Fibre optic Fabry-Pérot sensors, applications and reliability aspects

1st FIG International Symposium on Engineering Surveys for Construction Works and Structural Engineering

Invited lecture at The University of Nottingham, United Kingdom
Session 6 - Fibre Optic Workshop
June 29, 2004

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BAM-Laboratory: Fibre optic sensors

Outline

- **Short presentation of BAM, motivation for fibre sensor activities**
- **What does fibre Fabry-Pérot sensor (FFPI) mean (basics)?**
- **Types (modifications) of FFPI sensors and typical features**
- **Application examples**
  - Static measurements
  - Dynamic measurements
- **Scientific questions (selection) - reliability aspects**
- **Summary**

Federal Institute for Materials Research and Testing

Guideline:
Safety and Reliability in Chemical and Materials Technologies

Interacting Fields

- Safety
- Materials
- Chemistry
- Environment

Main Areas of Activity

- Chemical-Technological Tasks
- Material-Technological Tasks

Legal Status of BAM

The Federal Institute for Materials Research and Testing (BAM) is a senior technical and scientific Federal Institute with responsibility to the Federal Ministry of Economics and Labour.

BAM is responsible for

- The technical safety in the technical domain including development legal regulations and reference methods for chemical analysis and materials testing
- Assistance in developing standards and technical rules for the evaluation of materials, structures and processes
- The advancement of safety and reliability in chemical and materials technologies
- Special tasks according to the Explosives Act, the Weapon Act and the Act for the Transport of Dangerous Goods

The Departments of BAM

I	Analytical Chemistry; Reference Materials
II	Chemical Safety Engineering
III	Containment Systems for Dangerous Goods
IV	Environmental Compatibility of Materials
V	Materials Engineering
VI	Performance of Polymeric Materials
VII	Safety of Structures
VIII	Materials Protection; Non-Destructive Testing
S	**Interdisciplinary Scientific and Technological Operations**
Z	Administration and Internal Services

Division S.1:

Measurement and Testing Technology; Sensors

Laboratory S.11: Reliability of Testing and Measurement Systems

Laboratory S.12: Sensors and Measurement Systems;
Experimental Stress Analysis

Laboratory S.13: Optical Measurement and Testing Methods;
Optical Reference Materials

Projects Group S.1901: Fiber Optic Sensors

Characteristics of fibre optic sensors

- **Small dimensions** (Diameter < 0,5 mm), that means: excellent capability of integration into components
- **no electric or electronic components on-site, chemically inert, low energy demands, thermally stable**
  - in electromagnetic fields, in areas of high lightning activities
  - in high-voltage and nuclear power plants,
  - in explosive and aggressive environments,
  - under high temperatures (> 1000 °C).
- **high static and dynamic strain resolution** (in some cases < 0,1 µm/m, t. m. better than 10^{-5} %) and up to few MHz
- **Sensor fiber can be divided into several measuring sections** (on-line) evaluation of deformation profiles
- **Design of distributed fiber sensor networks**
- **Compatibility with advanced data transmission systems**

