BAM
Bundesanstalt für Materialforschung und -prüfung

Sicherheit in Technik und Chemie

2016-11-29

STATE-OF-THE-ART OF ULTRASONIC MONITORING OF CONCRETE

Dr. Ernst Niederleithinger

ANSHM Nov 30 2016, Melbourne

Teaser

- Will the iconic constructions of today last as long as those of the past?
- Or at least until the end of their designed life span?

Romesightseeing.net

Wikipedia/Mike Holzmann

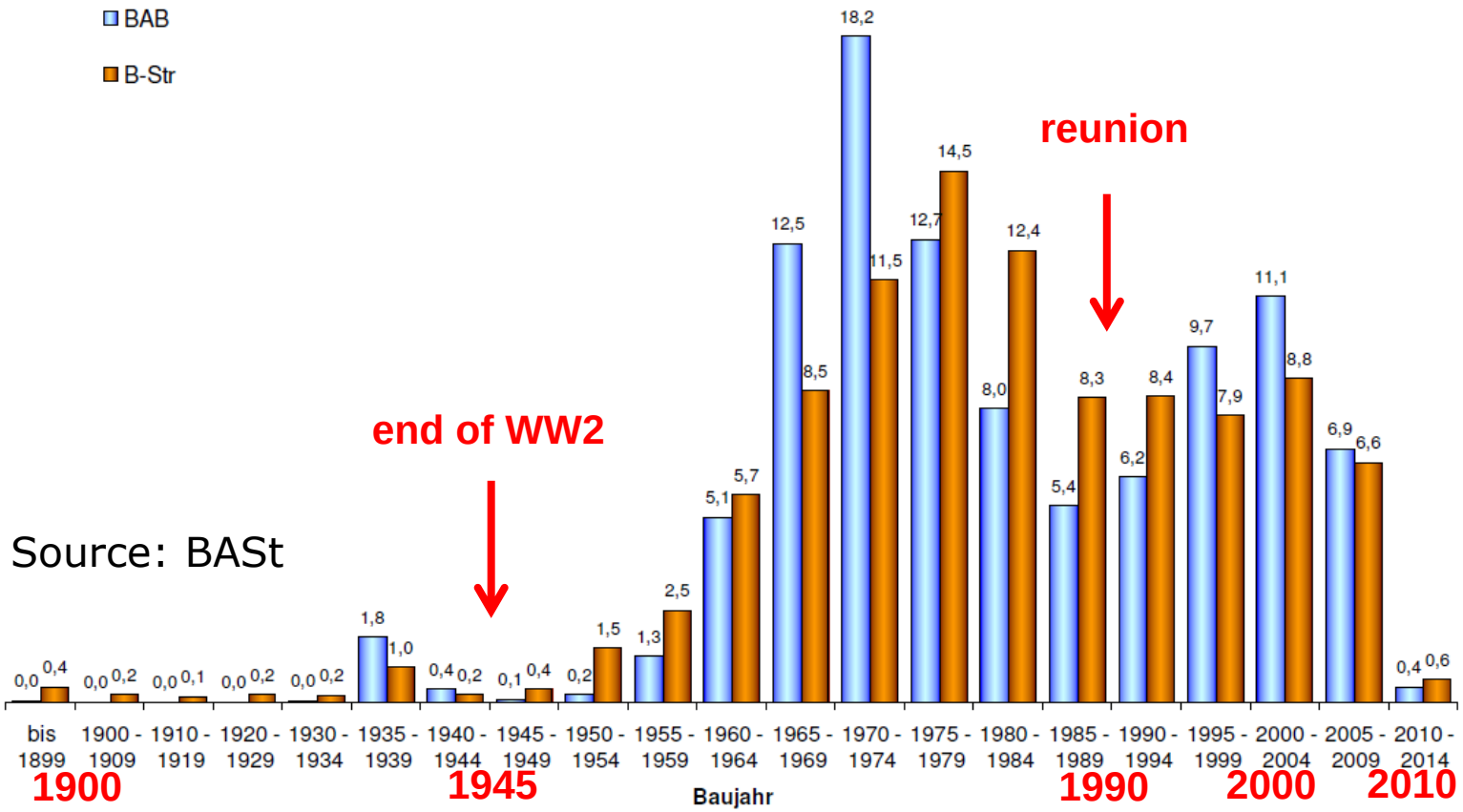
Teaser

– Sometimes the cause and amount of damage is obvious, but most times not that much.

Jonas Ekstromer / Scanpix Sweden via Reuters

Sweden, 2013

Why bother?



Age structure of bridges under federal administration in Germany

Content

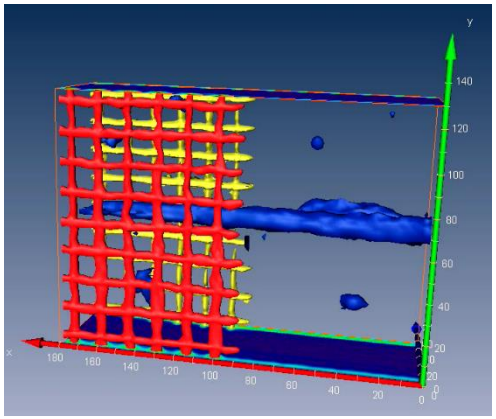
- Motivation – Why bother?
- Ultrasonics on Concrete – Recent Research at BAM
- How to detect changes in concrete by ultrasound?
- Hardware – embedded tranducers
- Experiments in lab and field
- Imaging of Changes
- Conclusions and Outlook

BAM: Bundesanstalt für Materialforschung und -prüfung

- Federal Institute for Materials Research and Testing
- Governmental research institute founded 1881 in Berlin, Germany
- About 1800 employees
- Safety in technology and chemistry
- Departmenst on NDT and civil engineering

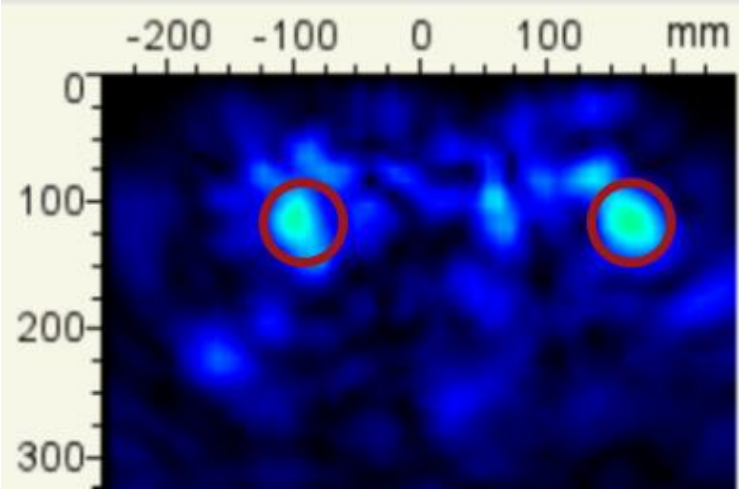
Division 8.2

- Division 8.2 NDT in civil engineering
- >25 years of research on NDT for concrete and masonry
- Ultrasound, acoustic, radar, impact echo, resistivity, LIBS …
- Interdisciplinary group, 35 persons



Why bother?

Ultrasound is meanwhile sucessfully established in lab investigations, quality assurance and inspection.



State of the art

Grouting Defects Localized by Ultrasonic Testing Including Phase Evaluation

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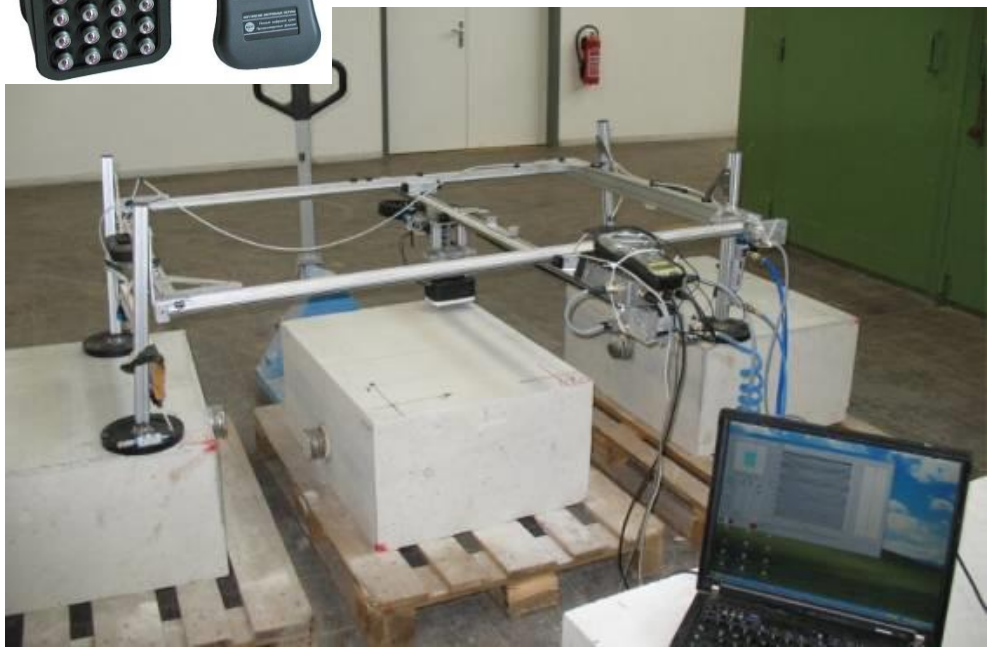
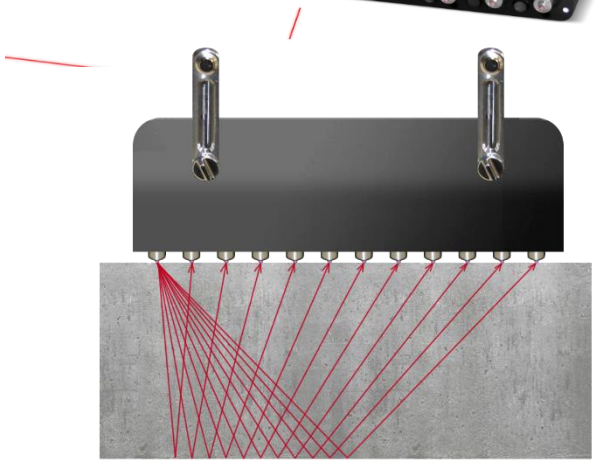
SMT 2014, Washington DC

