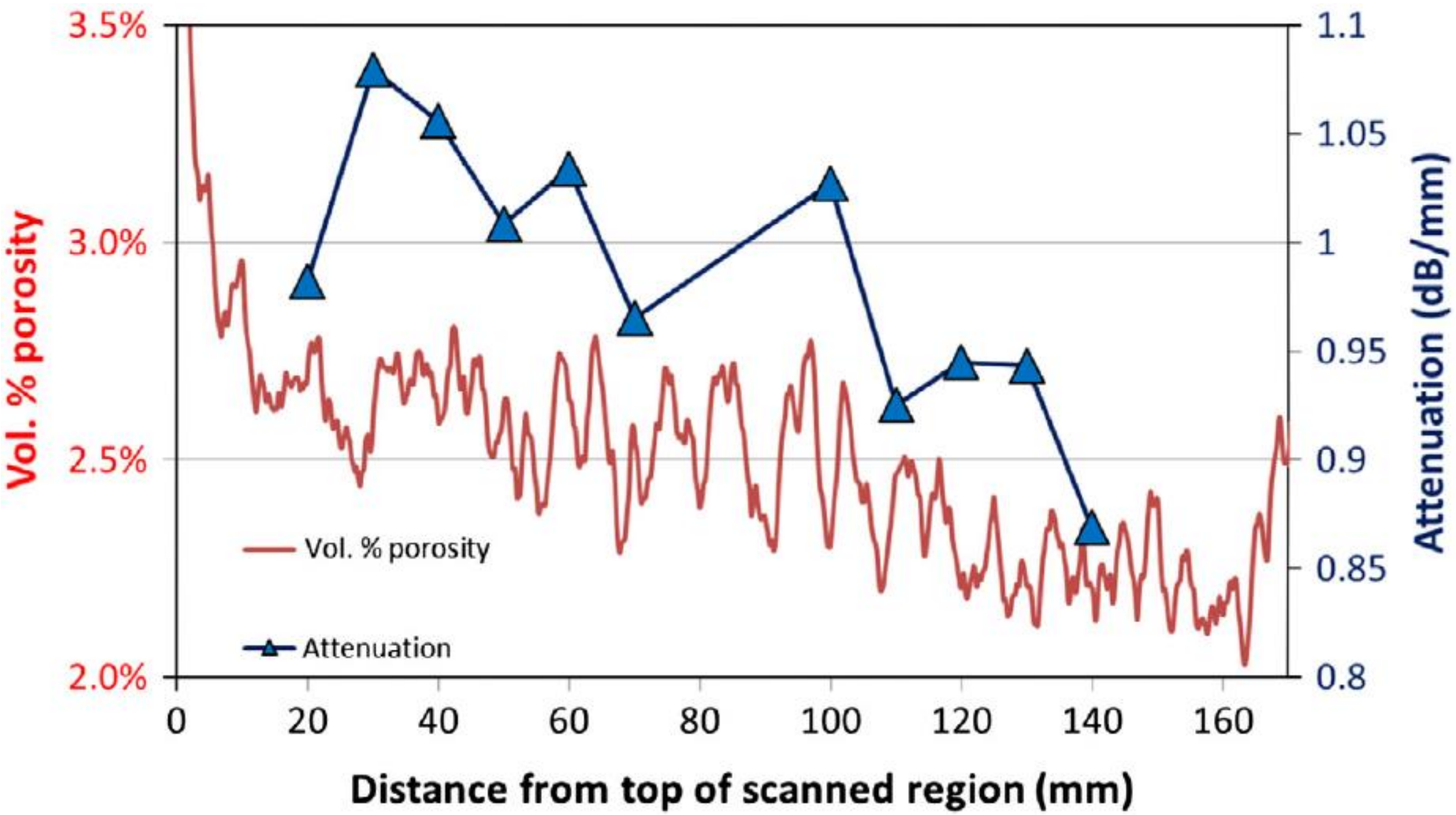
Strength decreases with attenuation

http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047

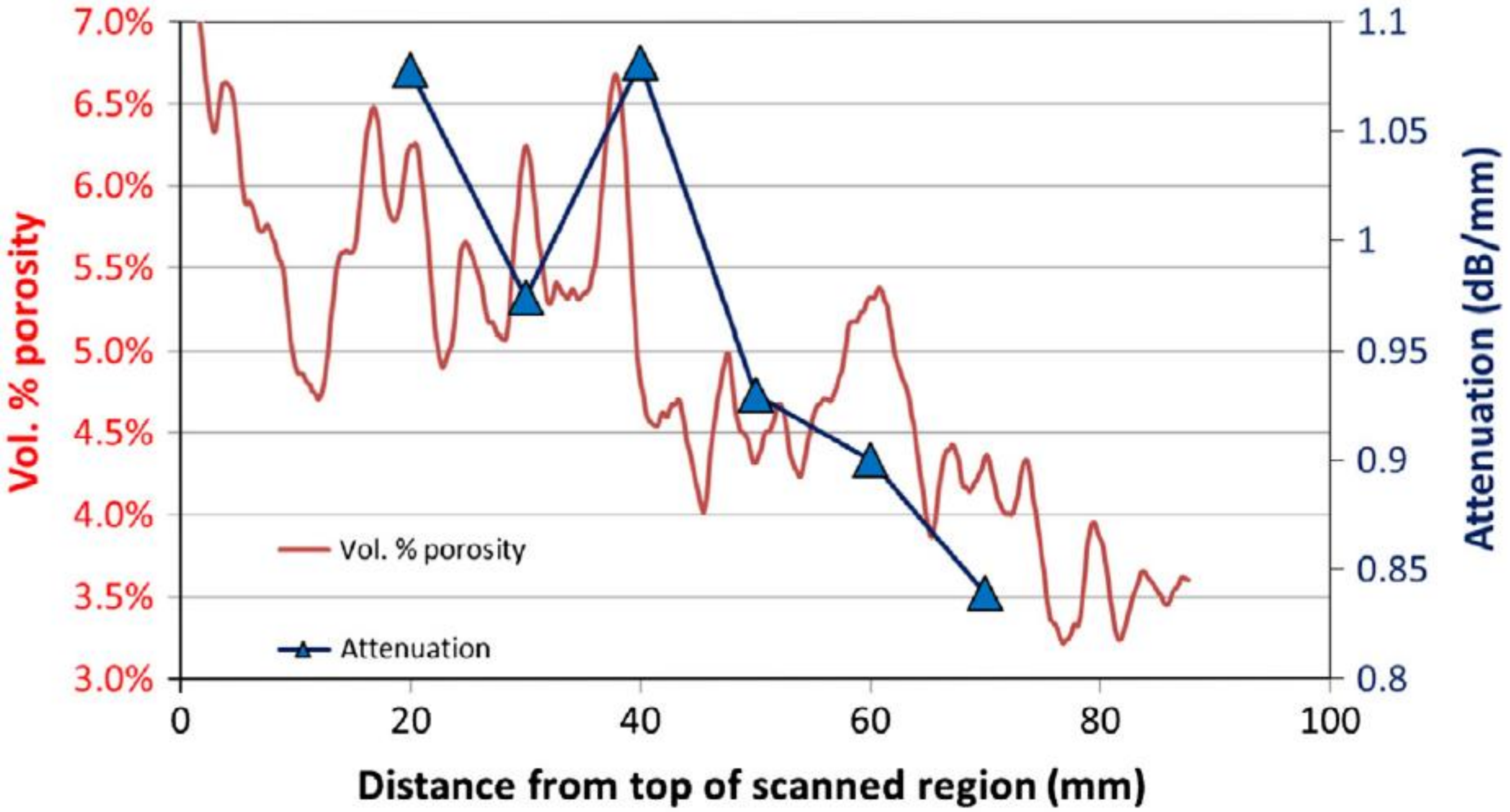


Positive correlation between strength and UPV holds

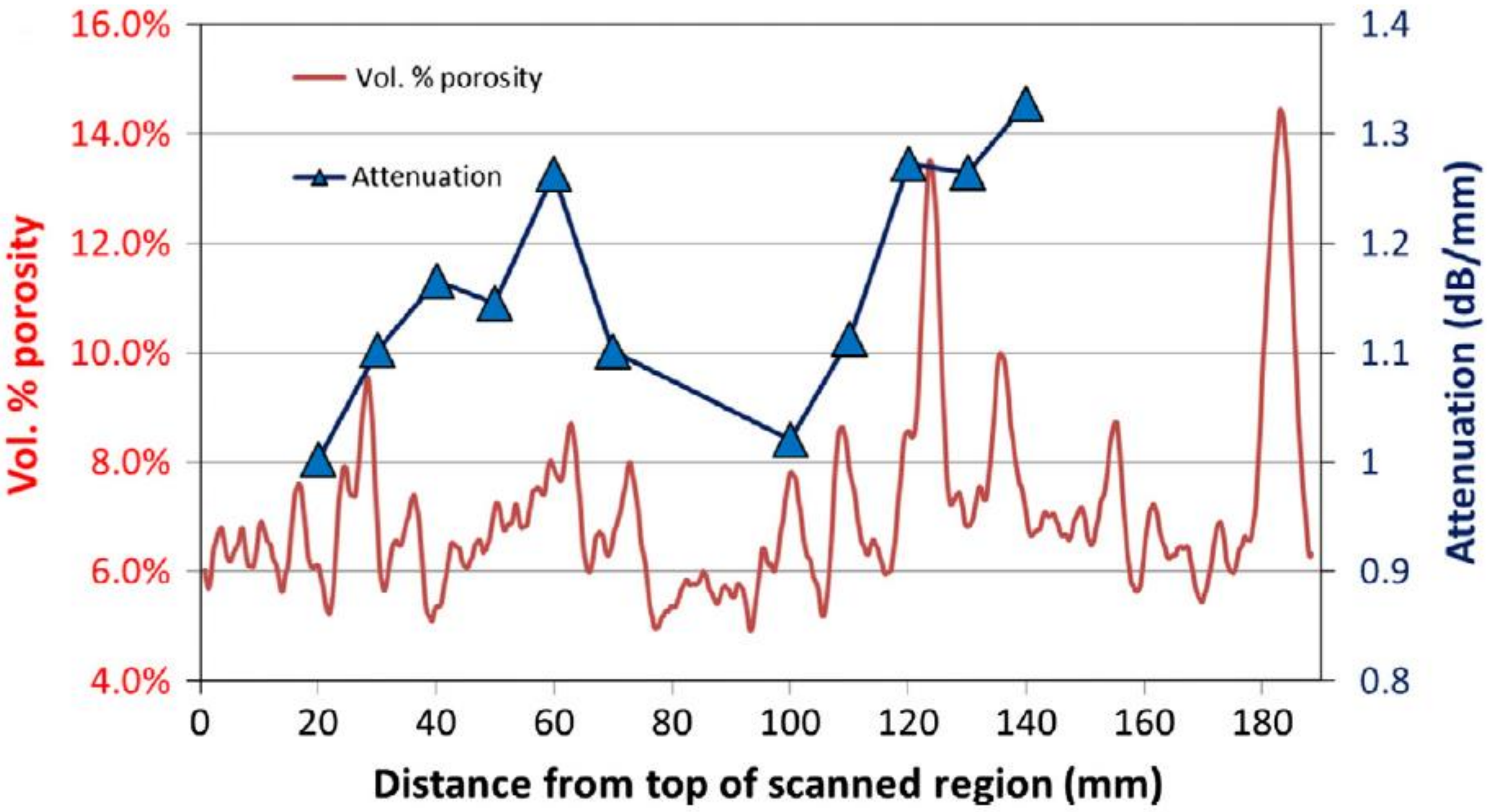
http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047