Motivation for fibre optic sensor activities

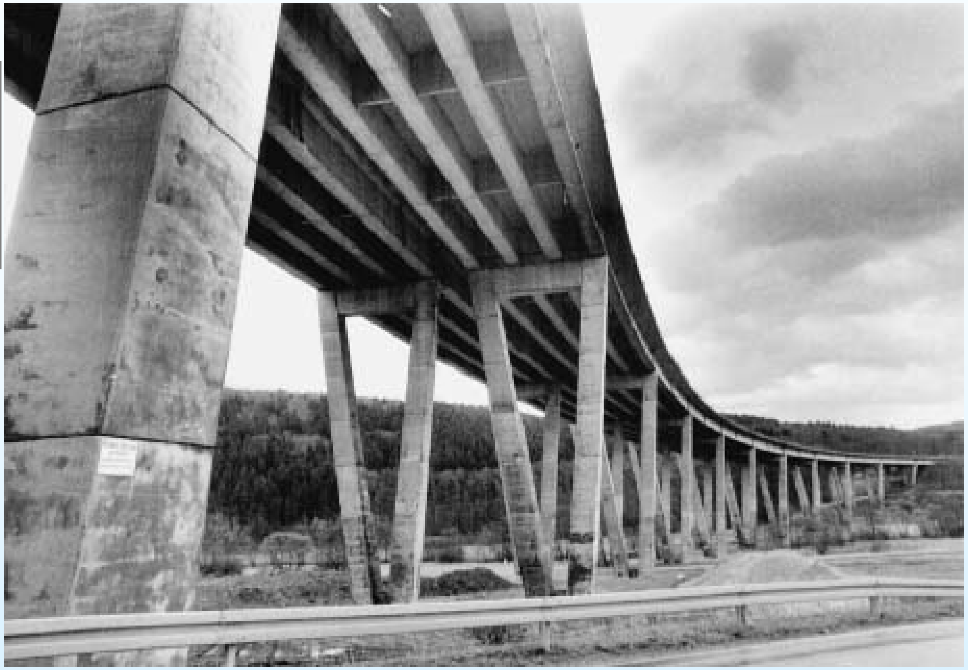
Ground instabilities - threatening slope failure

Monitoring of fixed unstable Kammereck rock above the railway track near St. Goar

Damage due to wrong materials use

VDI-Nachrichten: 28.07.2000, S. 12
Deutsche Bahn befürchtete Risse an "Fester Fahrbahn" aus Beton

Haigertalbrücke - Demolition because of bad quality of concrete

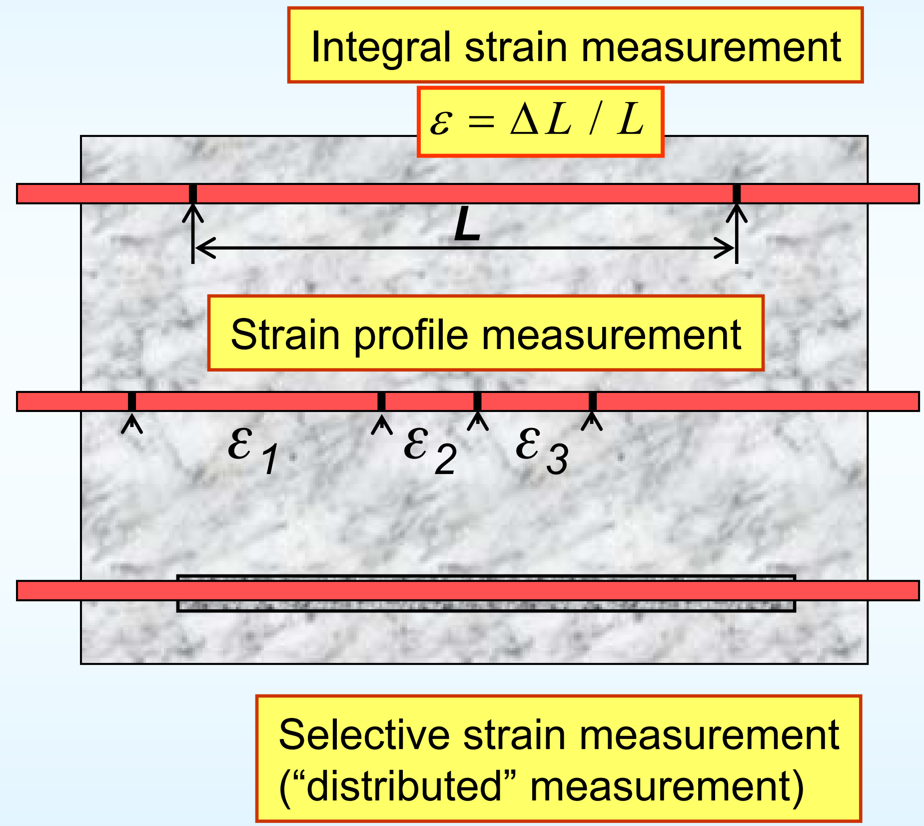


Evaluation of integrity of construction

Long-gage length sensors

Optical fiber is fixed:

- between two points
- at several points
- along the whole fiber.