State of the art: devices

ACS A 1220 Monolith

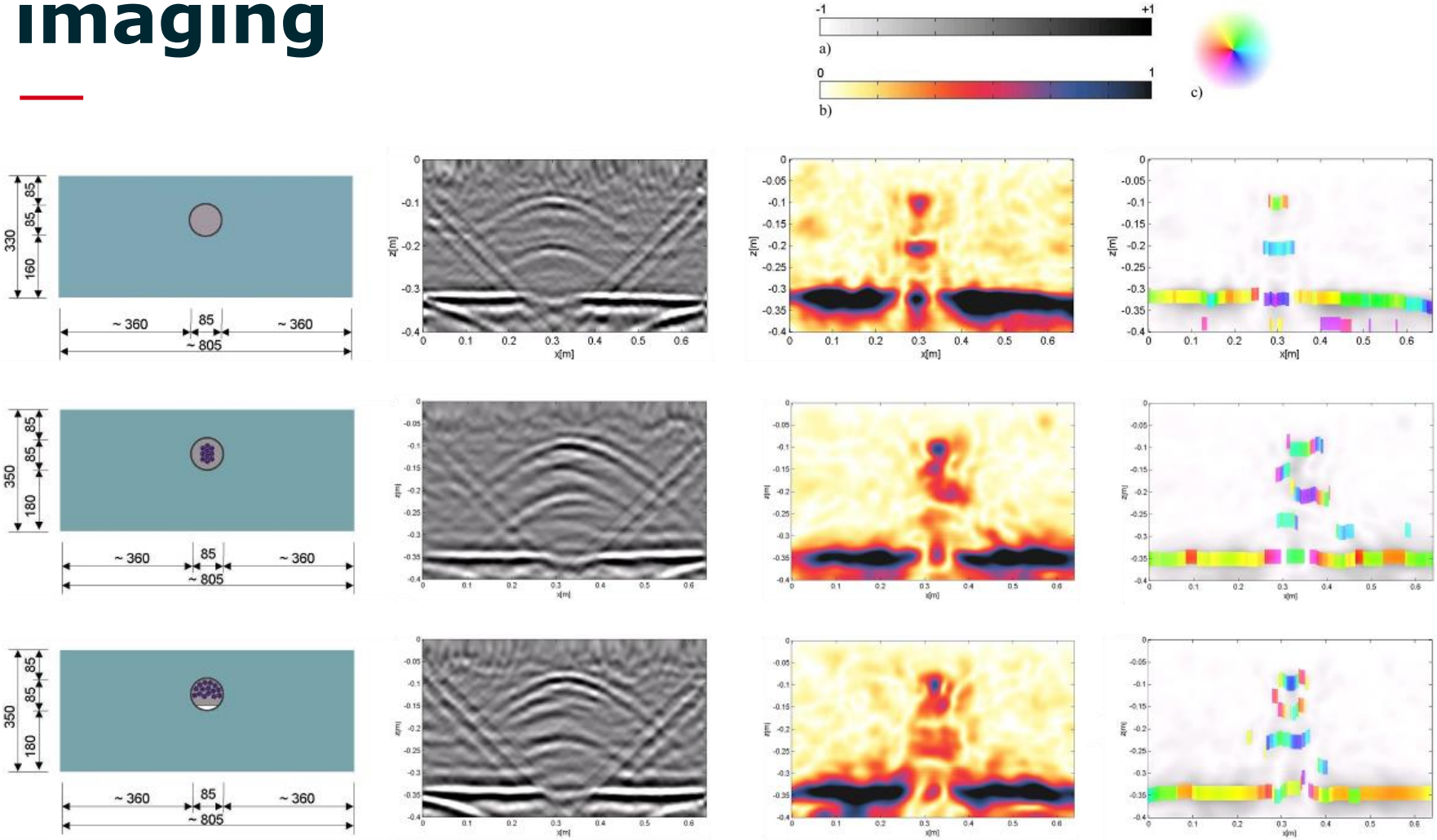
BAM scanning device for concrete inspections





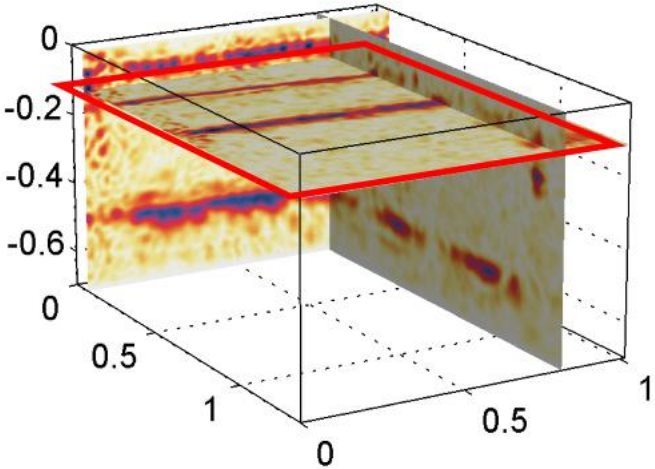
ACS A1040 Mira (www.acsys.ru)

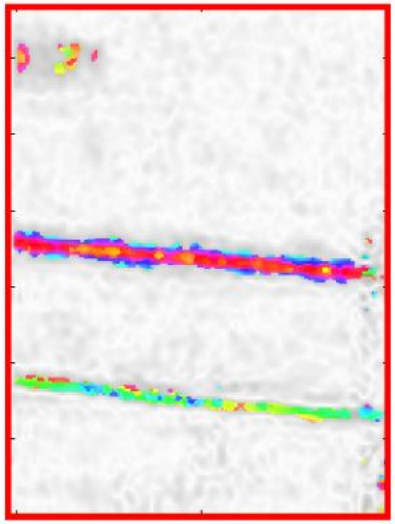
State of the art: imaging

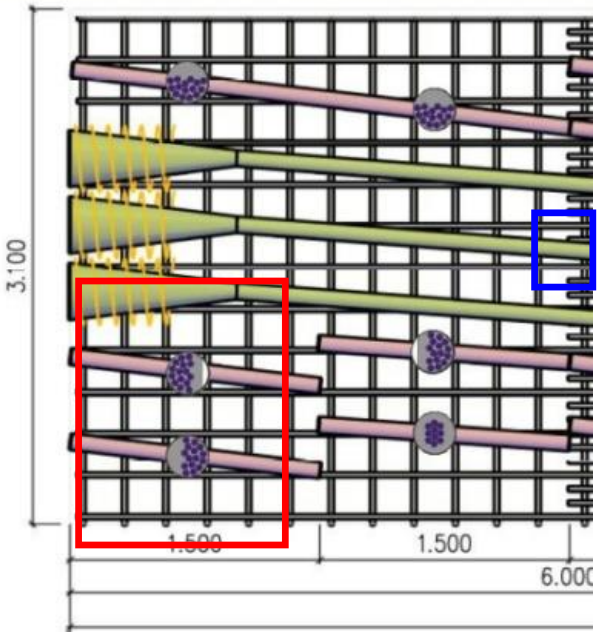


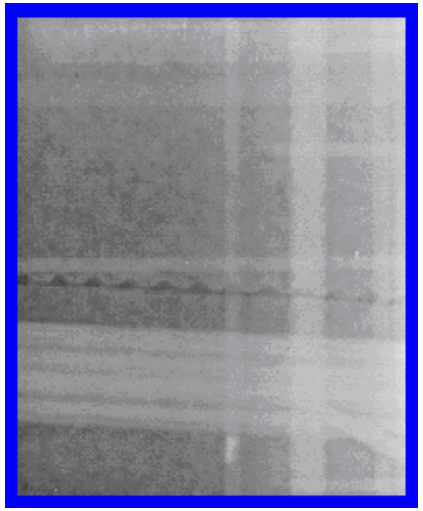
Structure Data SAFT Phase evaluation

State of the art: imaging



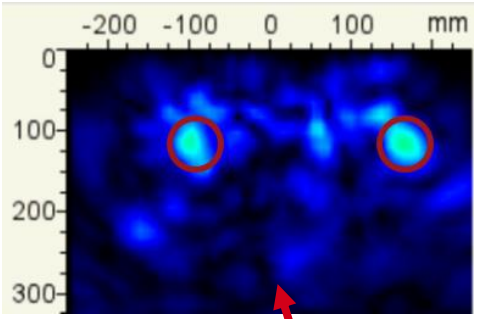






Tendon duct with artificial flaw in a mockup
At BAM TTS Horstwalde
Investigates by US echo and X-ray

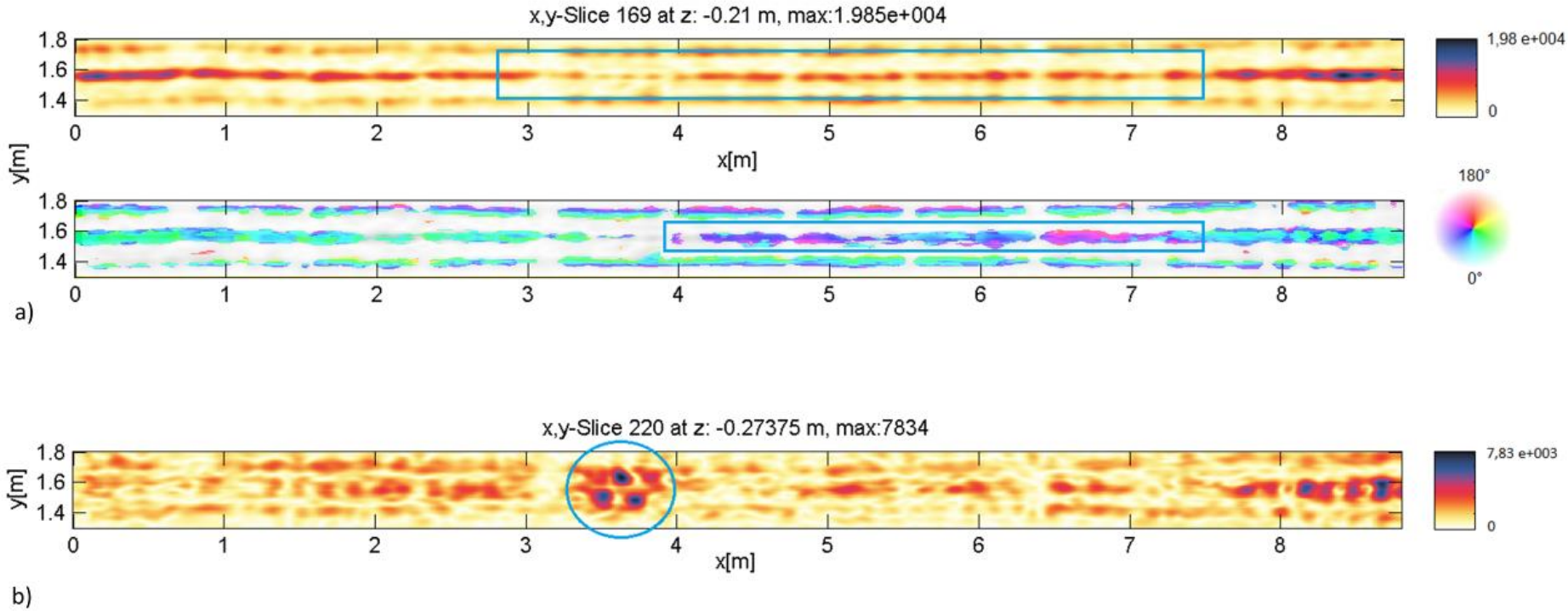
State of the art: imaging



Post tensioned bridge, investigation using A1040 Mira (55 kHz)

1 tendon damaged and accidentily filled with concrete before tensioning

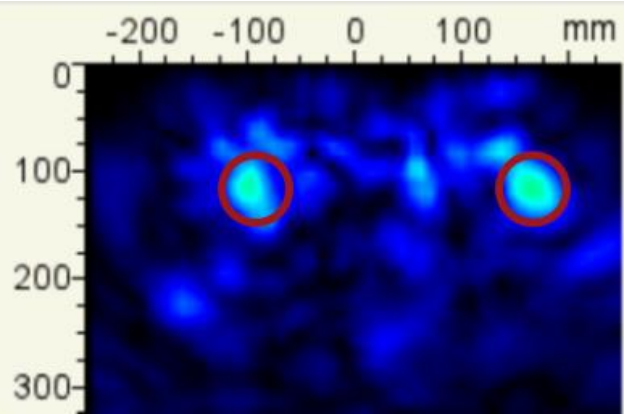
State of the art: imaging



Phase evaluation shows concrete filled part, amplitude shoes blockage

Quite high quality already! Again: Why bother?

Ultrasound is meanwhile sucessfully established in lab investigations, quality assurance and inspection.