http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047



http://dx.doi.org/10.1016/j.conbuildmat.2015.11.047


Vol. % porosity
Attenuation
16.0%
14.0%
12.0%
10.0%
8.0%
6.0%
4.0%
1.4
1.3
1.2
1.1
1
0.9
0.8
0
20
40
60
80
100
120
140
160
180
Vol. % porosity
Attenuation (dB/mm)
Distance from top of scanned region (mm)

strength	117.14	107.51
Attenuation	0.314	0.323

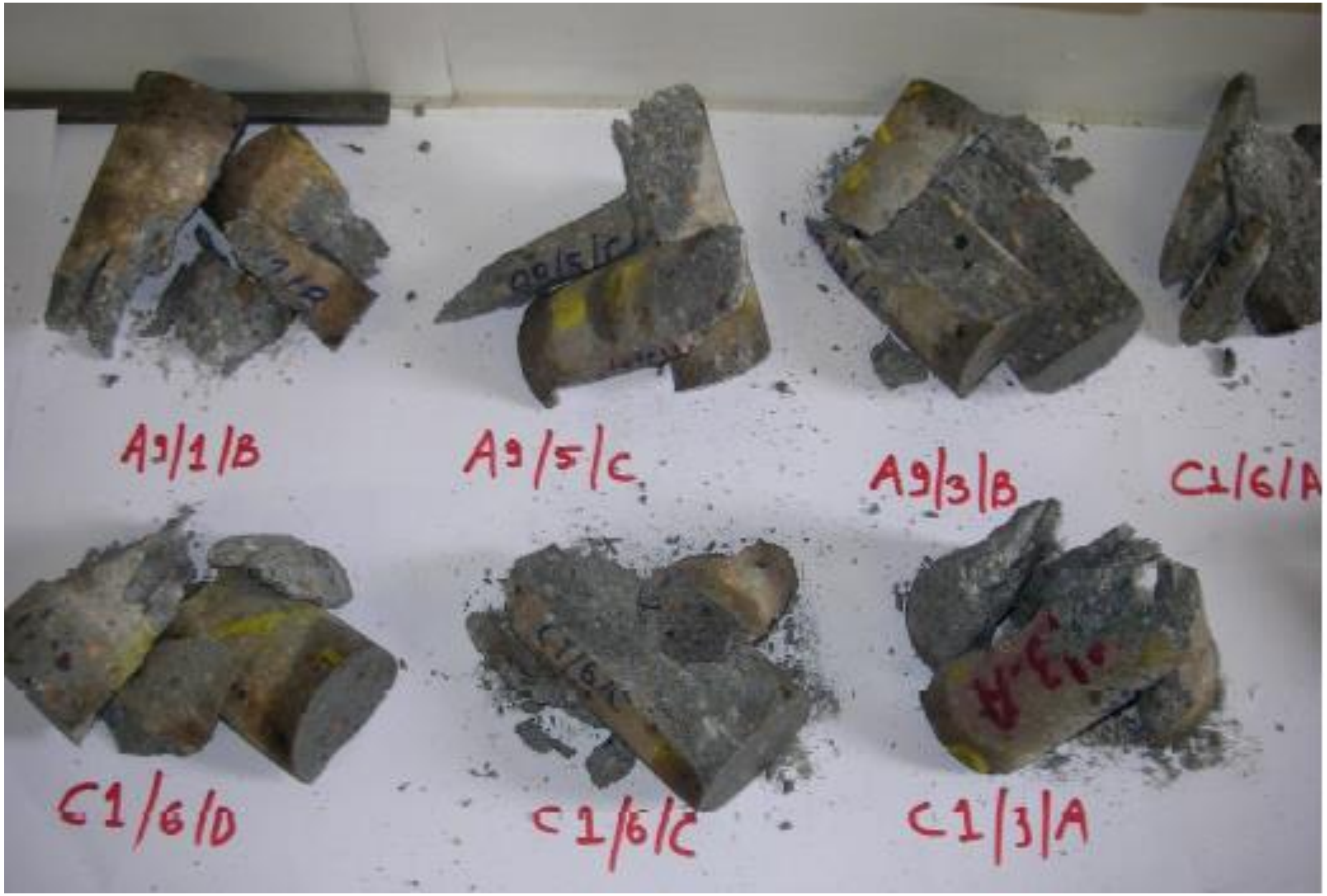
Strength (MPa)	131.44	85.21
Attenuation (dB/mm)	0.266	0.301

strength	70.61	109.12	119.44
Attenuation	0.306	0.258	0.255

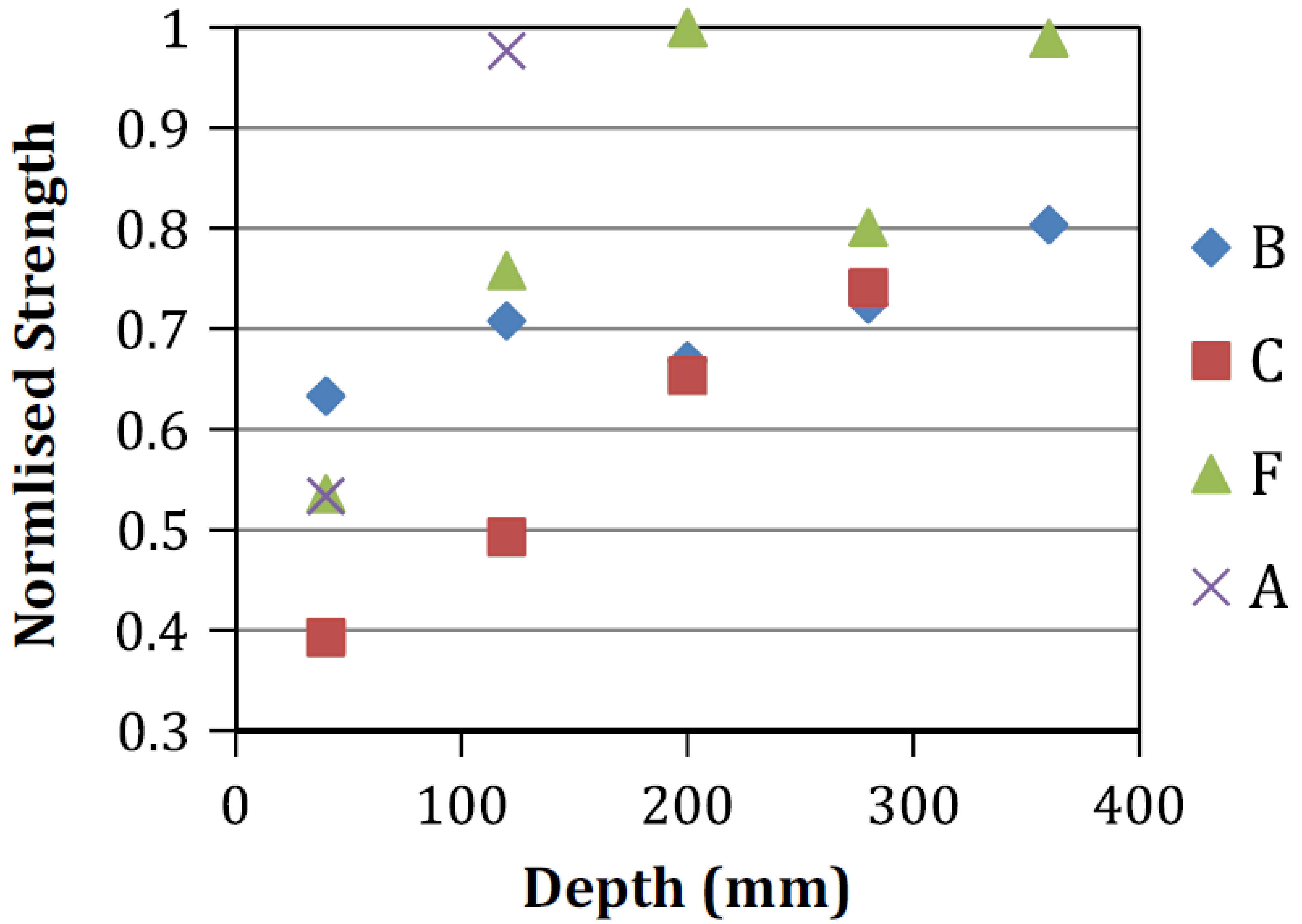
strength	94.54	125.3
Atten.	0.347	0.200

strength	94.26	66.41
Attenuation	0.247	0.250

strength	92.42	58.25
Attenuation	0.269	0.255



A9/1/B
A9/5/C
A9/3/B
C1/6/A
C1/6/D
C1/6/C
C1/3/A


Normlised Strength
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
100
200
300
400
Depth (mm)
B
C
F
A

Assessment of grouted samples from monopile wind turbine foundations

High quality cementitious grout is used to connect the monopile to the transition piece

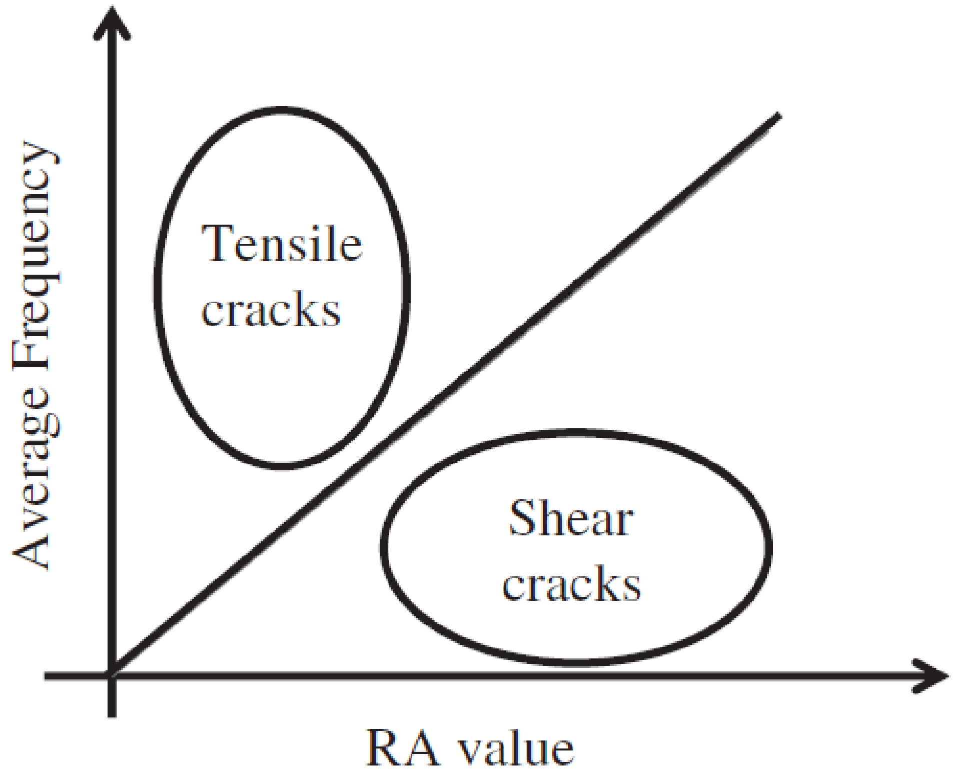
The grouted connection may exhibit deterioration due to loading and material-specific reasons.