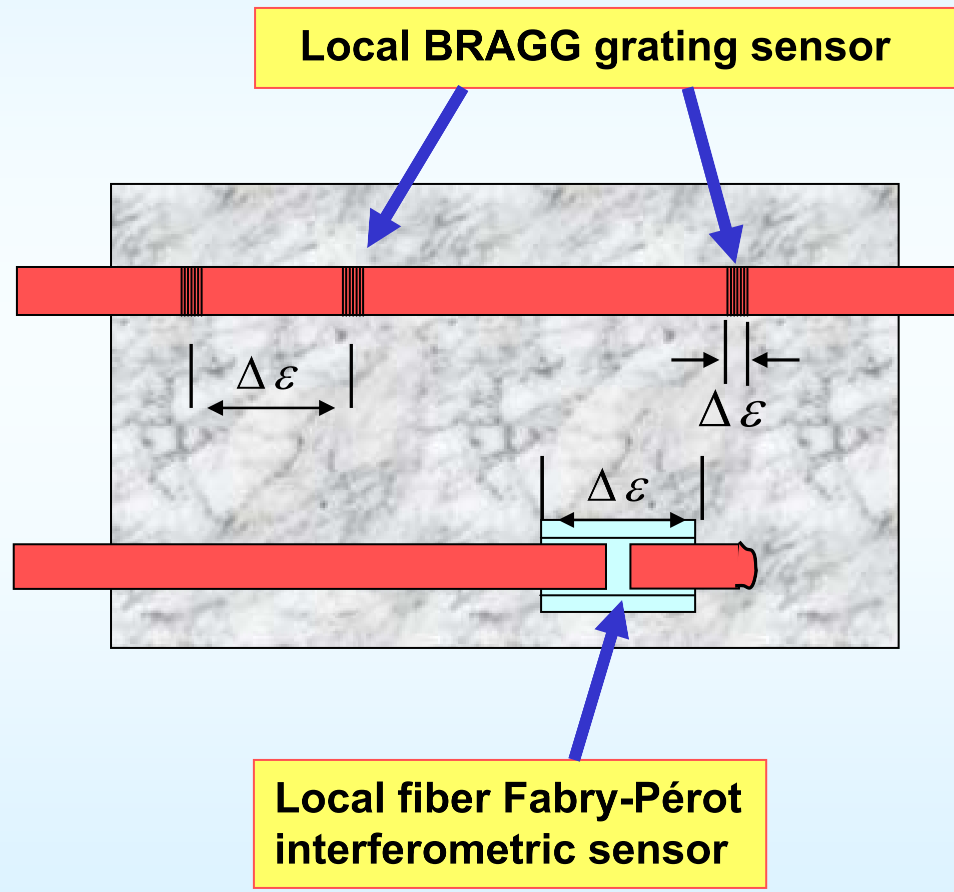


Short-gage length sensors

Sensitive element is positioned:

within the fiber
(intrinsic sensor)

Between two fiber end faces
(extrinsic sensor)