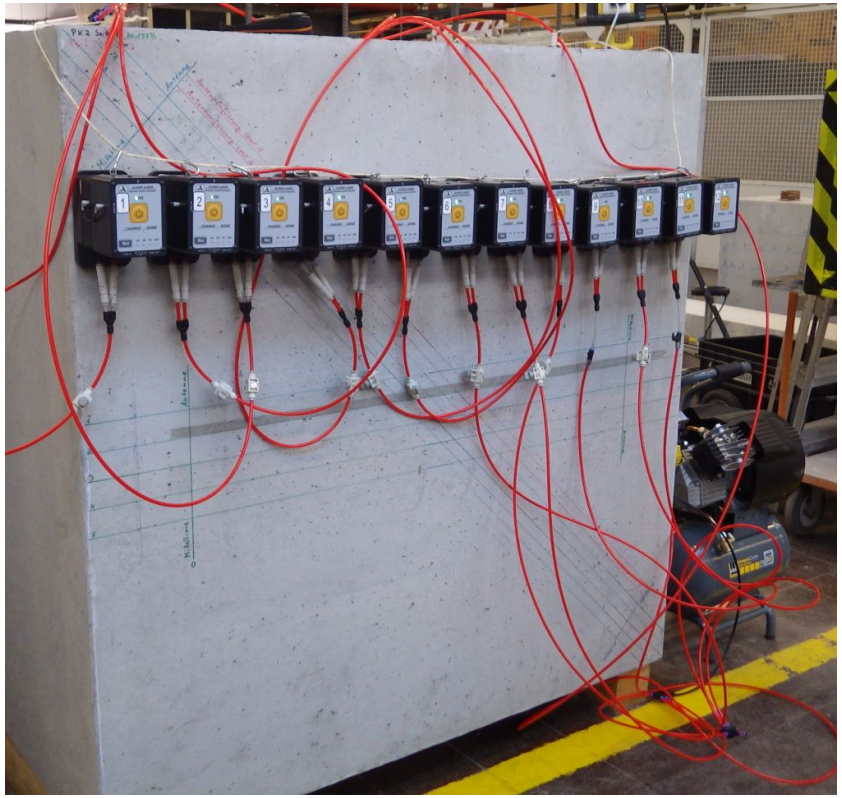
But there are still unsolved issues:

- **Depth of penetration**
- **Imaging complex structures**
- **Mapping diffuse deterioration**
- **Detecting „slow" damages**

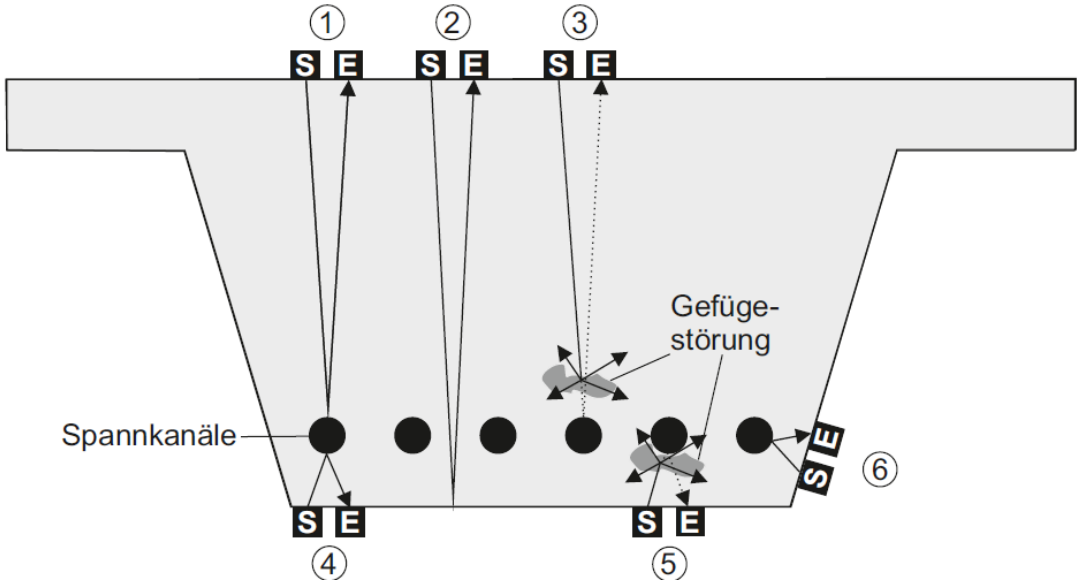
Deep penetration: Introducing the LAUS

New development for thick concrete elements

Large Aperture Ultrasonic System (LAUS)

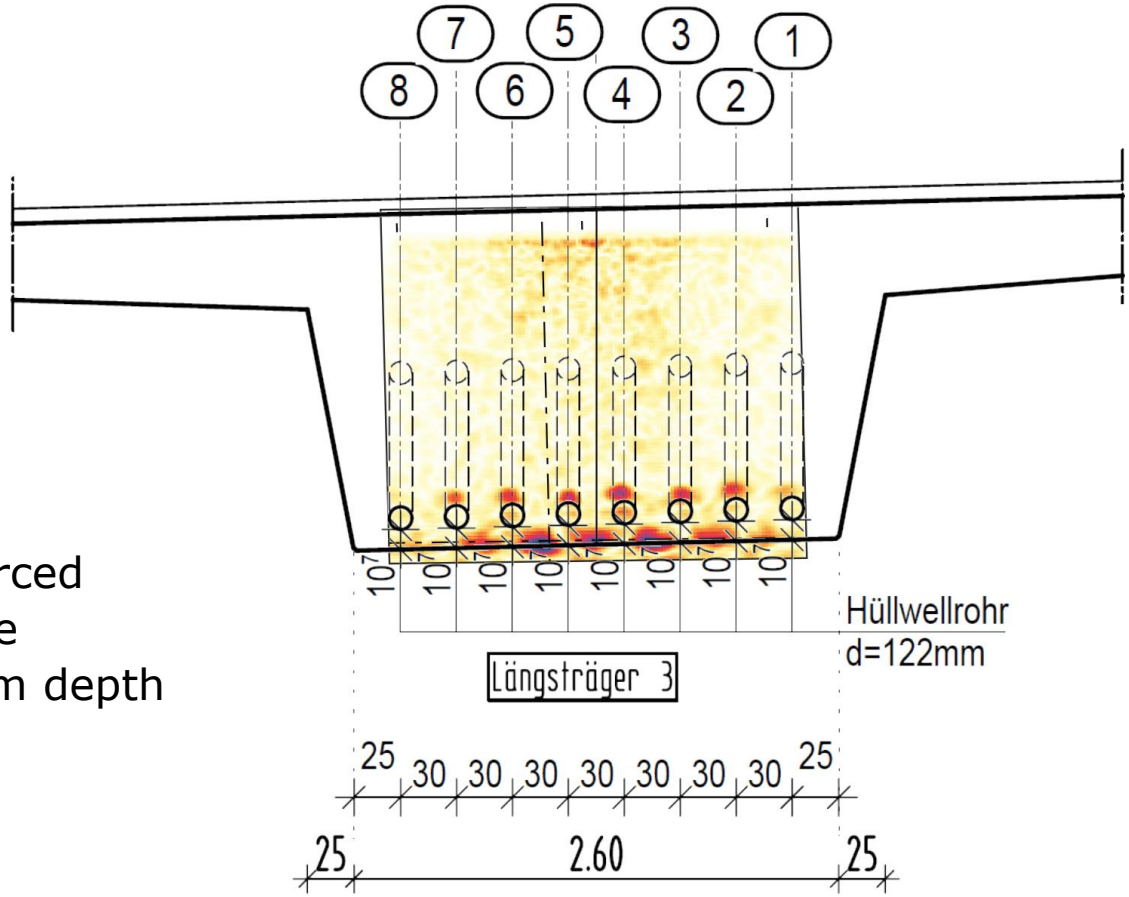


LAUS on a prestessed concrete bridge looking for honeycombing



- Bridge heavily reinforced
- LAUS 3D data volume
- Tendon ducts in 1.8 m depth
- Backwall 2 m depth

LAUS on a prestessed concrete bridge looking for honeycombing



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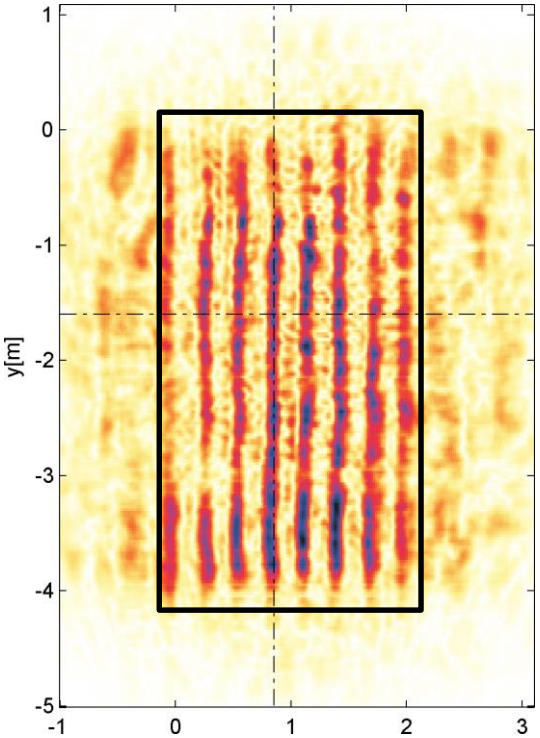
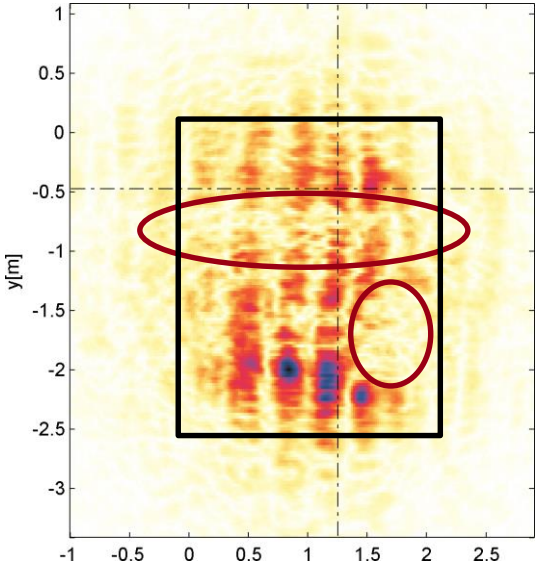
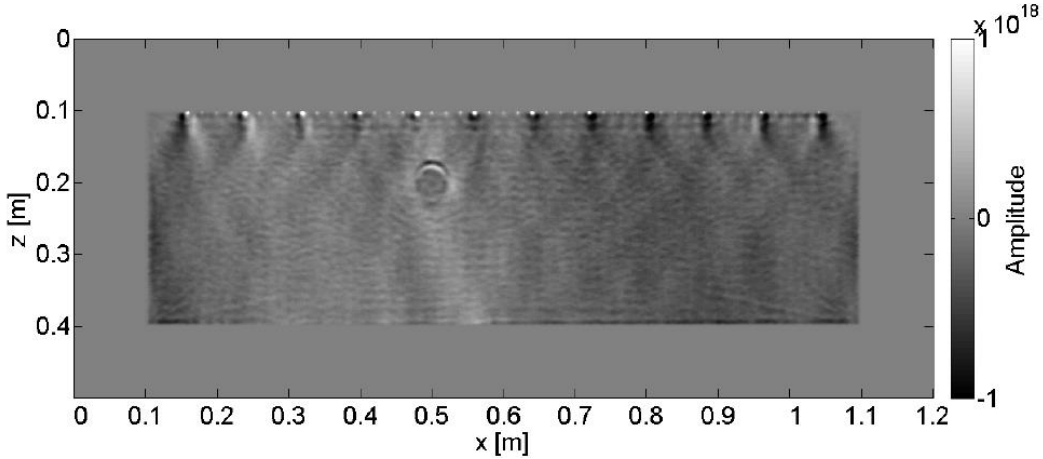




- Most tendons cllearly visible
- Some shadows: Drillhole,
  Honeycombing confirmedBridge heavily reinforced

Improving the imaging: Reverse Time Migration

- RTM is a geophysical imaging technique for echo measurements, now adopted to NDT.
- Use full wavefield in forward and reverse simulations
- Computationally expensive