The strength of the material is correlated to the depth from the top surface.

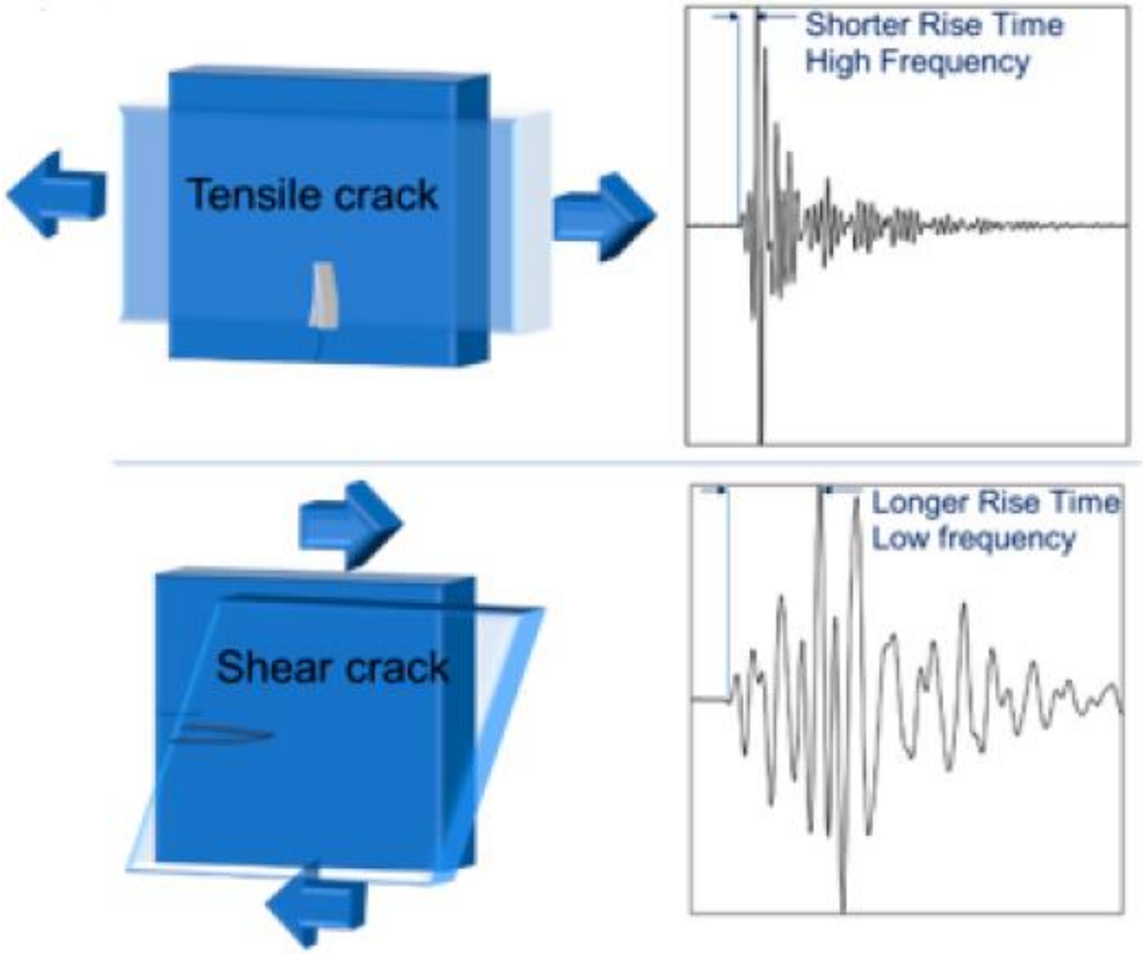
Ultrasound parameters (UPV and attenuation) exhibit good correlation with strength and porosity as measured by CT.

Characterization of damage based on acoustic emission:

In small scale it is straightforward



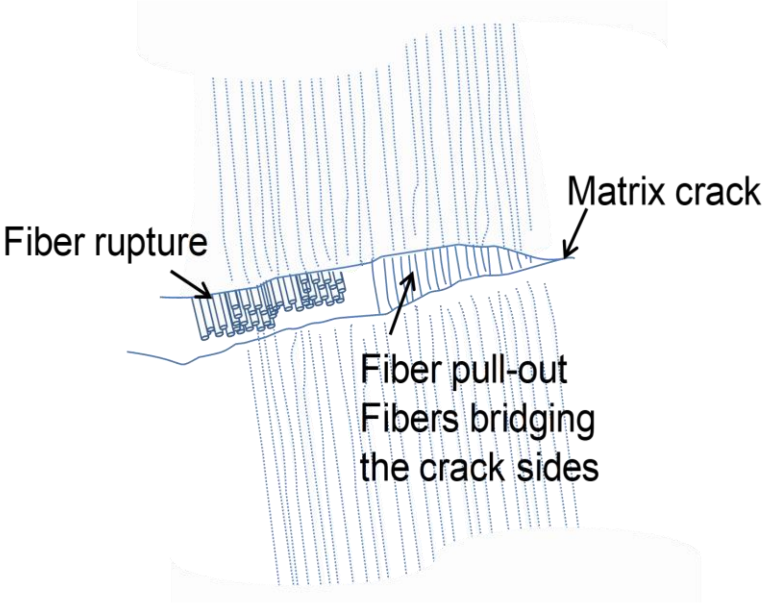
Recommendation of RILEM TC 212-ACD



Source of AE is an "Event"

In composite media cracking on the stiff phase is expected with higher speed and usually of less increment (e.g., one fiber diameter)

For matrix crack or debondings, the speed of cracking events will be lower due to lower stiffness and also it is expected that the increment is larger, until it meets a fiber, or until it propagates long enough so that the stress changes.



Ref.	Material	Test	Sensor	Frequency Distribution (kHz)			
				Matrix	Interfacial	Fibre/Matrix	Fibre
Ref.	Material	Test	Sensor	Amplitude Distribution (dB)			
				Matrix Cracking	Interfacial Debonding	Fibre/Matrix Friction and Fibre Pull-Out	Fibre Breakage
[40]	-	-	-	30–45	45–55	-	>55
[41]	Graphite/Glass	Tens., 4PB	PAC pico	60–80	70–90	-	-
[42]	CF/Ep	Buckling, 3PB	R15	43–65	45–75	50–85	-
[43]	CFRP	Tens. Cy	Fuji ceramic M204	40–70	-	-	60–100
[39]	GF/PET	Immersed bending fatigue	PAC U30D03	40–60	60–80	-	80–100
[44]	GF/Ep	Torque	WD AE	32–72	46–68	69–86	87–100
[45]	GF/Ep	3PB	PZT disc	35–82	50–95	-	>65
[33]	GF sandwich	3PB static/fatigue	PZT disc	40–76	72–100	-	>94
[46]	GF/PP	Tens., crack propagation	PAC micro 80	40–55	60–65	65–85	85–95

Would these values be the same for other conditions (size, shape, distance, sensors)?

doi:10.3390/ma10070685

Characterization of damage based on acoustic emission:

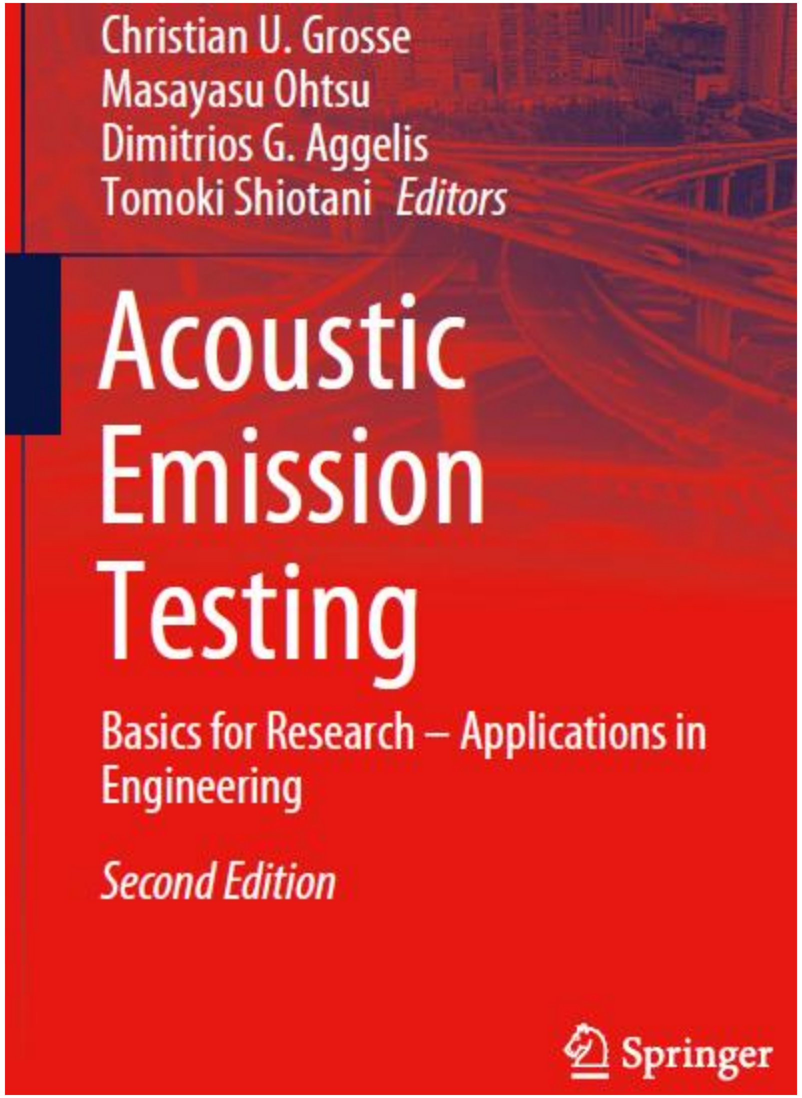
In larger scale?

Problems?