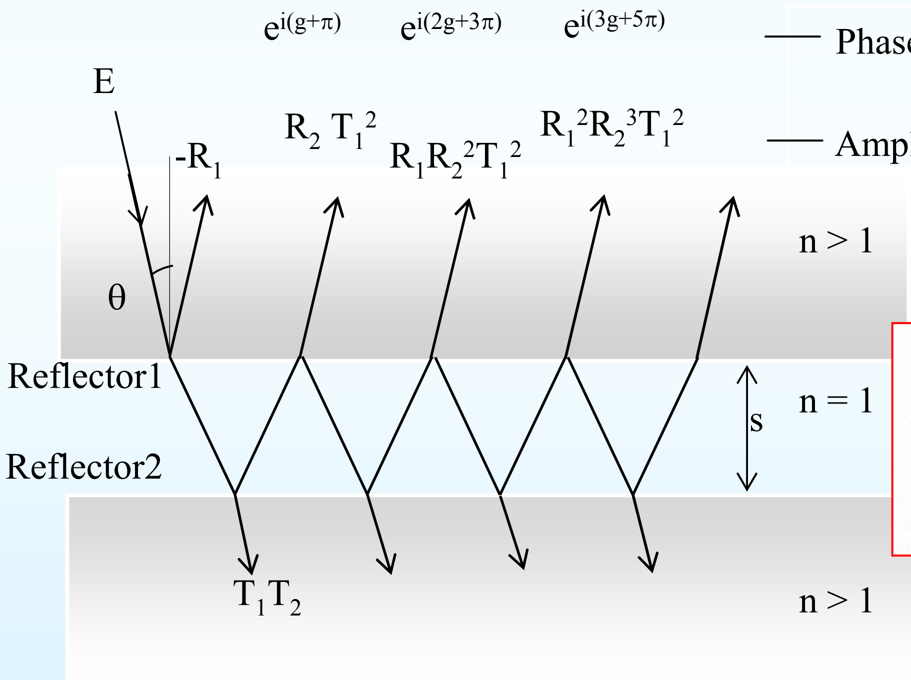


Few basics

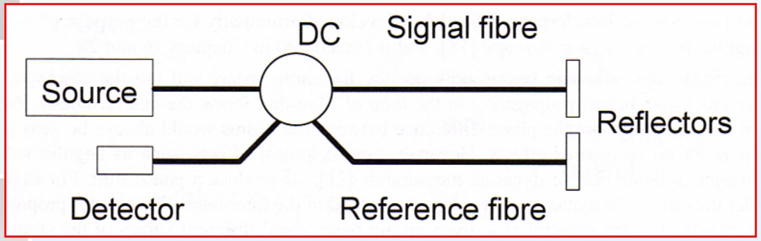
An interferometer converts a phase change to an intensity change

What does fibre Fabry-Pérot sensor (FFPI) mean?

1. Multiple beam interferometer



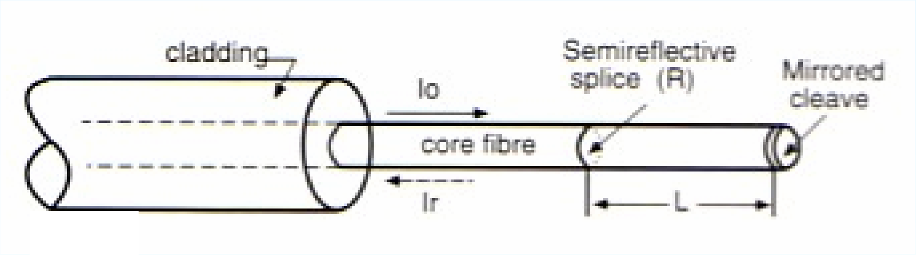
In contrast to dual beam interferometer



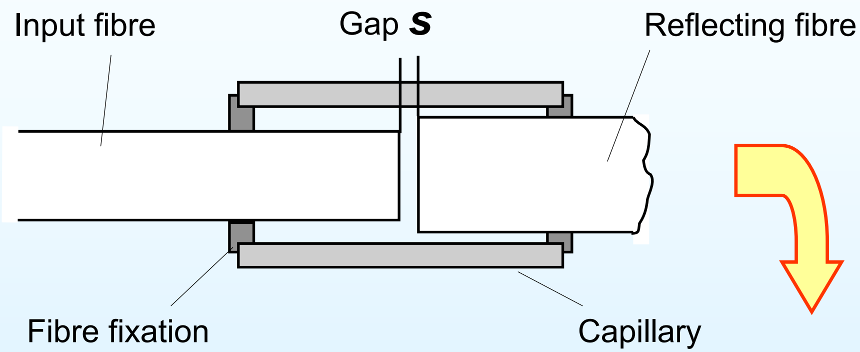
Interference of a number of waves → Sharp fringes

What does fibre Fabry-Pérot sensor (FFPI) mean?