Grohmann et al., 2016

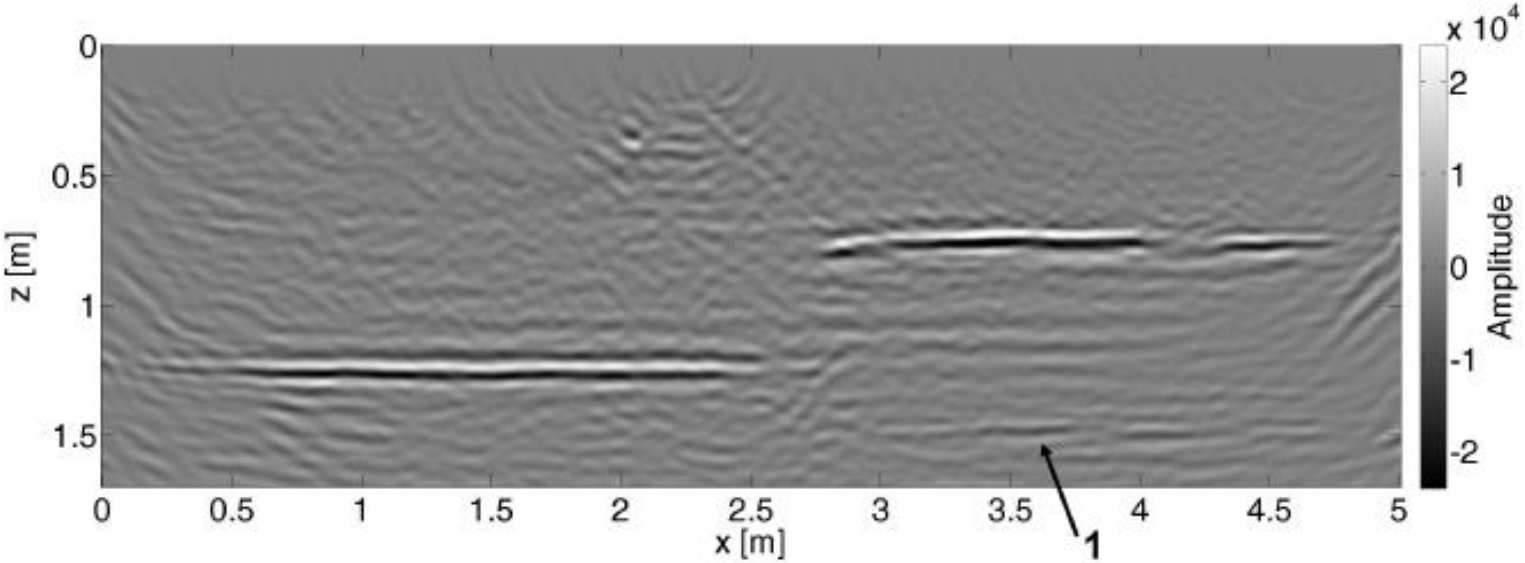
Improving the imaging: Reverse Time Migration

- Field test on 0.75-1.25 m thick foundation slab

Grohmann et al., 2016

Improving the imaging: Reverse Time Migration

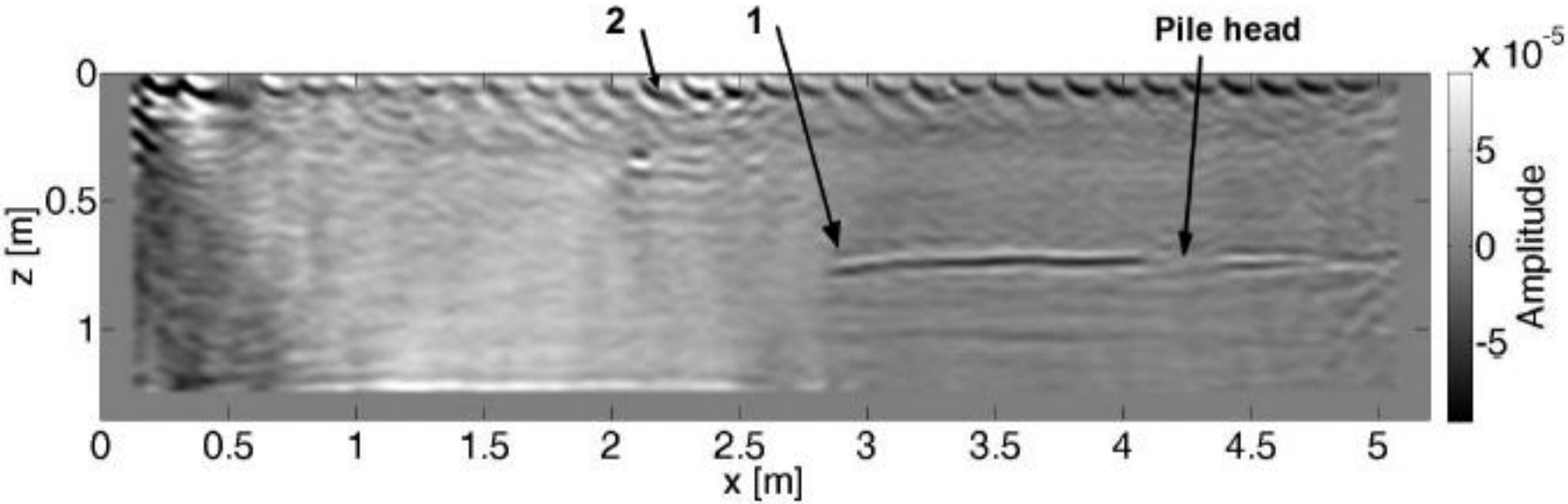
- Field test on 0.75 . 1.25 thick foundation slab
- Conventional SAFT image:



Grohmann et al., 2016

Improving the imaging: Reverse Time Migration

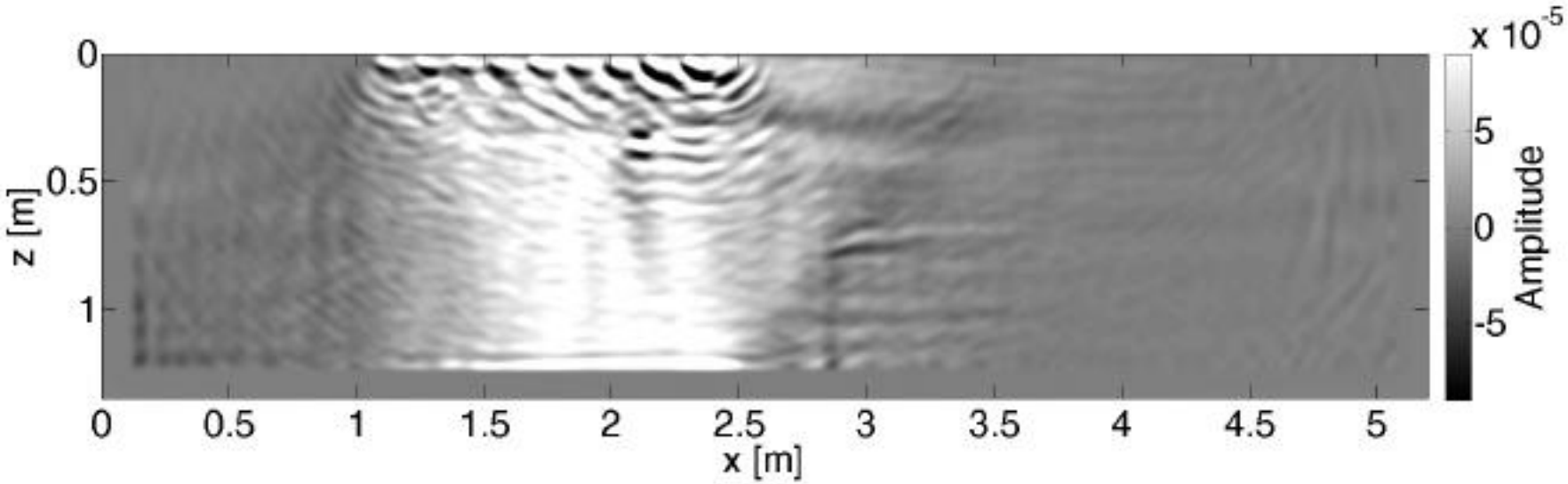
- Field test on 0.75 . 1.25 thick foundation slab
- Full RTM imaga



Grohmann et al., 2016

Improving the imaging: Reverse Time Migration

- Field test on 0.75 . 1.25 thick foundation slab
- Partial RTM image



Grohmann et al., 2016

2nd part: Monitoring

So much about imaging structures,

Now to something completely different:

Monitoring!

2nd part: Monitoring

Ultrasonic wave propagation depends on:

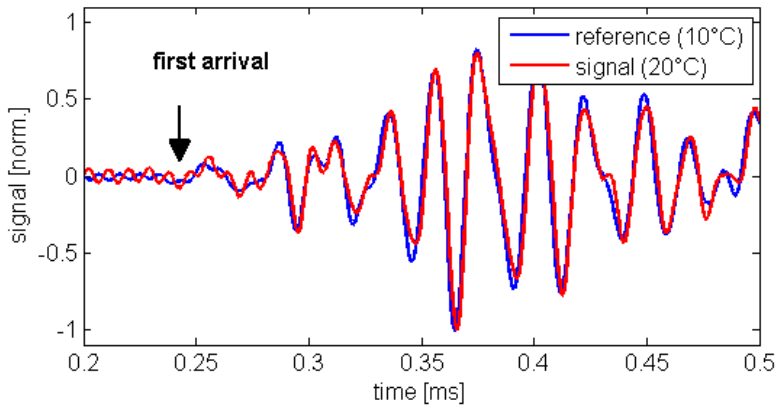
- Material properties (elastic moduli, density)
- Transducer and object geometry (including aggregates, cracks)
- Source and receiver characteristics (frequency, amplitude)

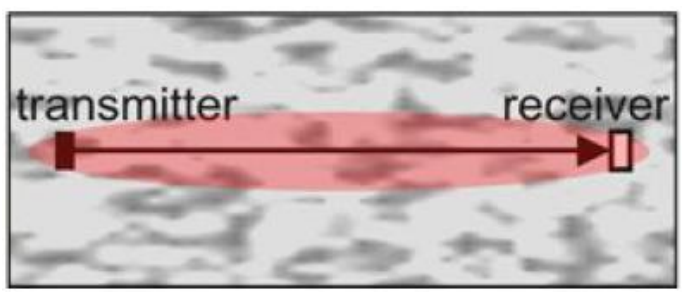
Influence on material properties (and thus US velocity, attenuation):

- Temperature
- Stress
- Moisture
- Any crack-relevant degradation mechanism

Using ultrasonic transmission for monitoring

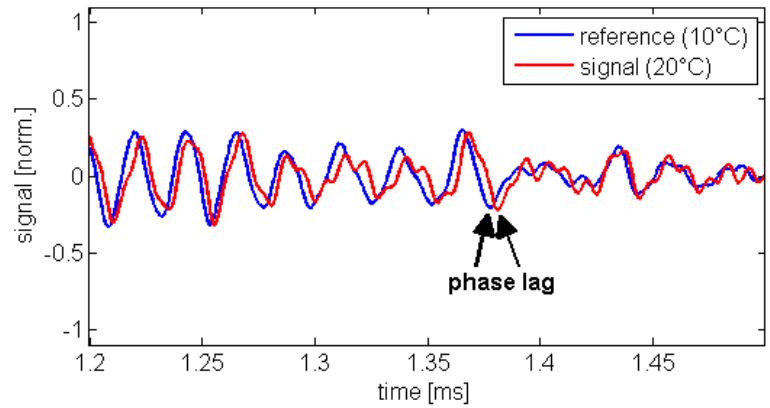
Time of flight: Early part of signals

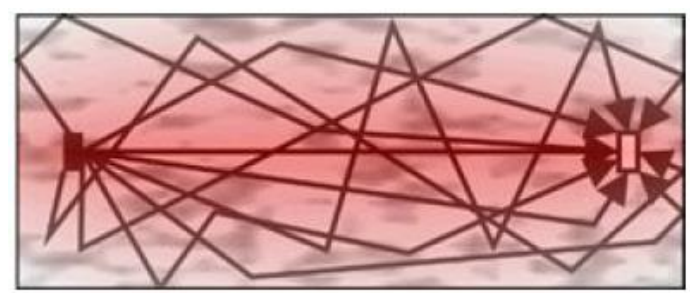




- Low sensitivity to changes
- Small volume of interest
- High directionality

CWI: use also late part of signal





- High sensitivity to changes
- High volume of interest
- Low directionality

Tools for feature extraction: Crosscorrelation

Normalized crosscorrelation
Measure for similarity of two signals x,y
1 if x=y
-1 if x = -y
0 if totally uncorrelated

$$r_{xy} := \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \cdot \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