Propagation distance, attenuation (of higher frequencies)

Dispersion (separation of wave modes)

Geometry effect

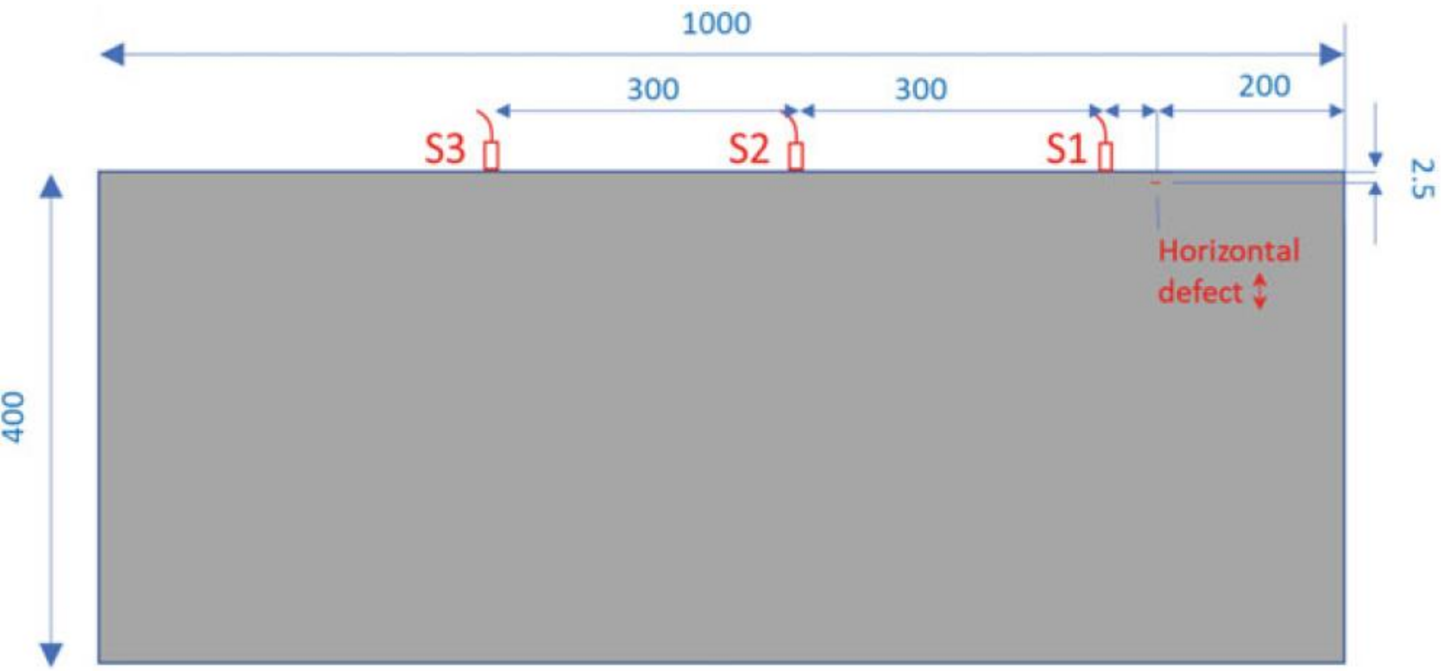


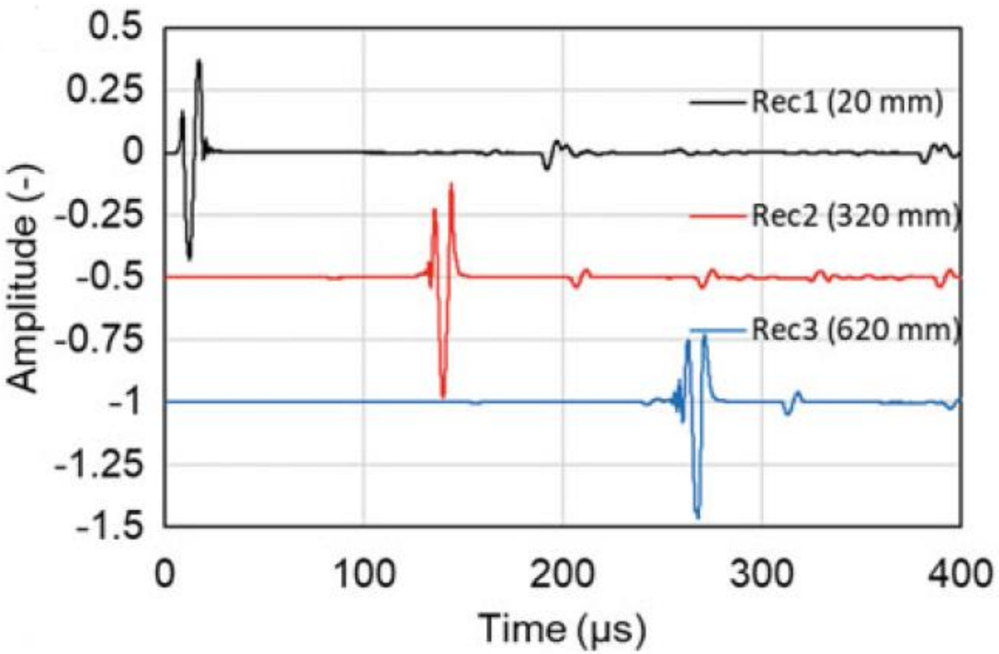
The difference that the dispersion makes is tremendous…