2. One-arm interferometer

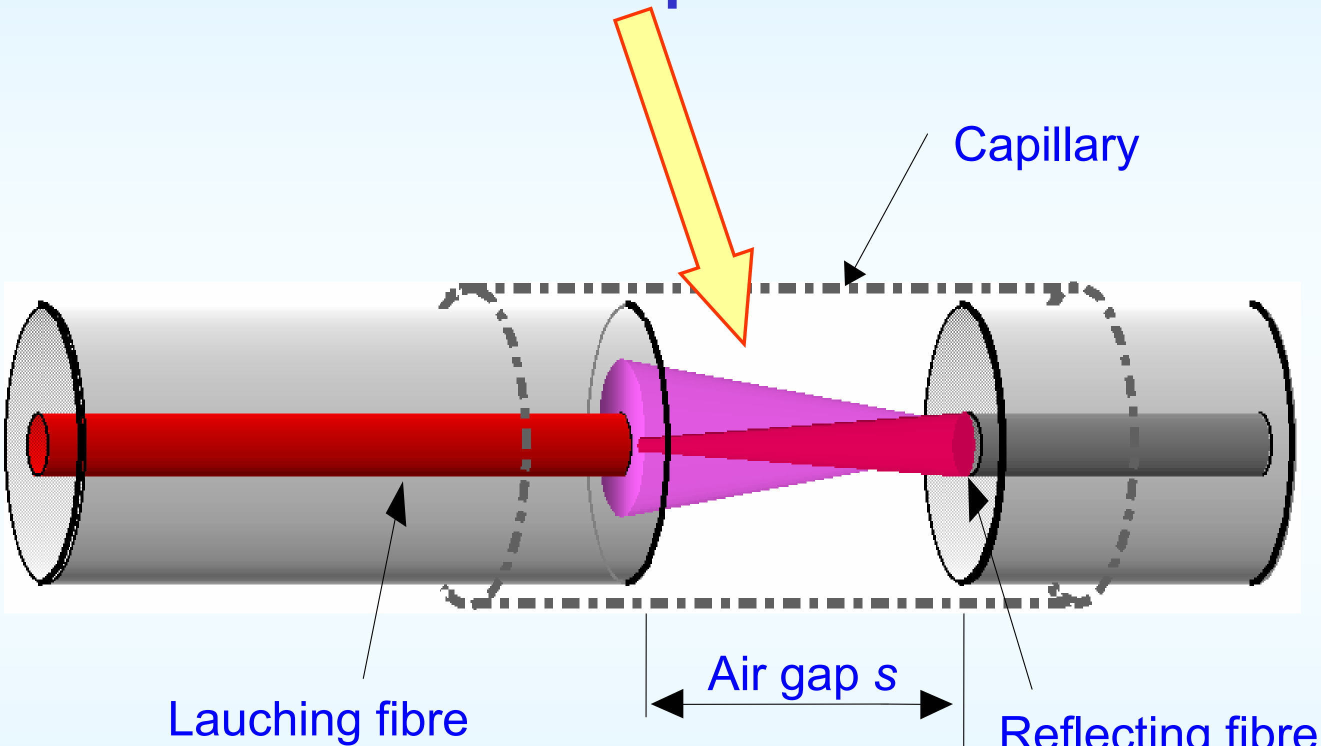


Intrinsic type



Extrinsic type

Area of multiple reflections