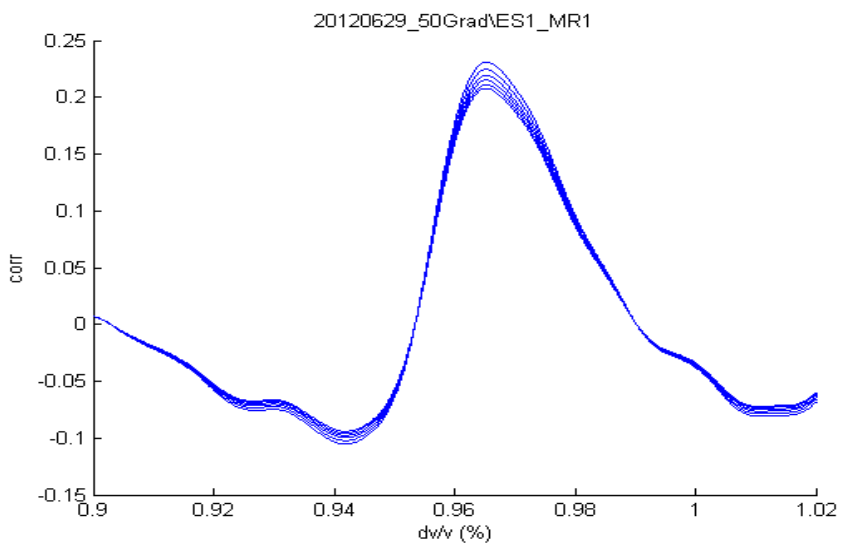
$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

Tools for feature extraction: Coda Wave Interferometry (CWI)

Signal is stretched or compressed in time until it best fits the reference (best fit determined by cross correlation)

Stretching factor v = dv/v

$$CC(\nu) = \frac{\int_0^T h_i(t\cdot(1-\nu))\, h_o(t)\, dt}{\sqrt{\int_0^T h_i^2(t\cdot(1-\nu))\, dt \int_0^T h_0^2(t)\, dt}} = \max .$$



Some assumptions made:
Velocity change homogeneous
Same change für p- and s-waves

Snieder, 2002, 2004
Sens-Schönfelder and Wegler, 2006
Planes et al, 2013

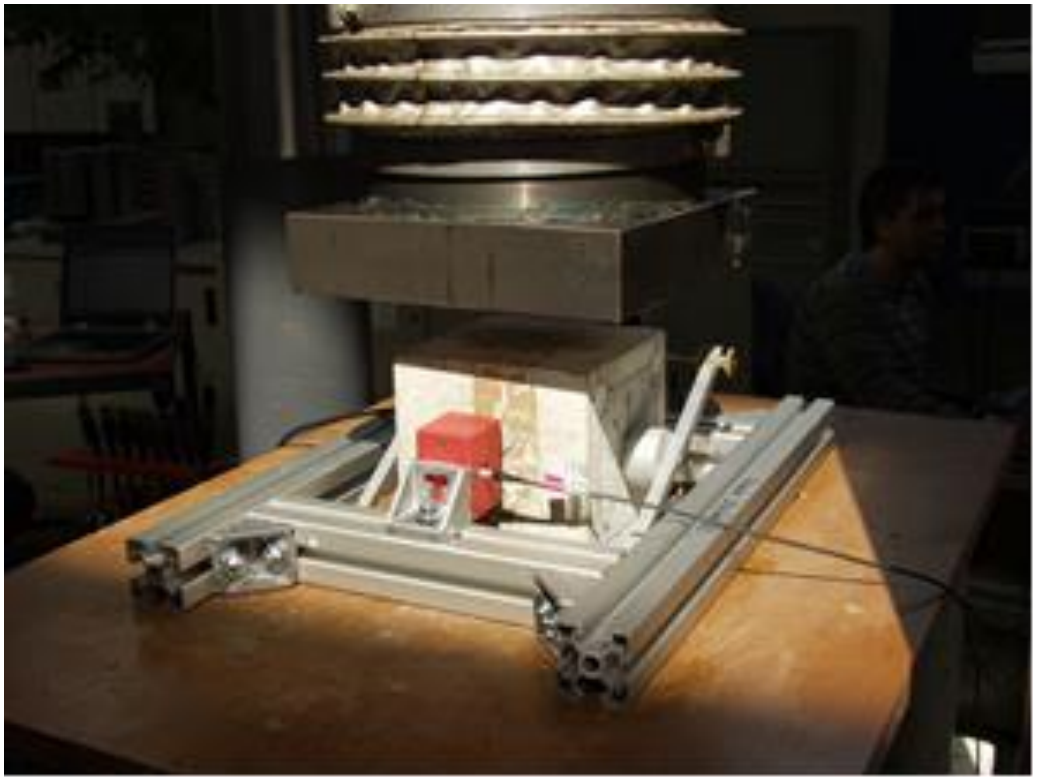
Ultrasonic properties as proxys for loads

Example for sensitivity: velocity change vs. stress dependence

Uniaxial load

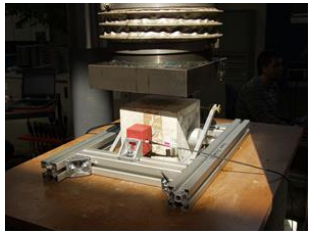
0- 45 Mpa

P-wave transducers 100 kHz



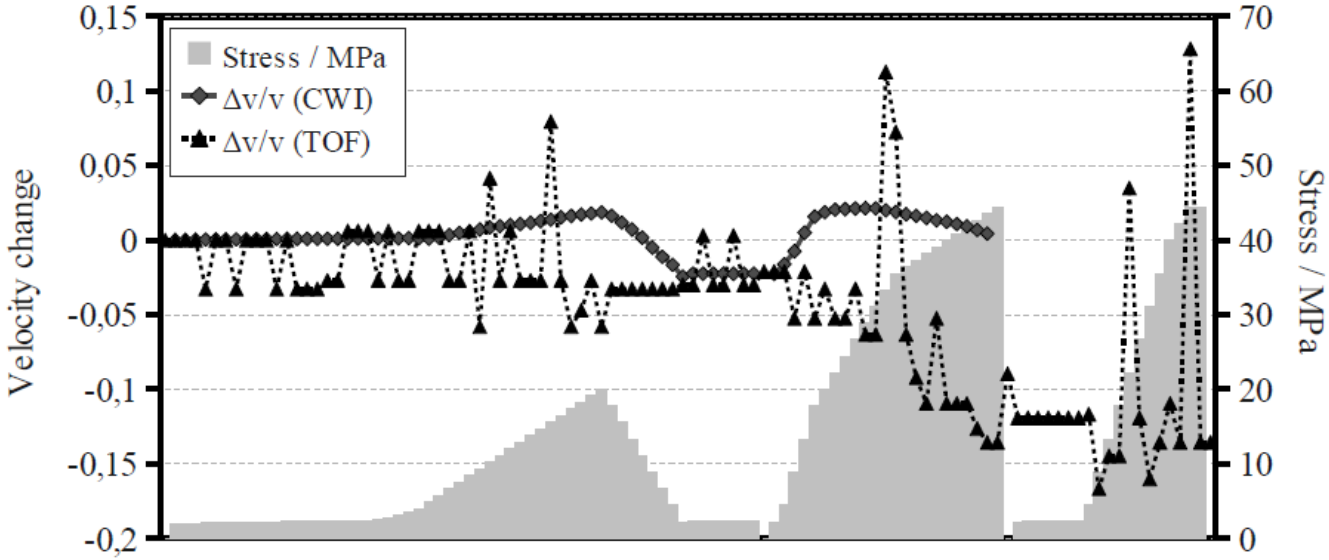
Stähler et al., 2009

Ultrasonic properties as proxys for loads



Example for sensitivity:
velocity change vs. stress dependence

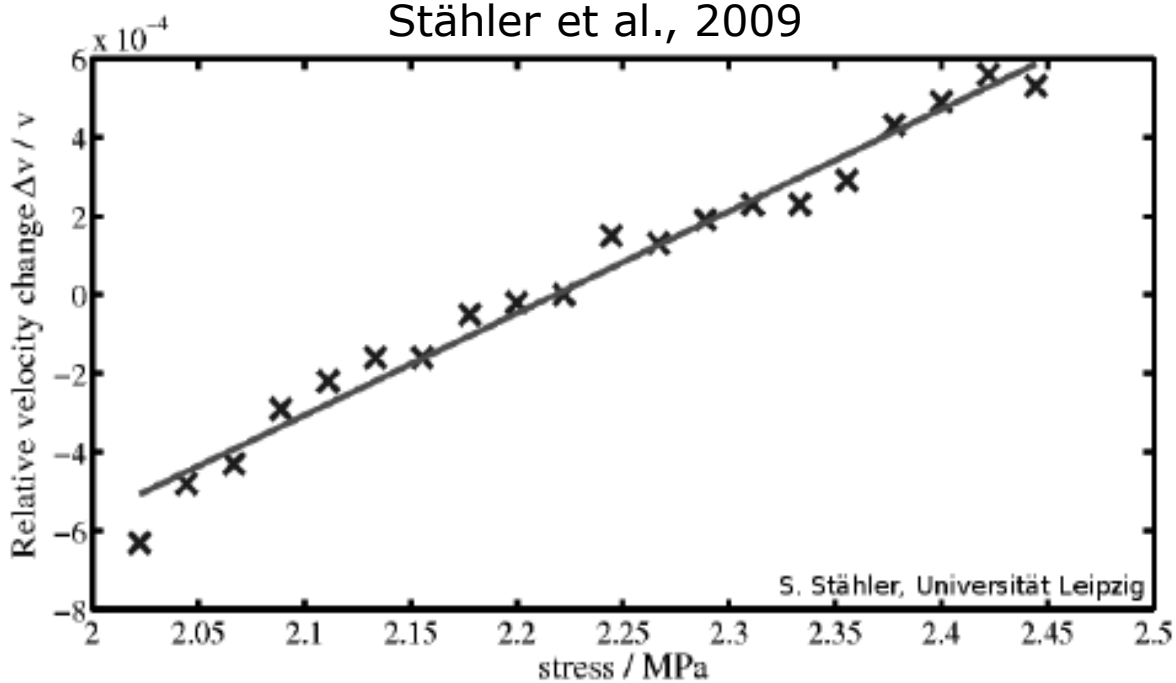
Stähler et al., 2009



Ultrasonic properties as proxys for loads

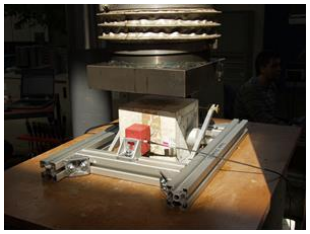
Example for sensitivity: velocity change vs. stress dependence