https://doi.org/10.1007/978-3-030-67936-1_9

The difference that the dispersion makes is tremendous…

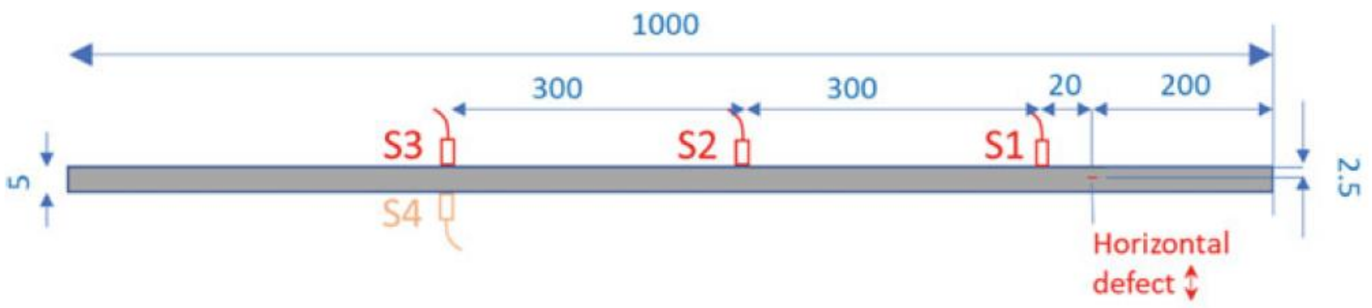
Simulation study

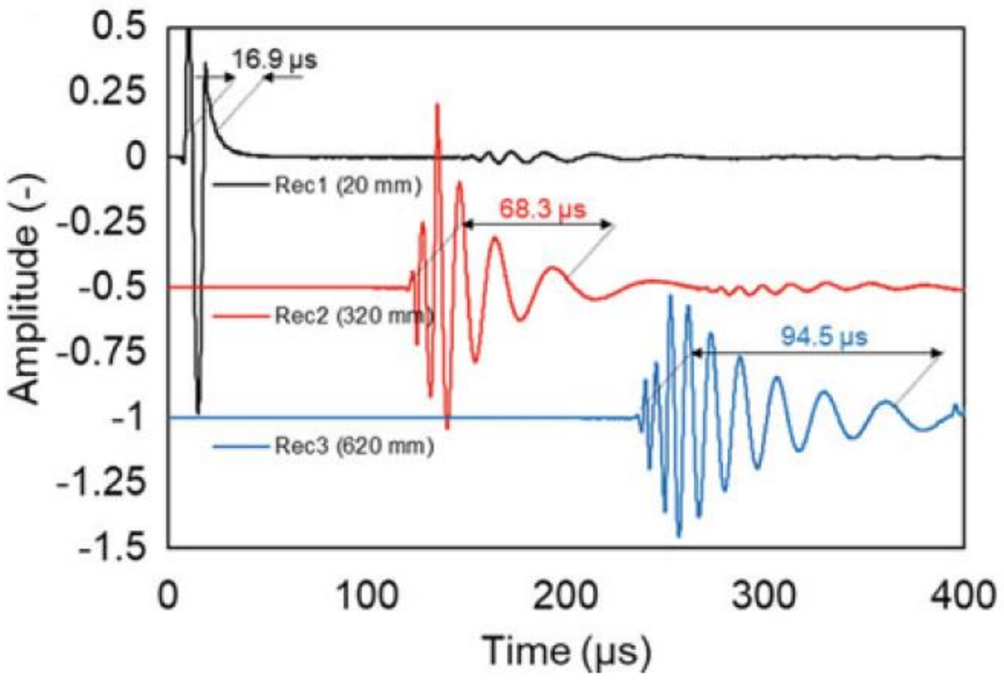




https://doi.org/10.1007/978-3-030-67936-1_9

One cycle of 100 kHz propagating on a half-space

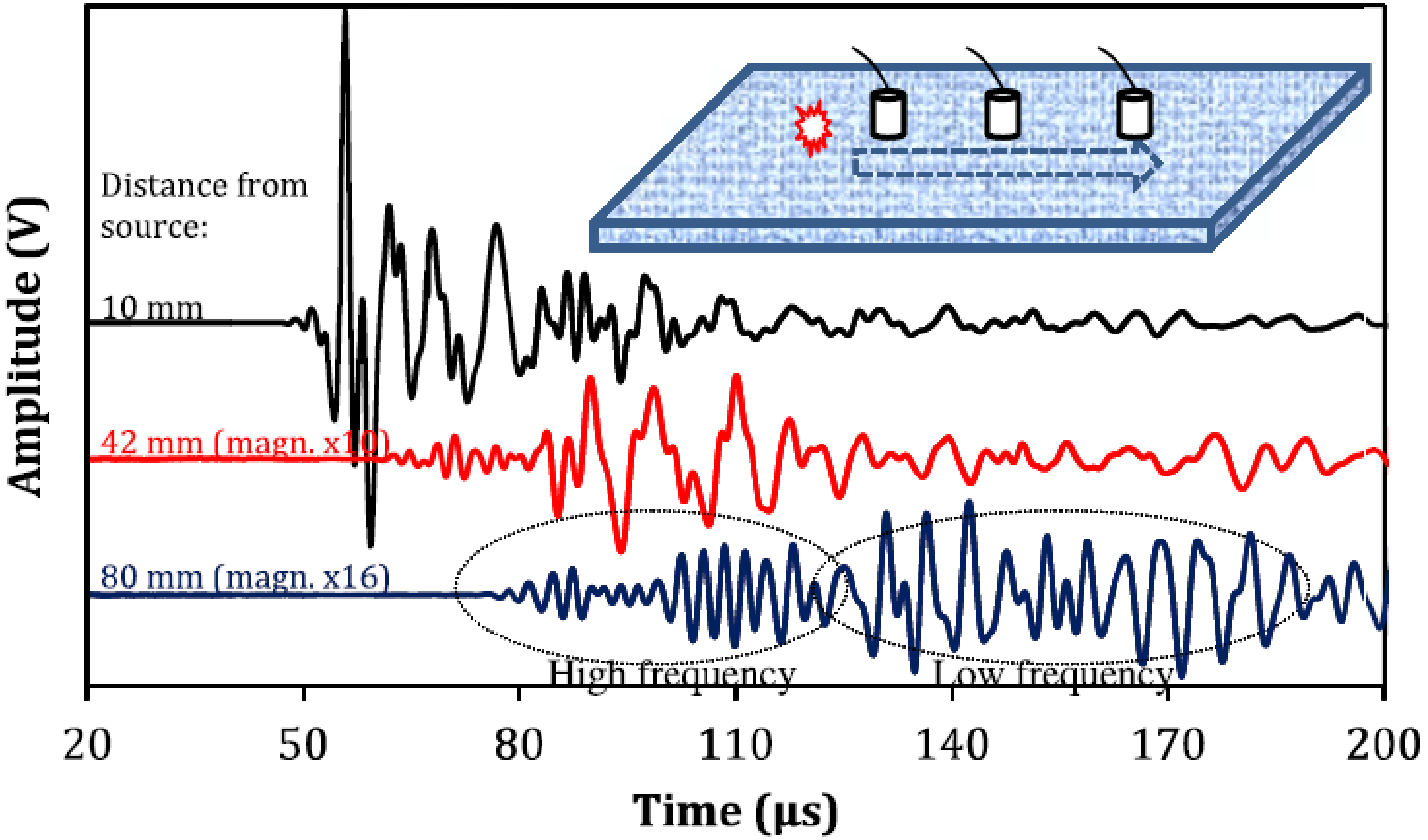




One cycle of 100 kHz propagating on a plate of 5 mm

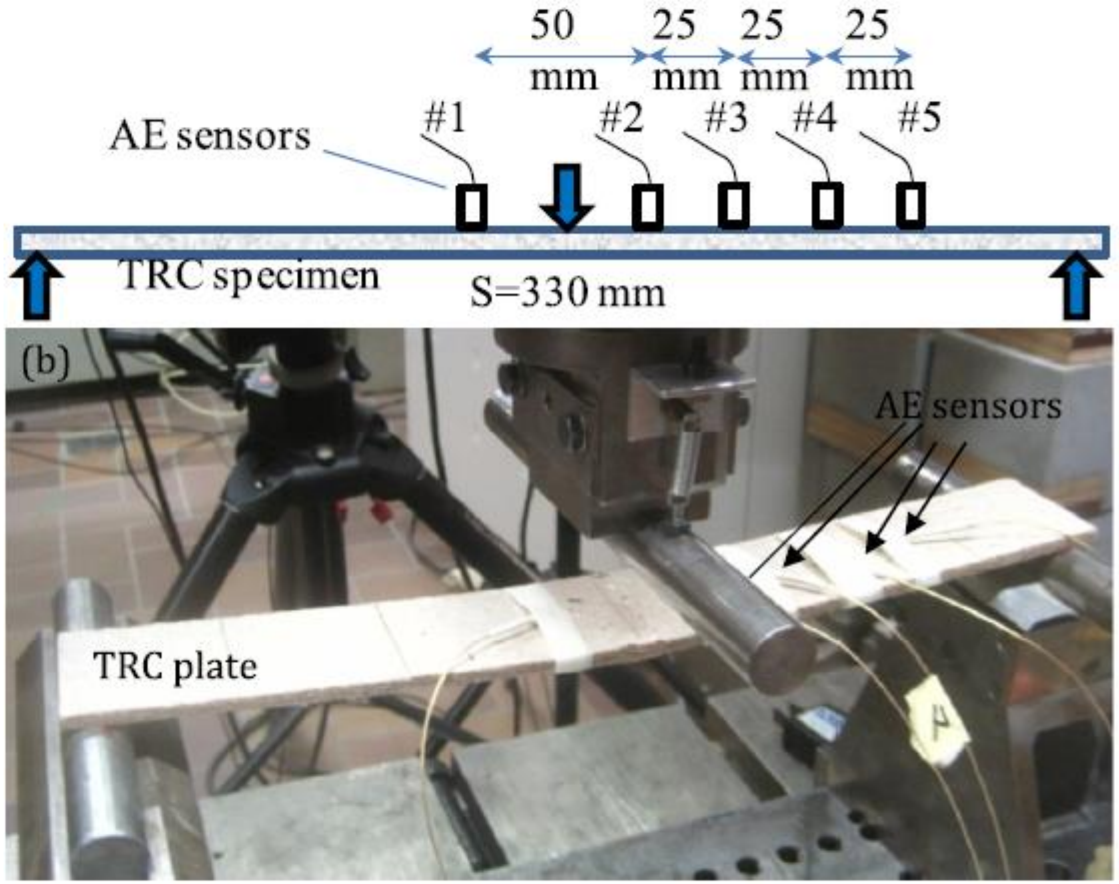
https://doi.org/10.1007/978-3-030-67936-1_9

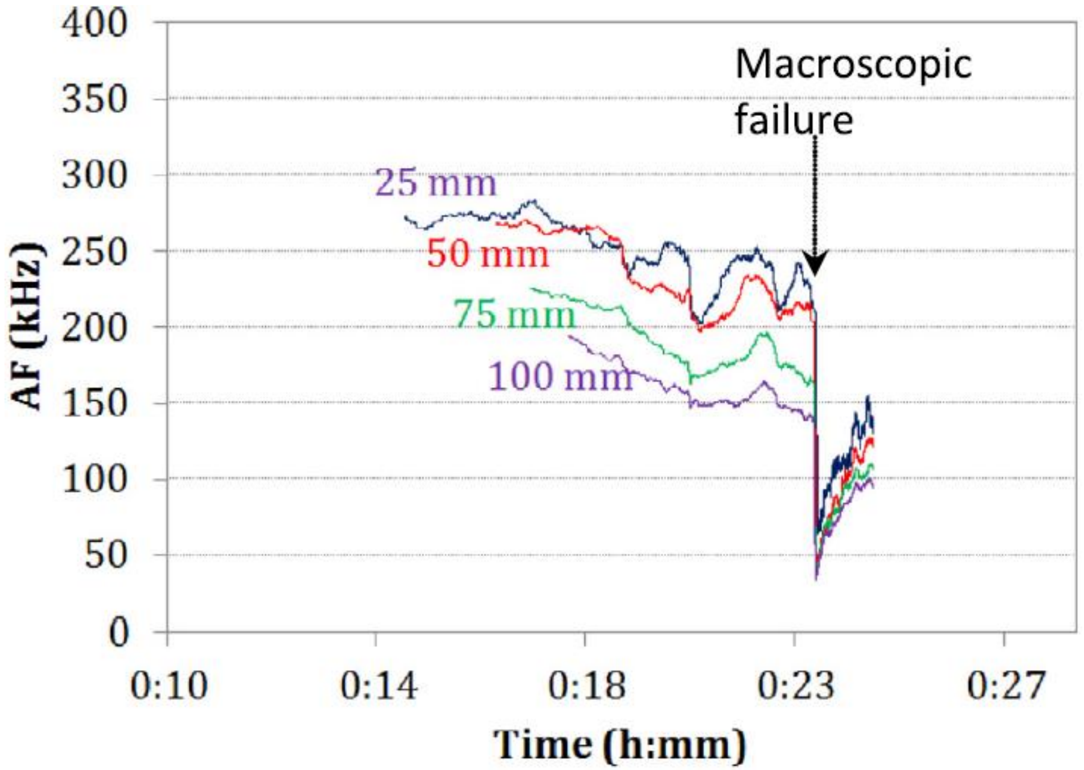
The difference that the dispersion makes in waveforms



http://dx.doi.org/10.1016/j.cemconcomp.2013.08.001

The difference that the dispersion makes in AE parameters

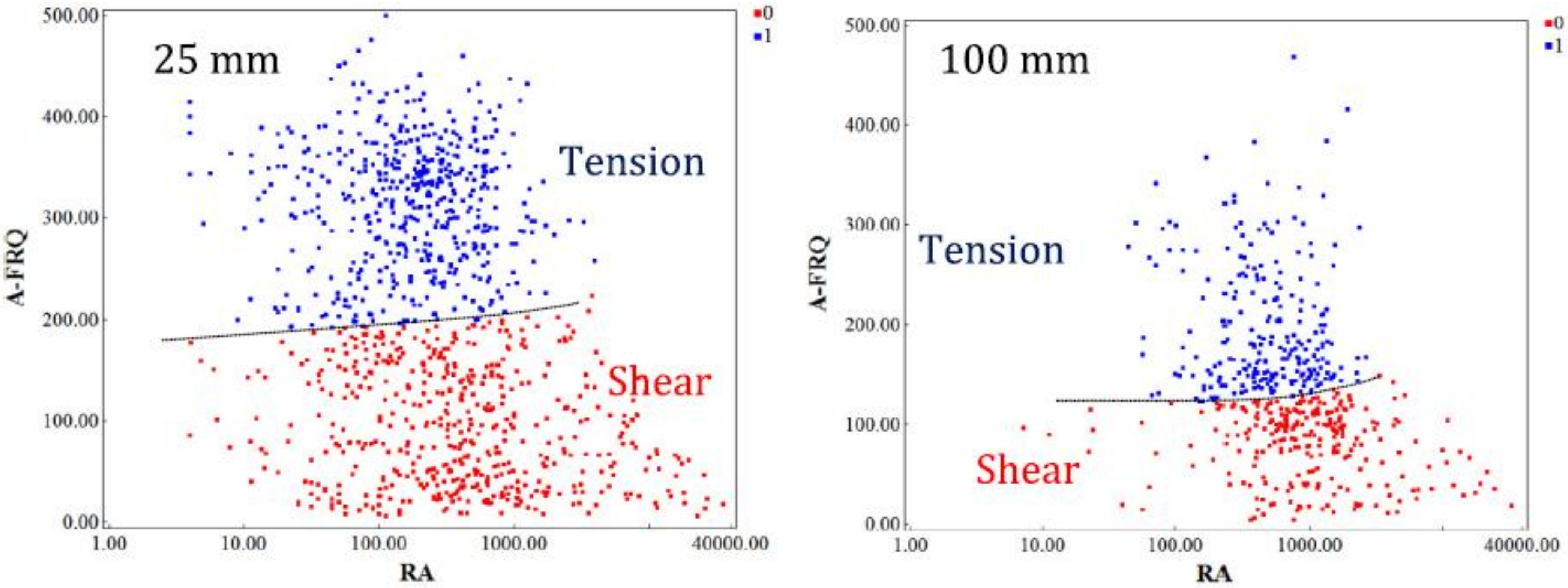




http://dx.doi.org/10.1016/j.conbuildmat.2017.06.166

MeMC MECHANICS OF MATERIALS & CONSTRUCTIONS
DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service
Karlsruhe Institute of Technology
UNIVERSITY OF PATRAS