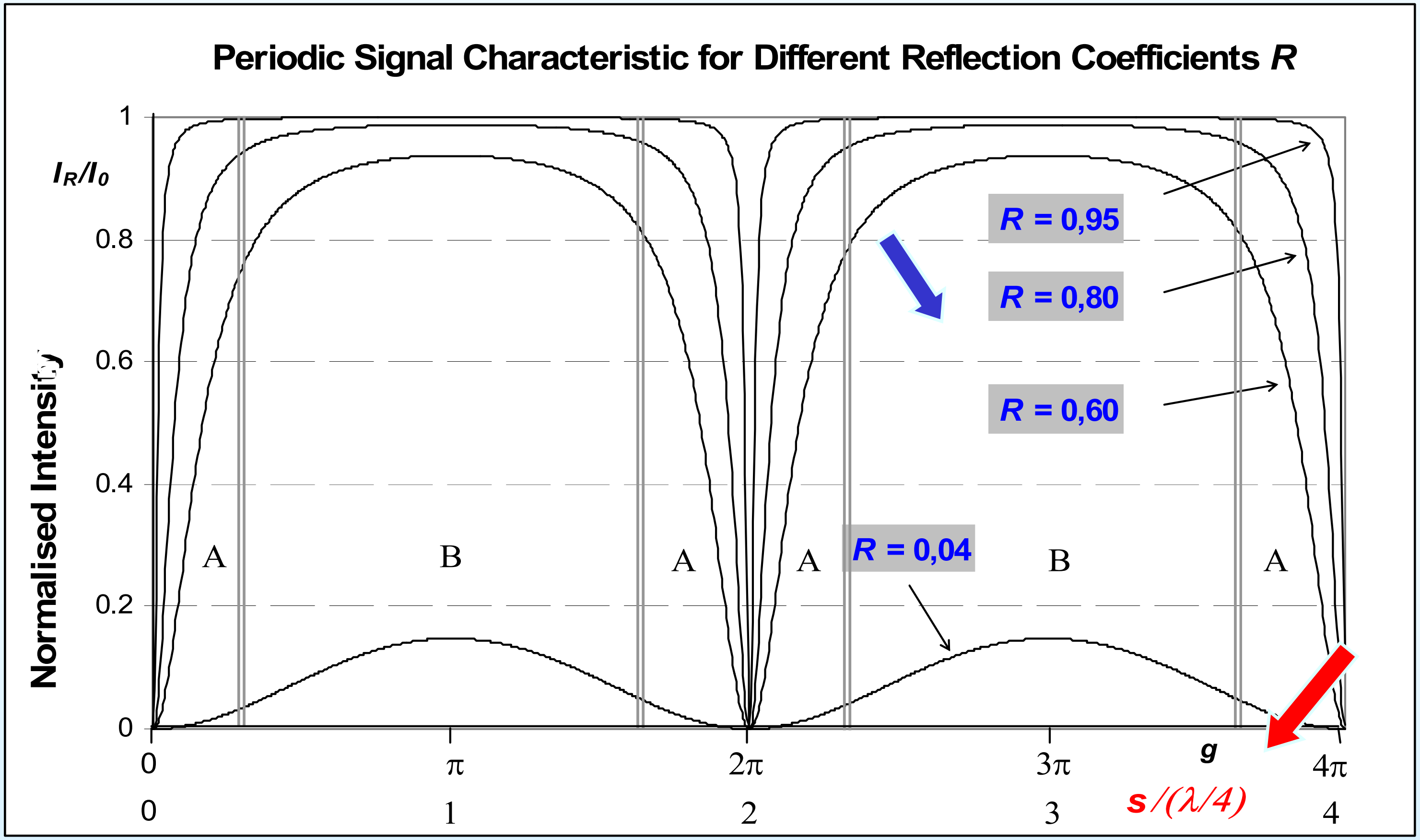


Varying the distance between the fibre endfaces (gap),

What does fibre Fabry-Pérot sensor (FFPI) mean?