Stähler et al., 2009



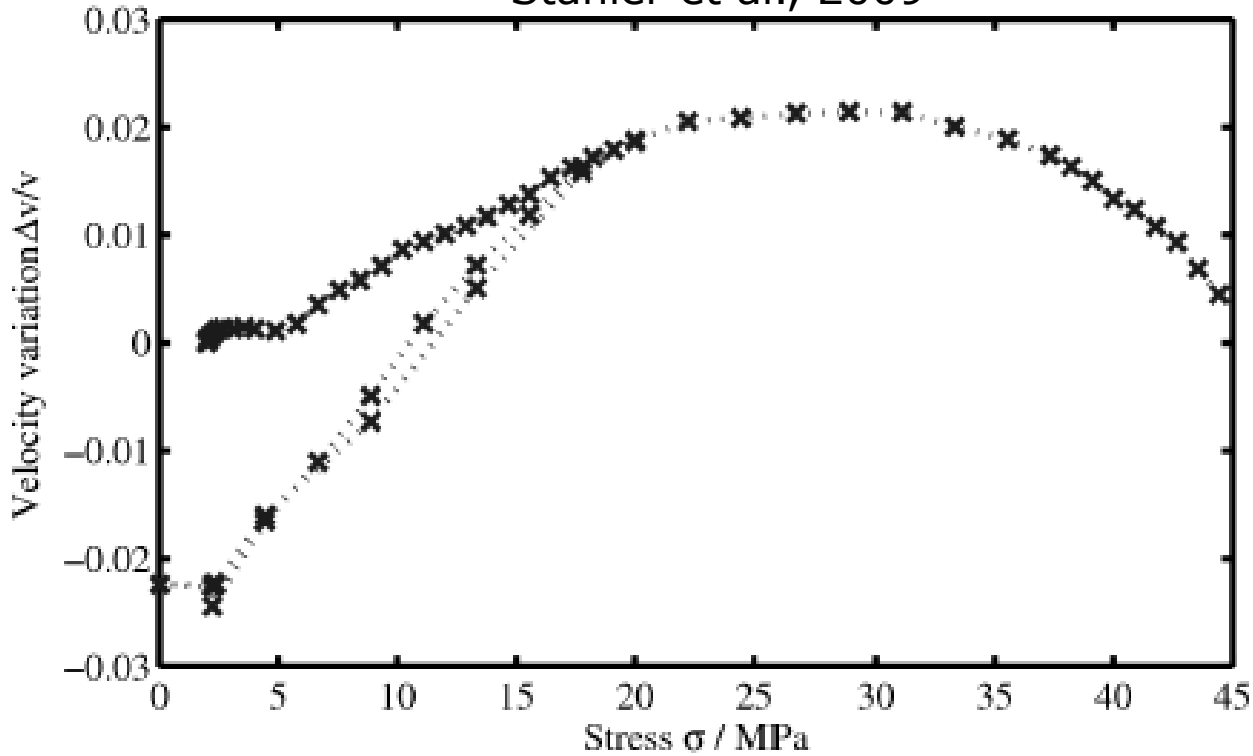
Small load changes

Ultrasonic properties as proxys for loads



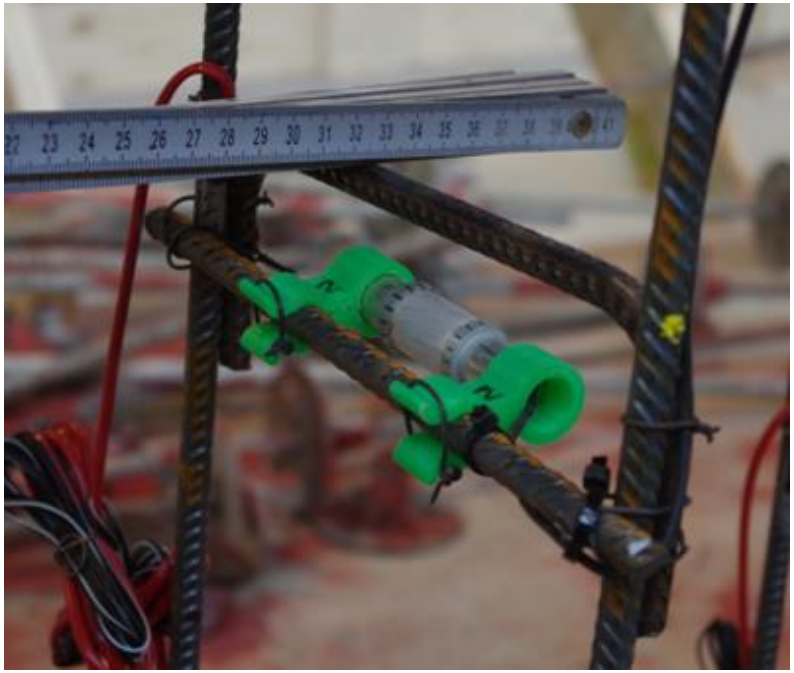
Example for sensitivity: velocity change vs. stress dependence

Stähler et al., 2009



Full load cycles

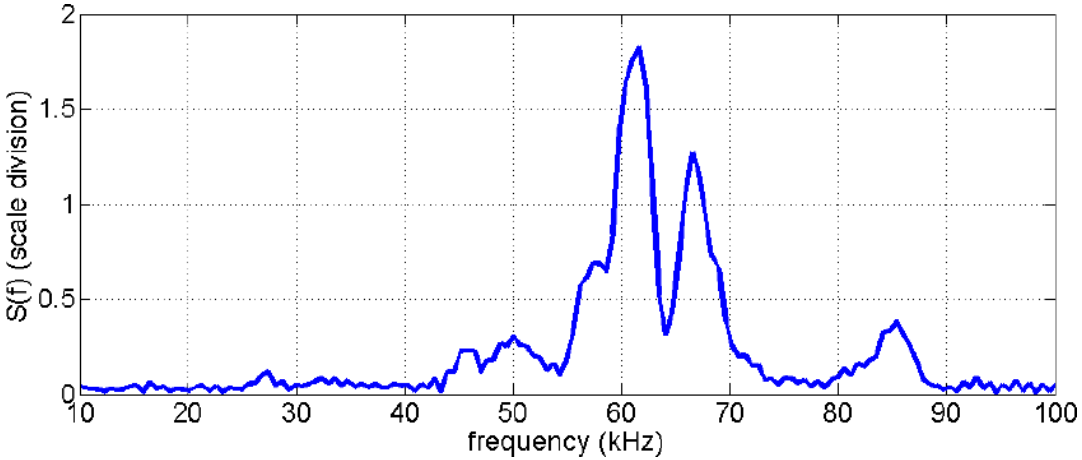
Embedded Ultrasonic Transducers



- 75 mm by 20 mm
- 60 kHz (40 – 90 kHz)
- Embedment in new and old structures

Niederleithinger et al., 2015

Embedded Ultrasonic Transducers



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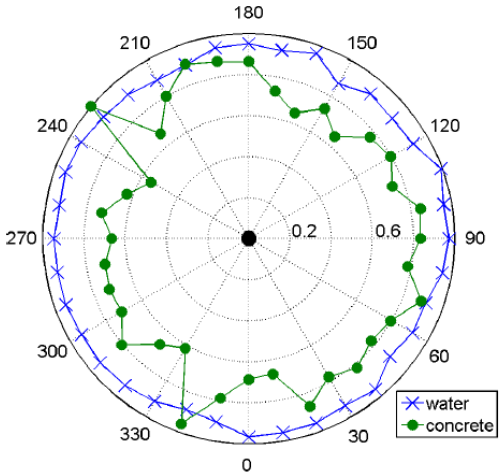
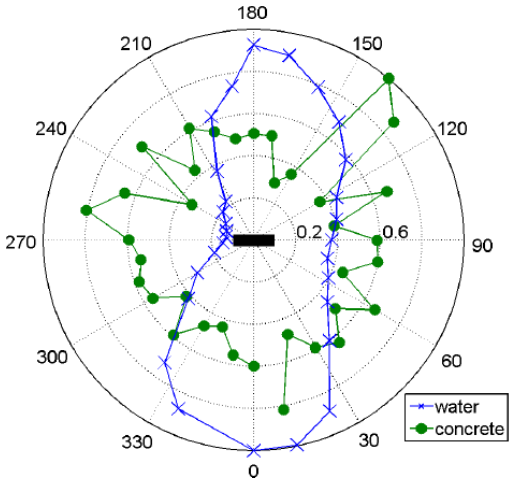


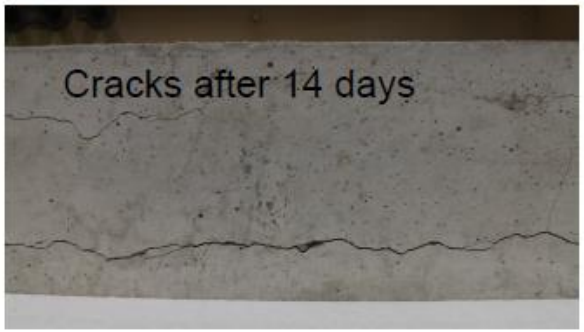


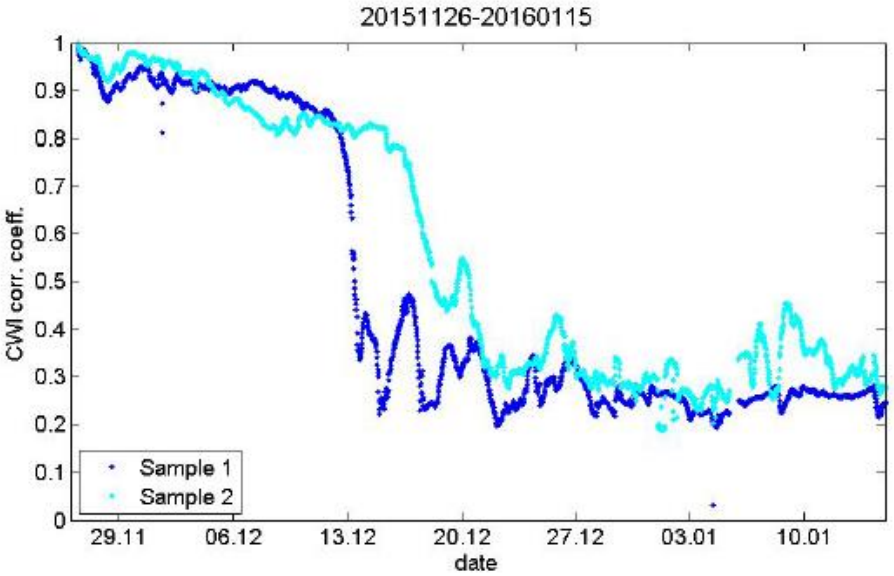
Niederleithinger et al., 2015

Ultrasonic properties as proxys for loads

Corrosion experiment

2 Rebars corroded in small specimens - US-Transmission along the rebars



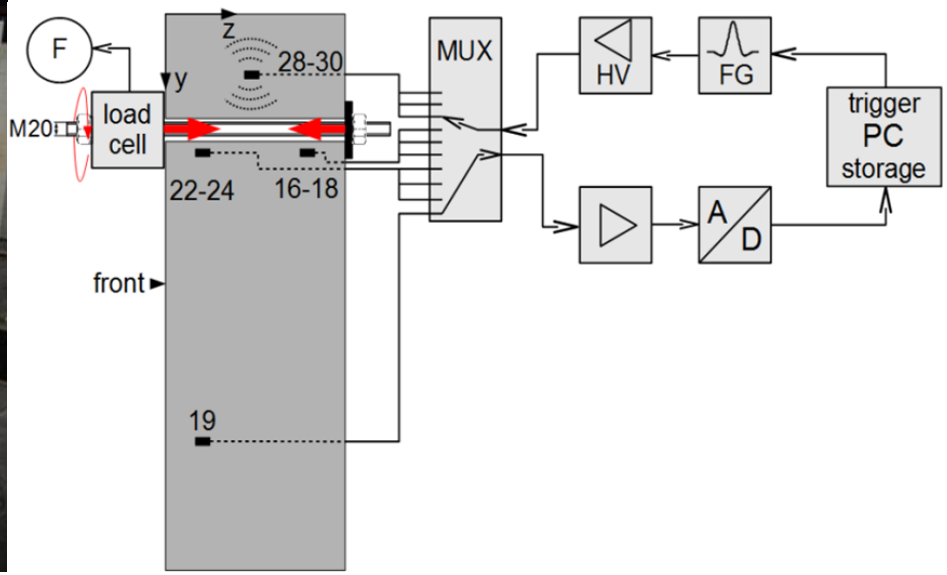


Aachen load experiments

BASt/RWTH/BAM experiments, unpublished

Imaging load distribution by CWI

- Compressional load via bolt/nuts/load cell
- Load <20% of strength limit
- 10 US sensors used via multiplexer