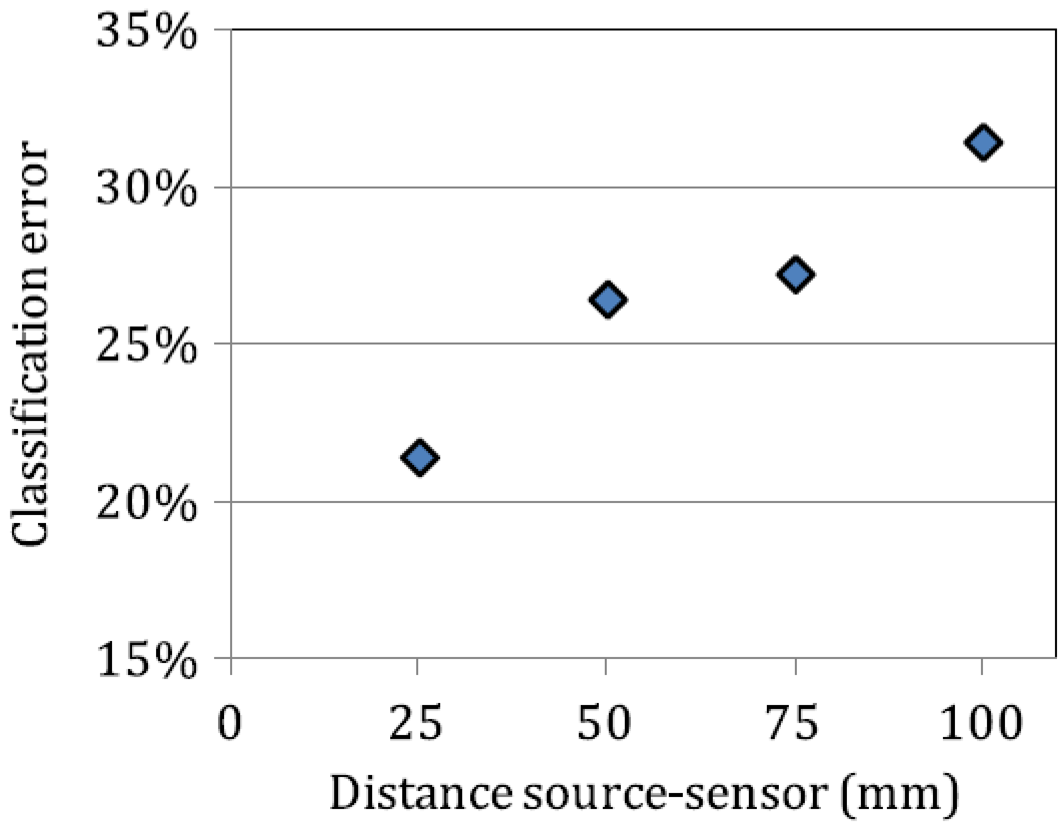
The difference that the dispersion makes in classification of AE signals



Even 75 mm longer propagation strongly changes the separation line.

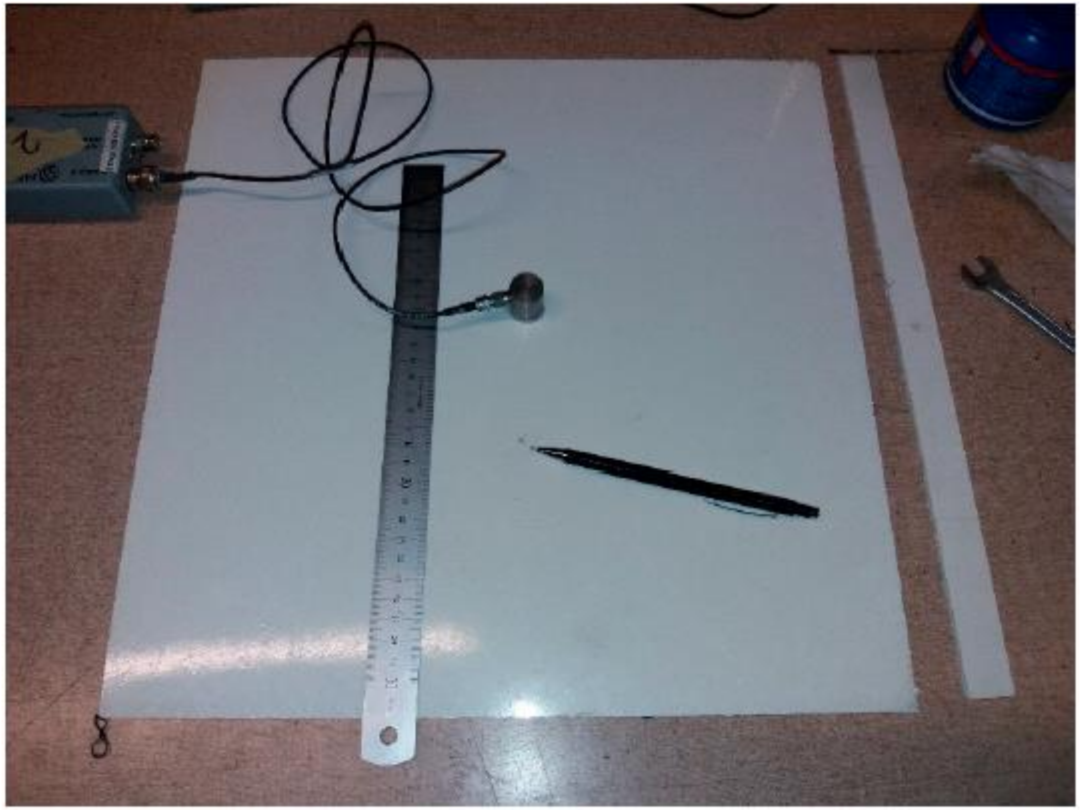
http://dx.doi.org/10.1016/j.conbuildmat.2017.06.166

The difference that the dispersion makes in classification of AE signals



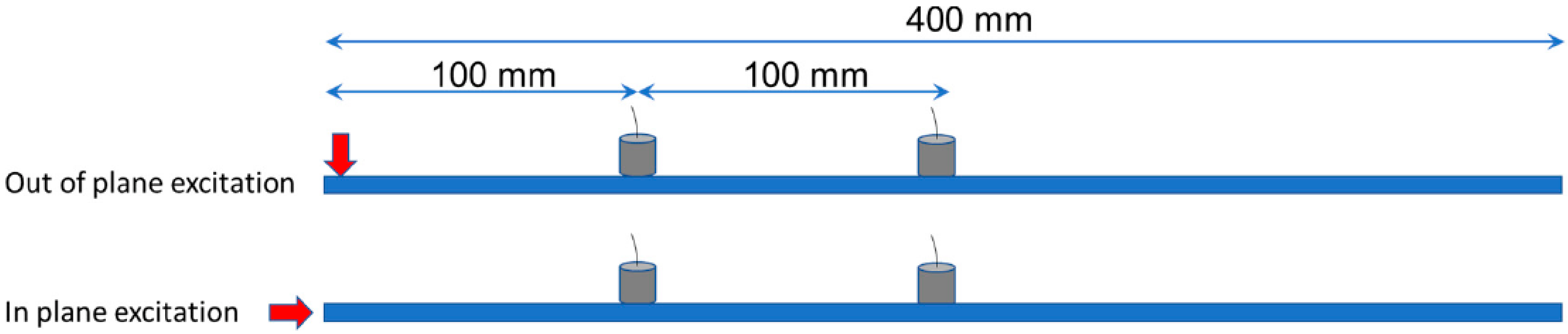
http://dx.doi.org/10.1016/j.conbuildmat.2017.06.166