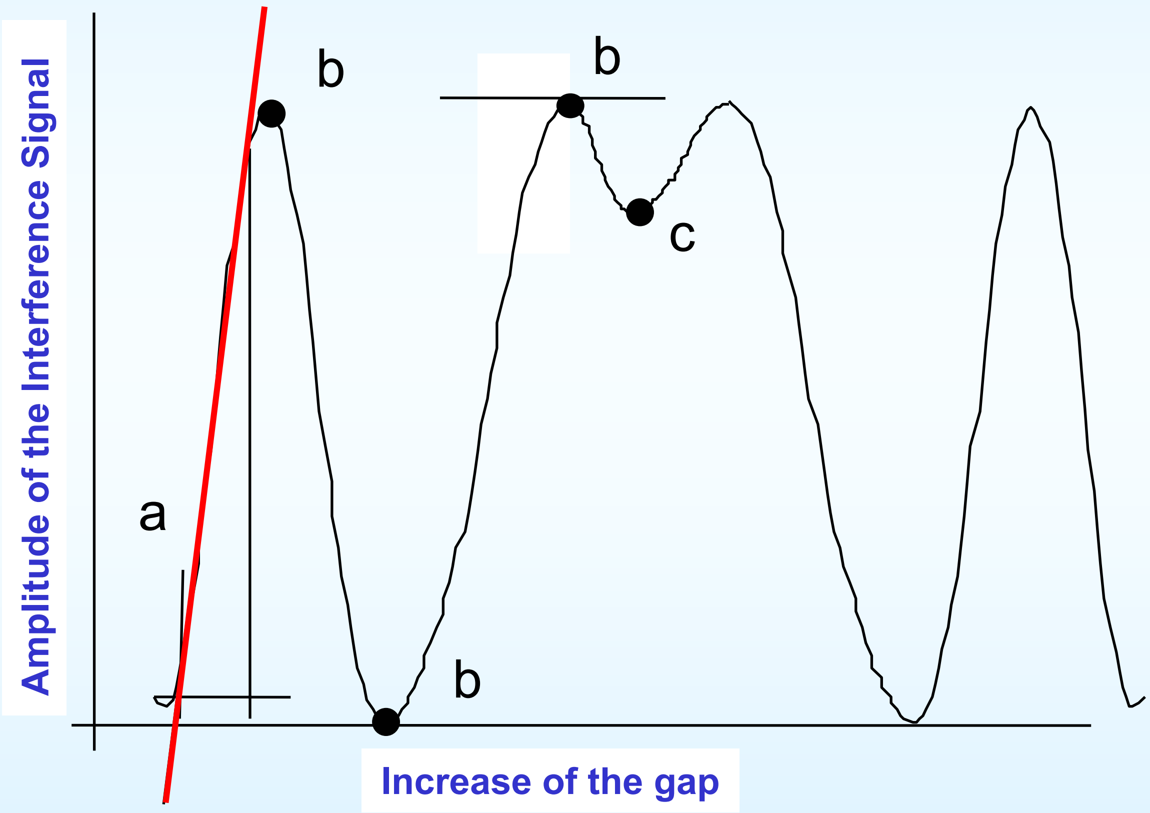
3. Periodic (ambiguous) signals

$$\frac{I_R}{I_0} = 2R\left[1 + \cos\left(\frac{4\pi s}{\lambda_0}\right)\right]$$



What does fibre Fabry-Pérot sensor (FFPI) mean?