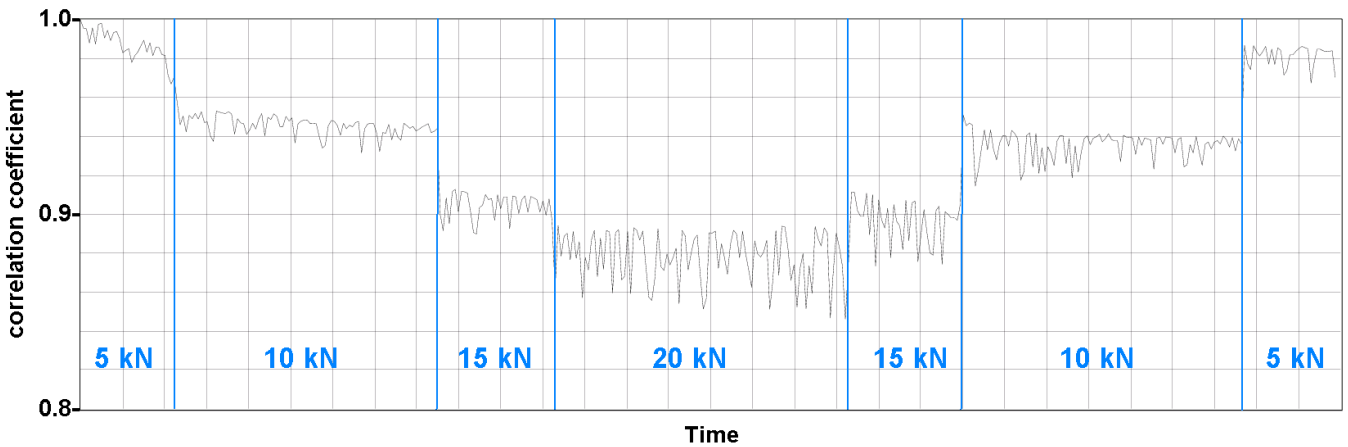


Niederleithinger et al., 2014

Imaging load distribution by CWI

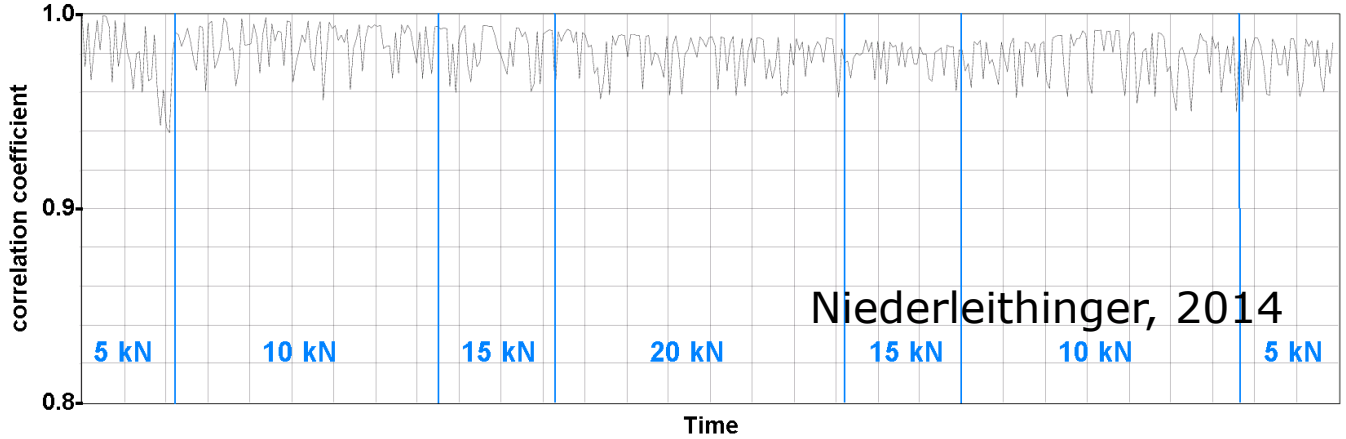
Cross correlation:

sensors close to load impact



Niederleithinger et al., 2014

sensors far from load impact

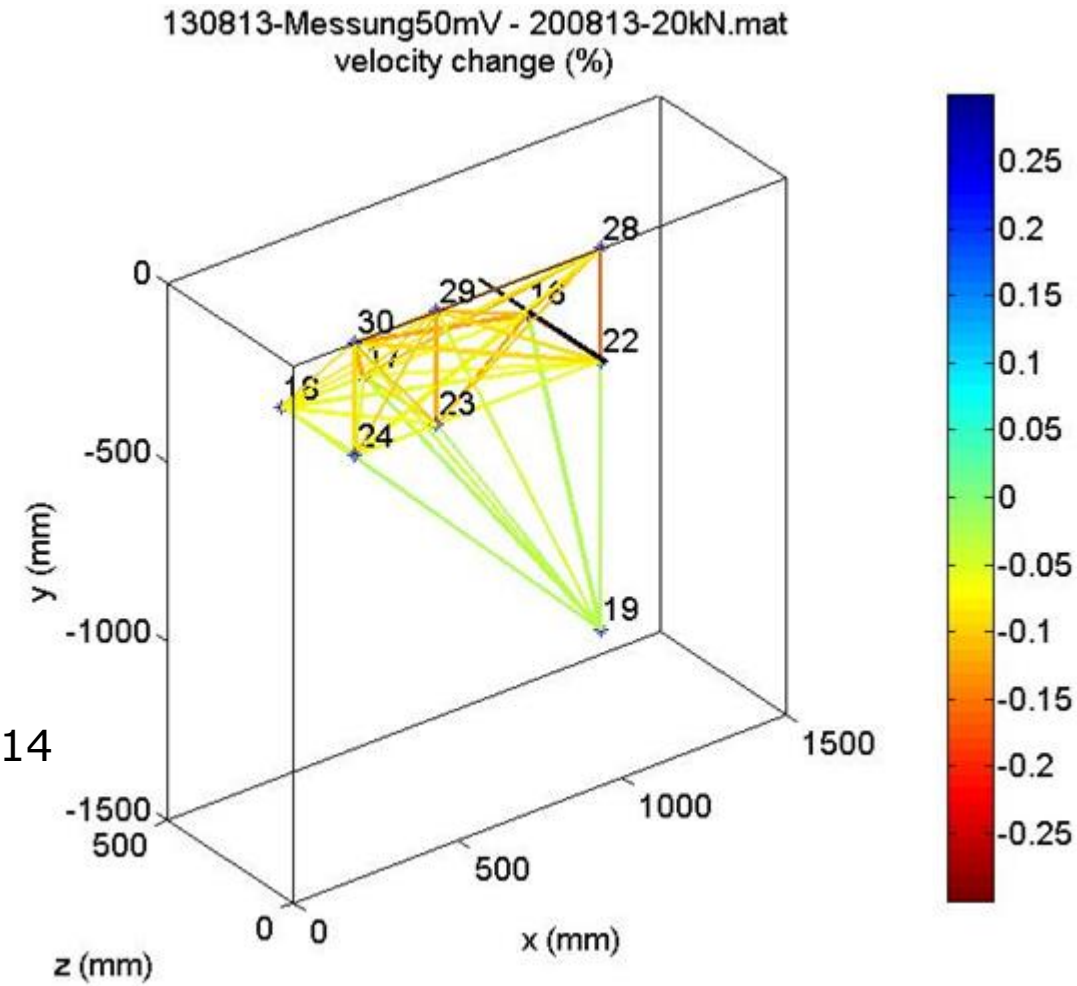


Niederleithinger, 2014

Imaging load distribution by CWI

Pairwise evaluation of CWI

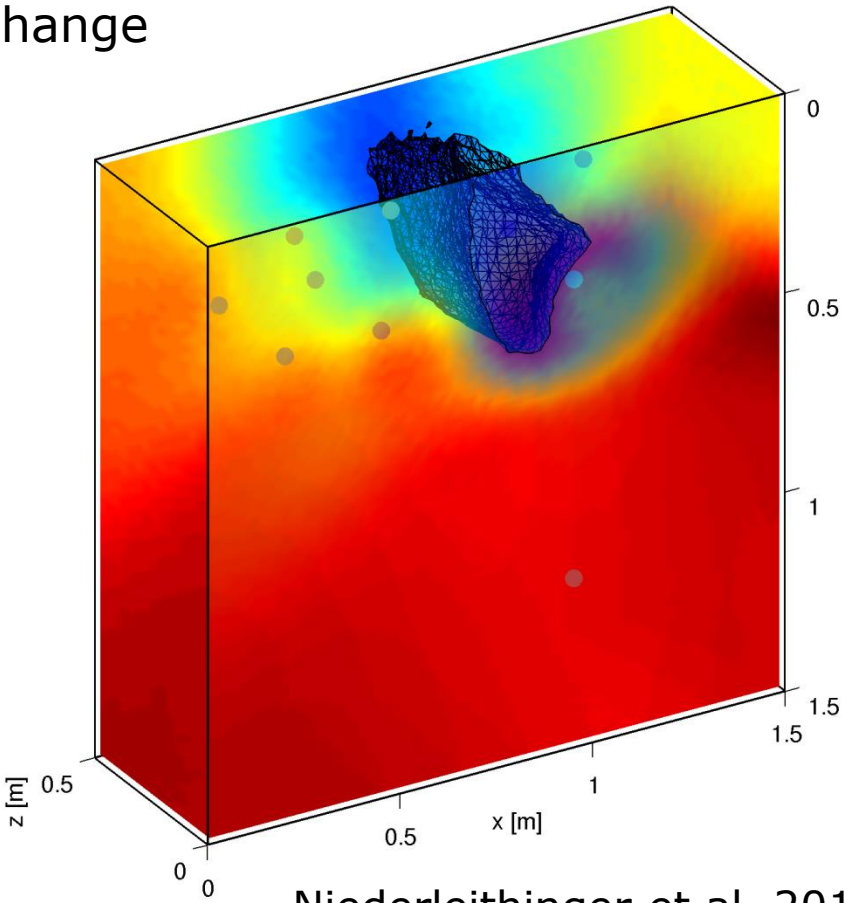
dv/v color coded



Niederleithinger et al., 2014

Imaging load distribution by CWI

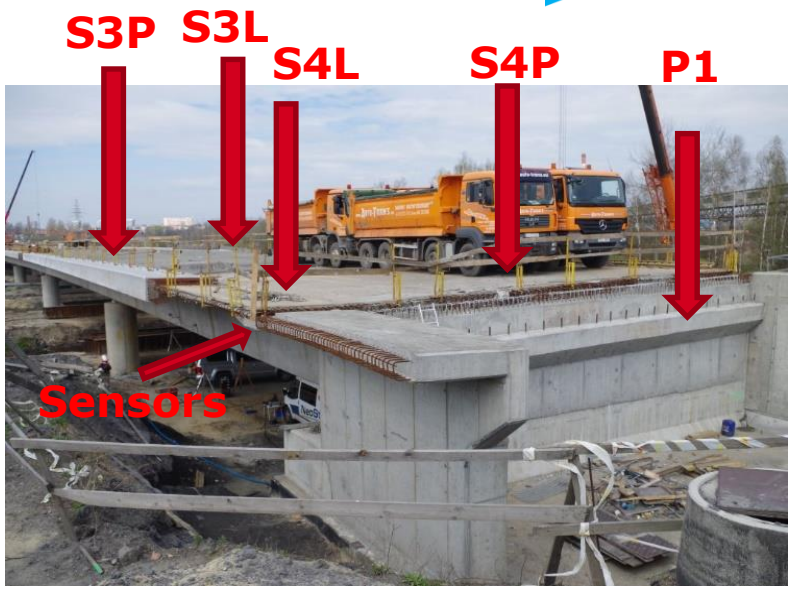
- „Decorreletion Imaging“
- Blue: high change, red : low change
- Under research