Effect of dimension on the wave propagation/AE behavior of the composite plates

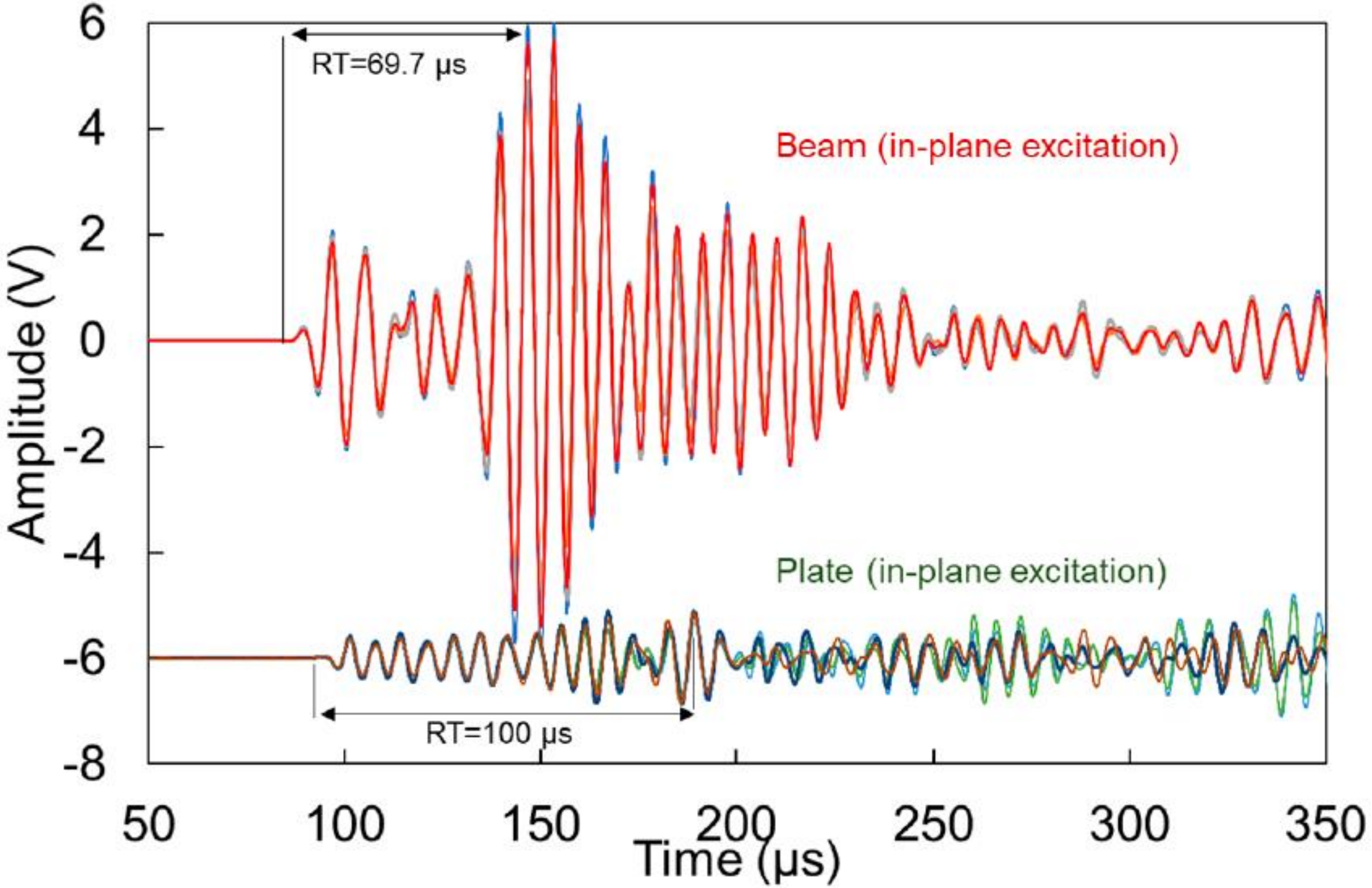


Materials 2020, 13, 955; doi:10.3390/ma13040955

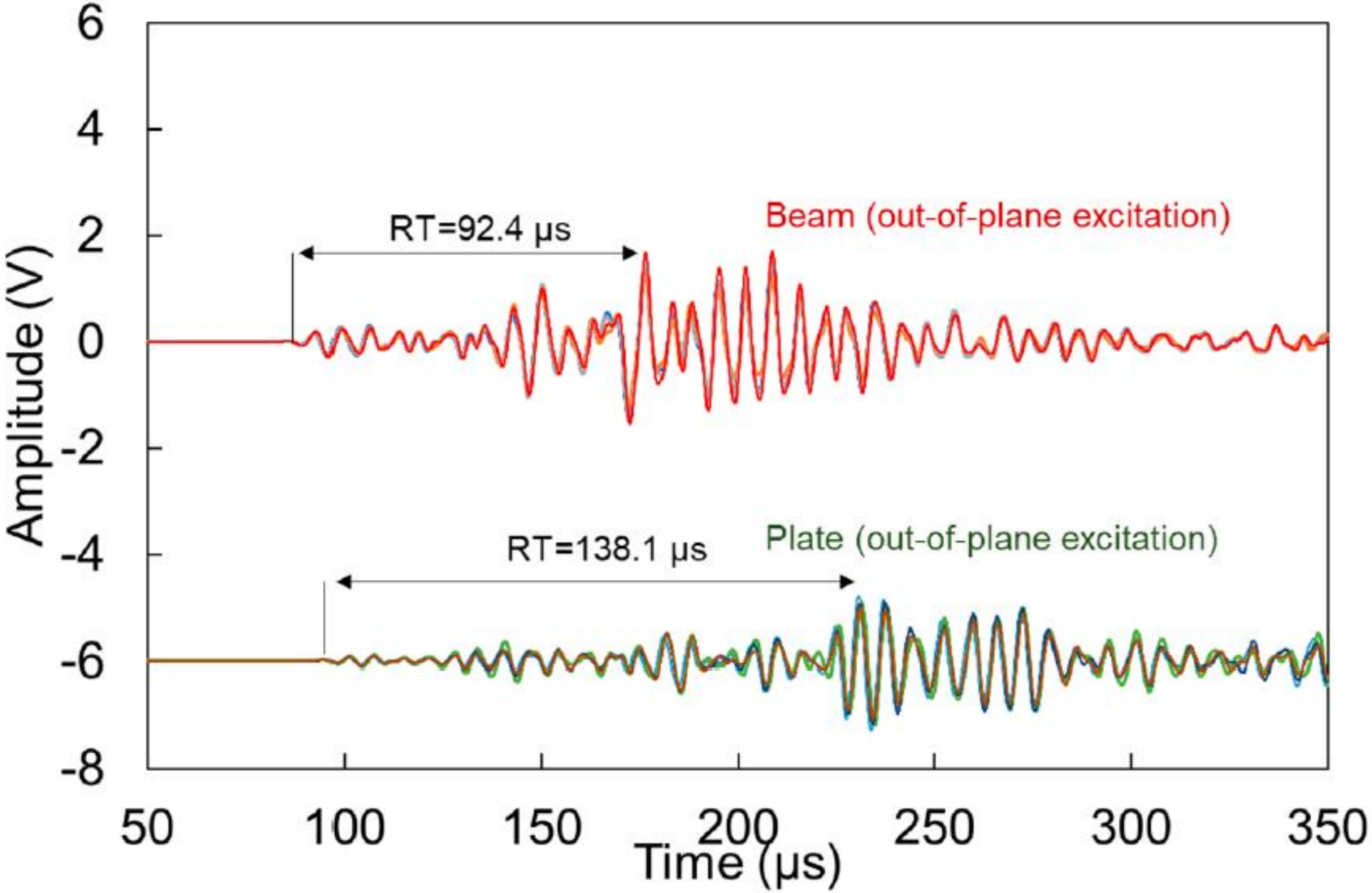
Effect of dimension on the wave propagation/AE behavior of the composite plates



Materials 2020, 13, 955; doi:10.3390/ma13040955



Materials 2020, 13, 955; doi:10.3390/ma13040955



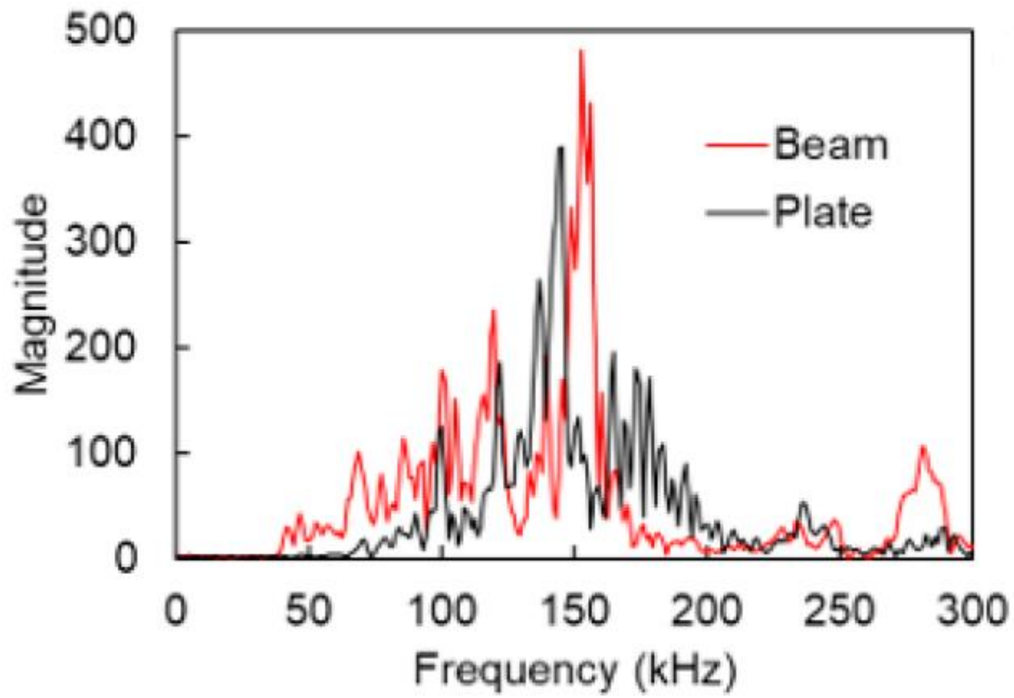
Materials 2020, 13, 955; doi:10.3390/ma13040955

Table 1. Basic waveform descriptors under different excitation in beam and plate geometry.

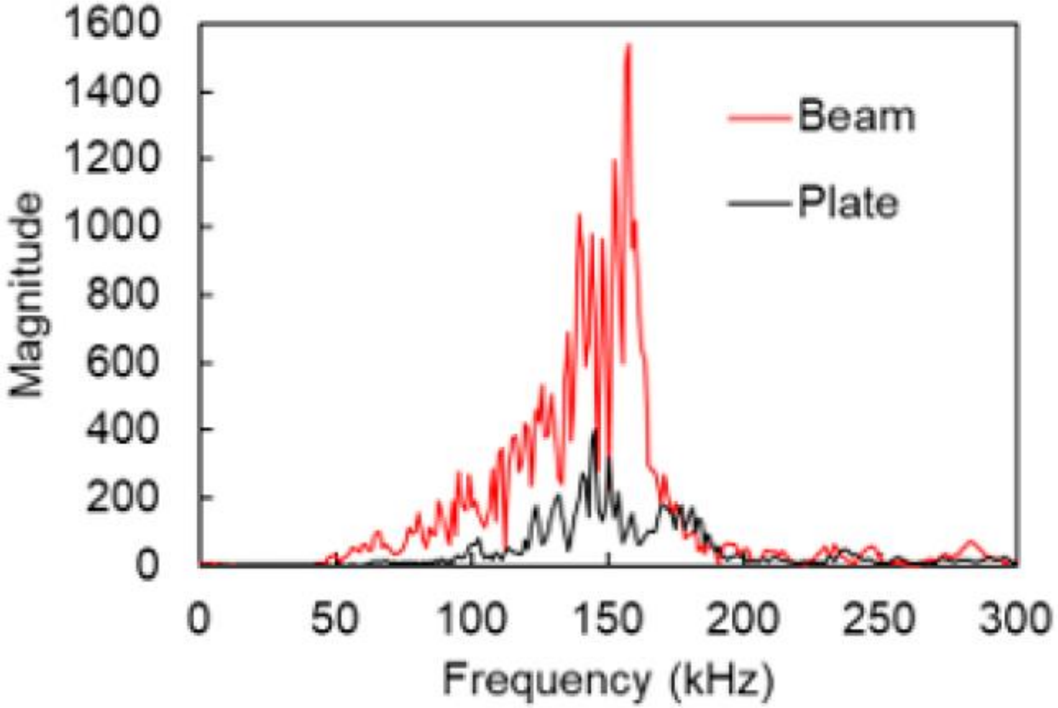
	Out of Plane (Simulating Delamination)	In Plane (Simulating Cracking)	Out of Plane (Simulating Delamination)	In Plane (Simulating Cracking)	Out of plane (Simulating Delamination)	In plane (Simulating Cracking)
	RT (μs)	RT (μs)	Amp (dB)	Amp (dB)	PF (kHz)	PF (kHz)
beam	92.4	69.7	84.6	95.1	152.6	157.5
plate	138. 1	100	80.0	78.8	145.3	145.3