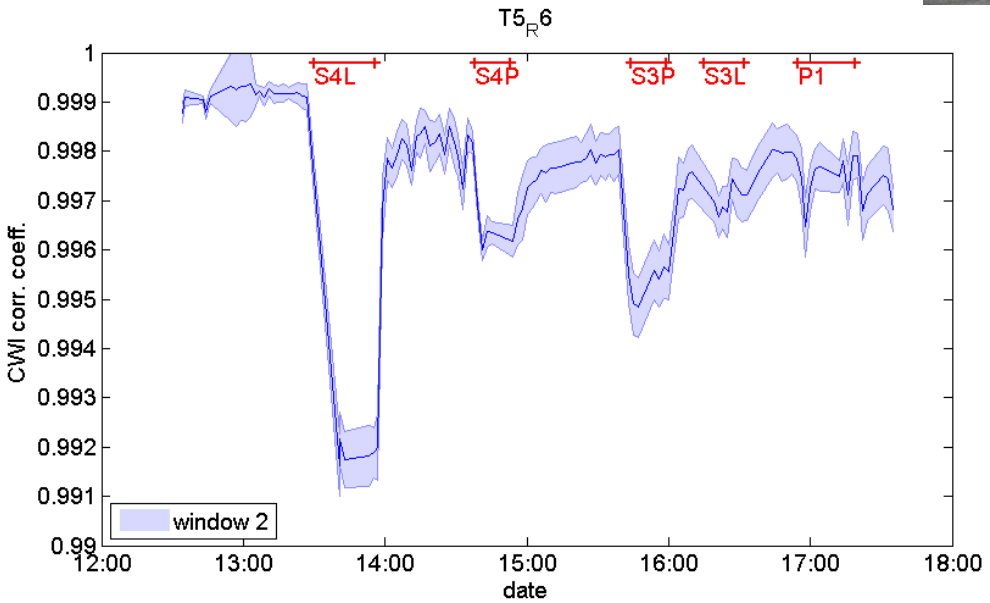
Niederleithinger et al. 2014

Imaging algorithms:
Larose et al.
Planes et al
Kanu
Sens-Schönfelder

Bridge load experiment



- 8 transducers in a bridge in Poland
- Mandatory load tests before opening
- Evaluation of CWI correlation coefficients



- Loads detectable
- Even if load on neighboured girders

Method comparison

Correlation

- Online monitoring of changes
- Low spatial resolution, no quantitative values

Coda Wave Interferometry

- Quantitative values (velocity change)
- Low spatial resolution, not online

Interferometric Imaging

- Localization, (quantitative values)
- Intense data processing, a priori knowledge

Ultrasonic Monitoring
Why is it special?

Modal/vibration analysis

- Global assessment (entire structure)
- Low to medium sensitivity, low resolution

Ultrasonic Monitoring

- Zonal assessment (critical parts of a structure)
- High sensitivity to changes, medium resolution

Strain gauges etc.

- Local values only
- Intense data processing, a priori knowledge

Conclusions

Ultrasonic tools are moving to the next level

1) Large Aperture Ultrasonic System (LAUS) will allow depth penetration of > 5m

2) Reverse Time Migration (RTM) allows imaging of complex strctures

3) Embedded transducers and tools like Coda Wave Interferometry (CWI) can monitor and locate subtle changes in structures

Open questions

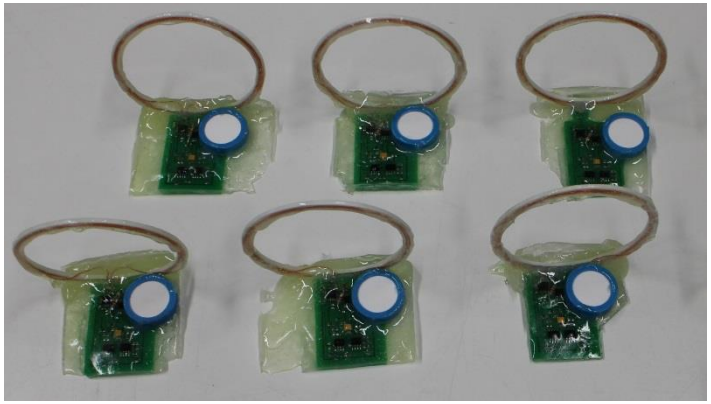
1) Speed RTM of imaging

2) Quantification of US monitoring features in terms of material properties

3) Larger, faster networks

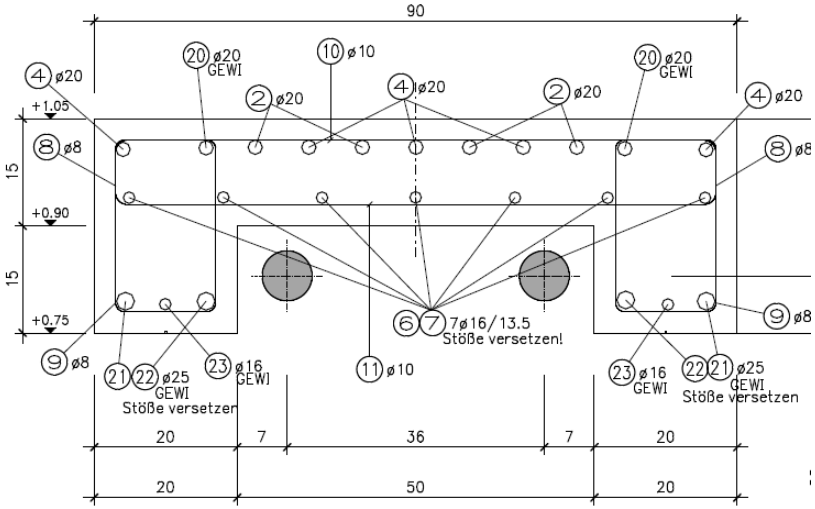
Add-On 1: RFID

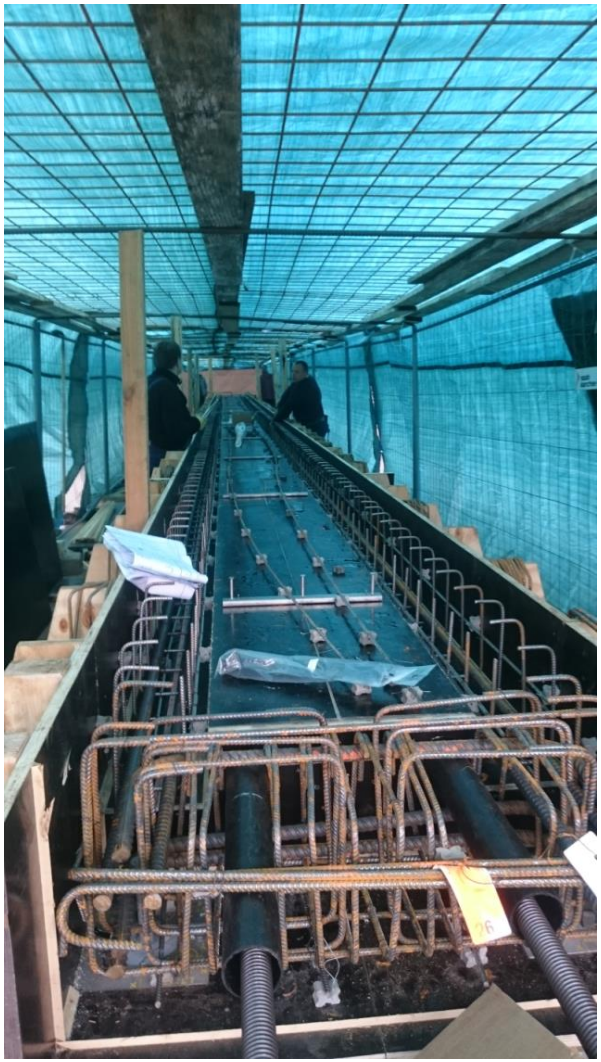
RFID-Tags for Humidity, temperature, corrosion
(Dr. Christoph Strangfeld)

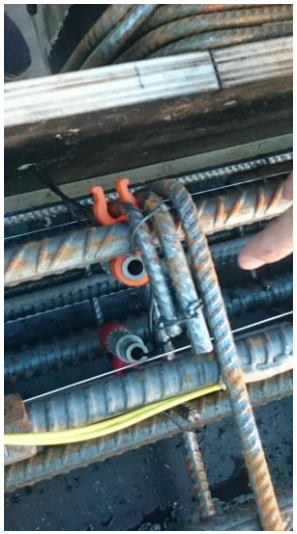


Add-On 1: BLEIB reference structure

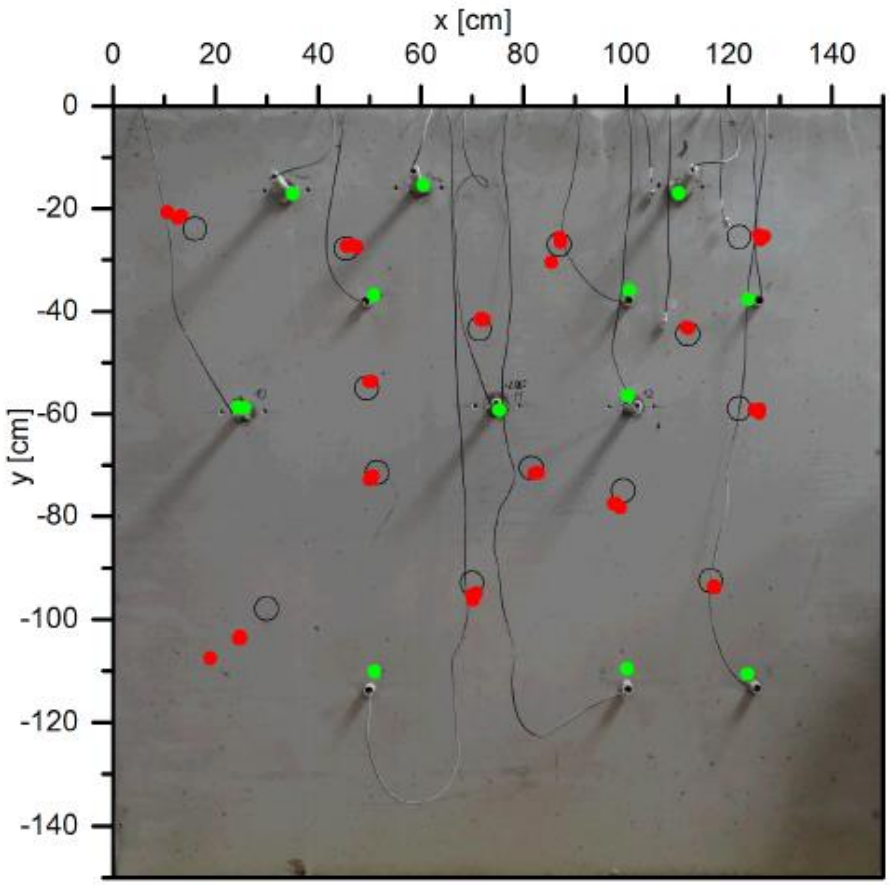
- 2 spans, 12 m each
- inverse U-shaped, 0.9*0.3 m²
- Various load and damage mechanisms
- Fiber optics
- Acoustic emission
- Vibration based monitoring
- Ultrasonic embedded transducers
- RFID sensors







Add-On 3: Combination with acoustic emission



Pencil breaks:

- Black circles original location
- Red dots: AE localization

Transducer as AE source:

- Green dots: AE localization

Niederleithinger et al. 2015