Materials 2020, 13, 955; doi:10.3390/ma13040955

FFT for different excitations and specimen sizes



Out-of-plane



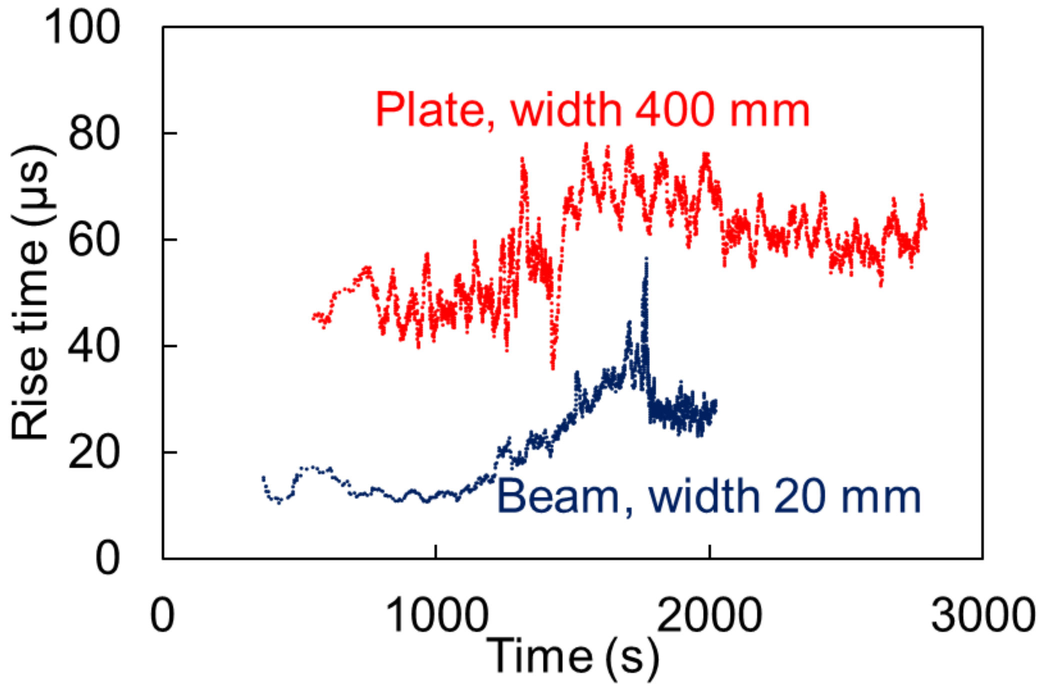
In-plane

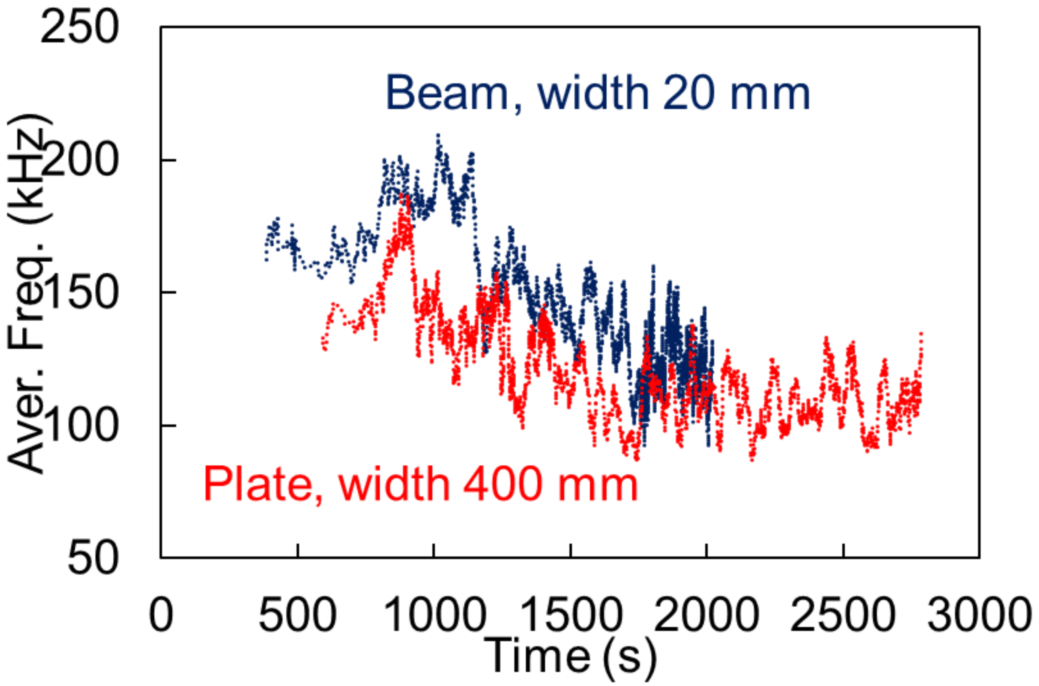
Materials 2020, 13, 955; doi:10.3390/ma13040955

AE experiment in plate and beam

Materials 2020, 13, 955; doi:10.3390/ma13040955

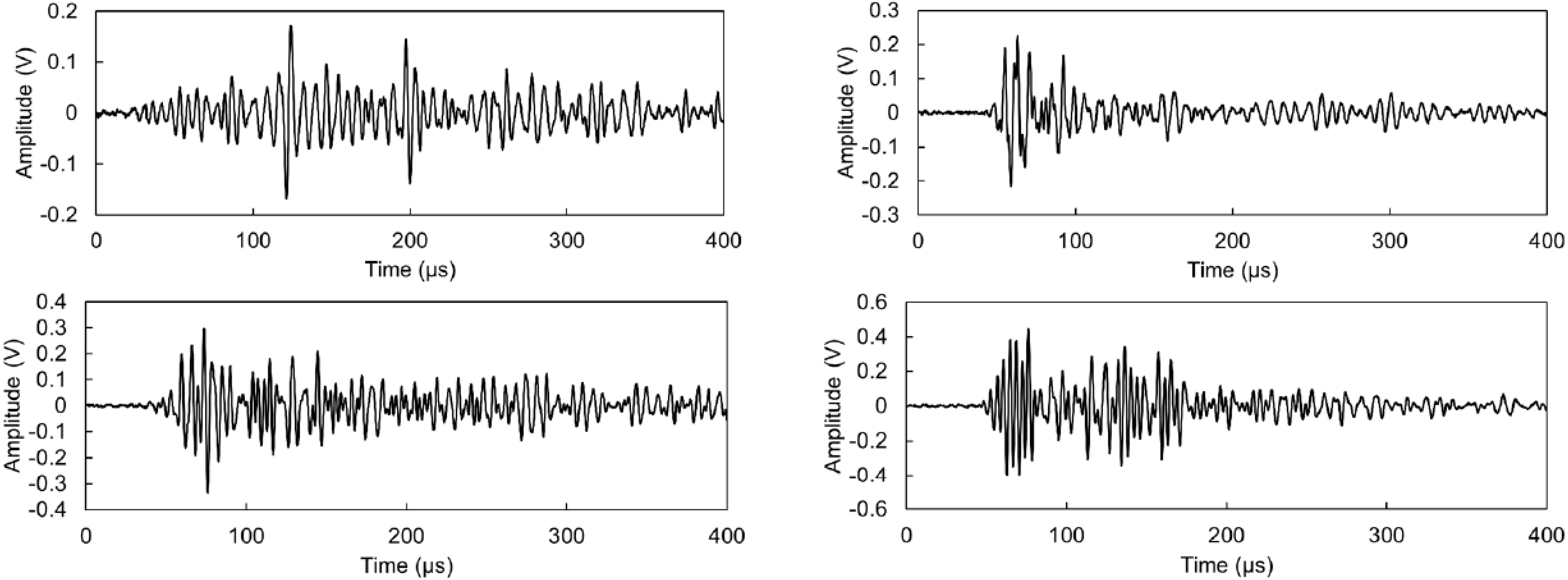
AE experiment in beam and plate





Materials 2020, 13, 955; doi:10.3390/ma13040955

AE from matrix cracking in plate and beam



Plate

Beam

Materials 2020, 13, 955; doi:10.3390/ma13040955

Effect of dimension (beam vs. plate) on the AE parameters for the same fracture mode (matrix cracking)

Table 2. Basic waveform descriptors of cracking signals in beam and plate geometries.

	RT (μs)	DUR (μs)	Amp (dB)	AF (kHz)	IF (kHz)
beam	14.0	65.6	56.4	170.1	389.1
plate	46.0	335.3	60.4	136.6	274.3

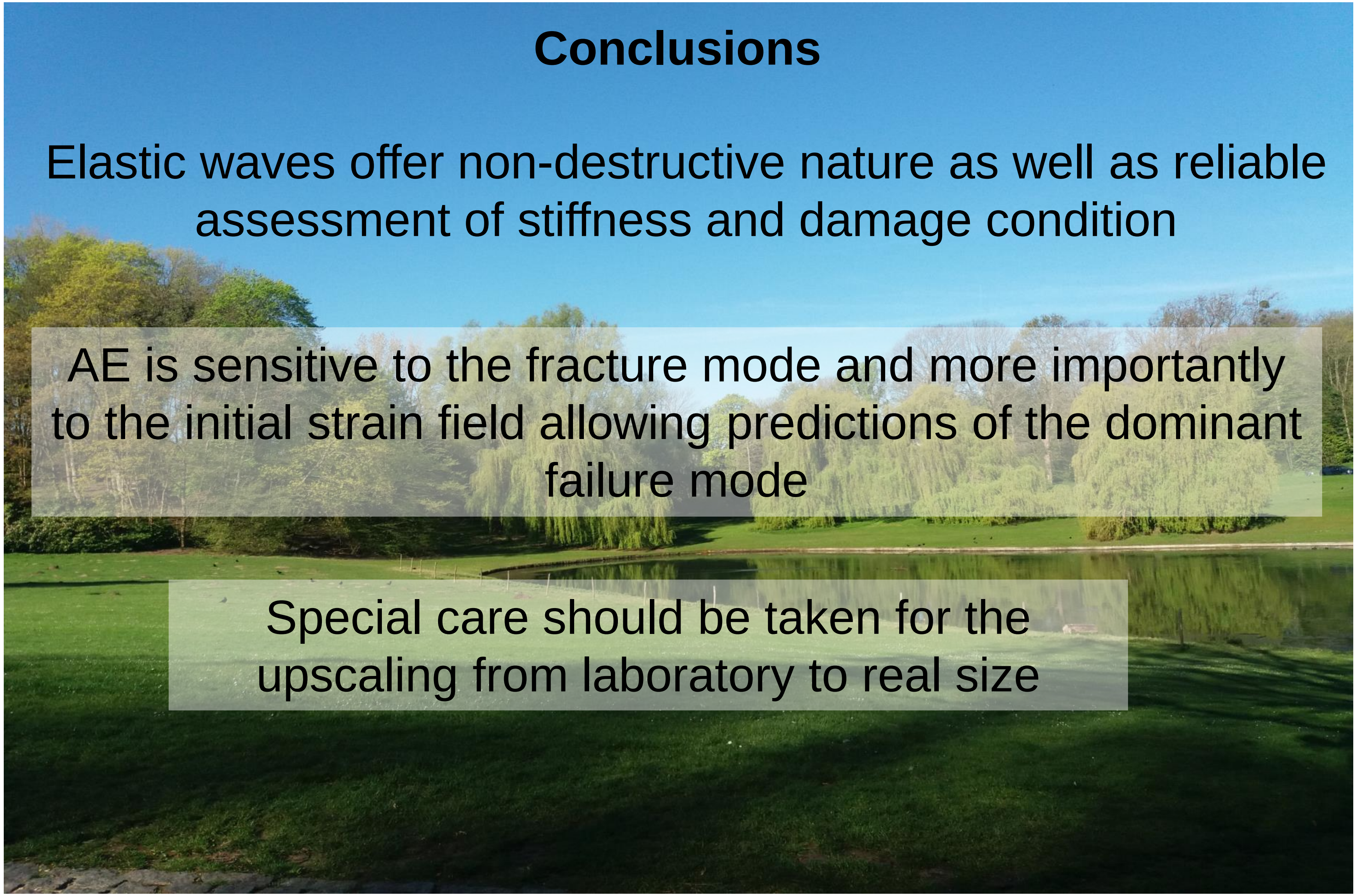
Materials **2020**, 13, 955; doi:10.3390/ma13040955

Conclusions

Elastic waves offer non-destructive nature as well as reliable assessment of stiffness and damage condition

AE is sensitive to the fracture mode and more importantly to the initial strain field allowing predictions of the dominant failure mode

Special care should be taken for the upscaling from laboratory to real size



Wolluwe park, Brussels

Thank you

daggelis@vub.be

VUB Etterbeek Campus, Brussels