4. Periodically high sensitivity



High resolution of gap changes, but ambiguity

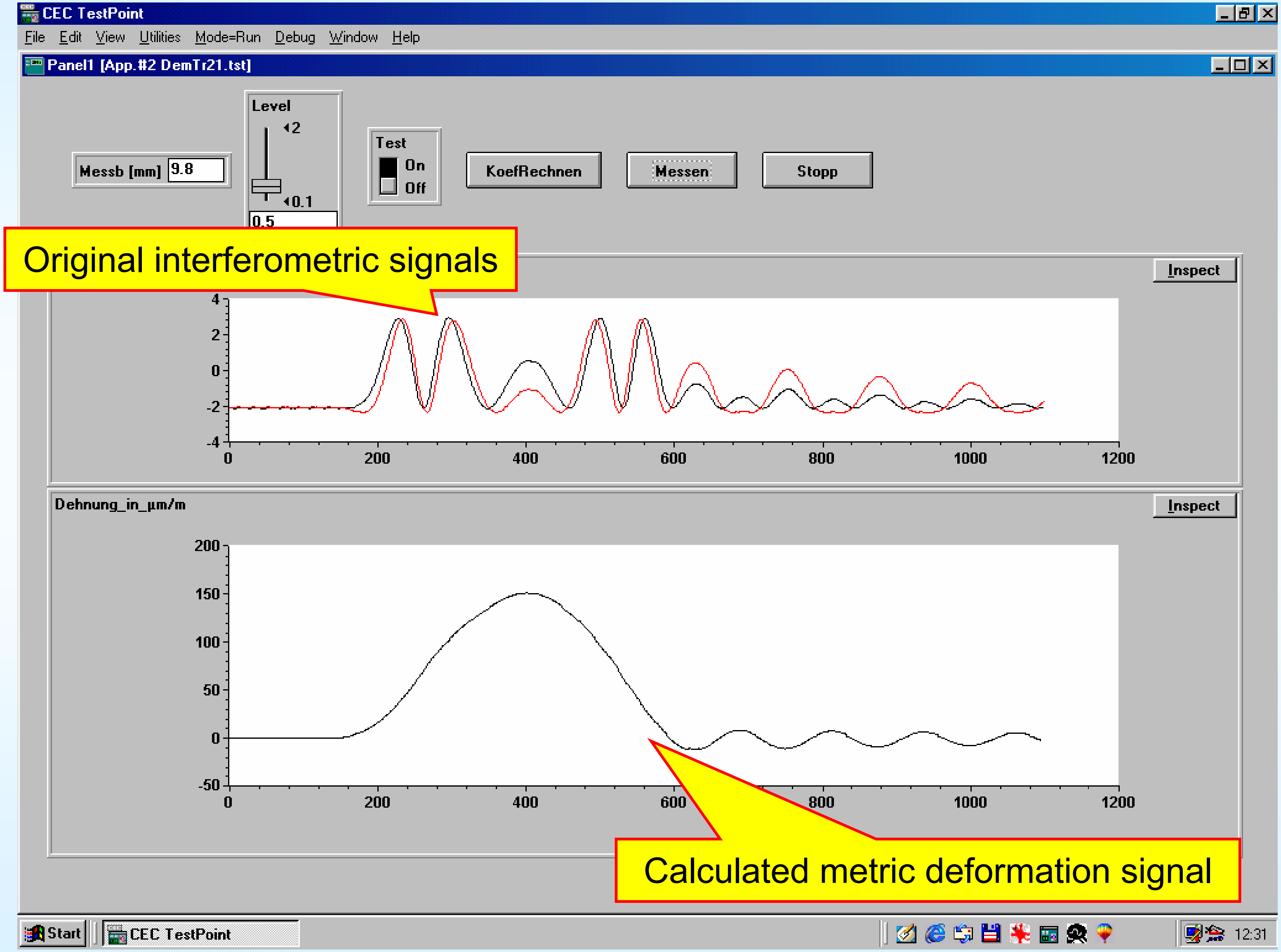
Measures to overcome the ambiguity:

- **Using several wavelengths** (provided by two laser diodes) **and photodiodes**

- **Using a white-light source, a second interferometer** (which reproduces the gap variations) **and a CCD array**

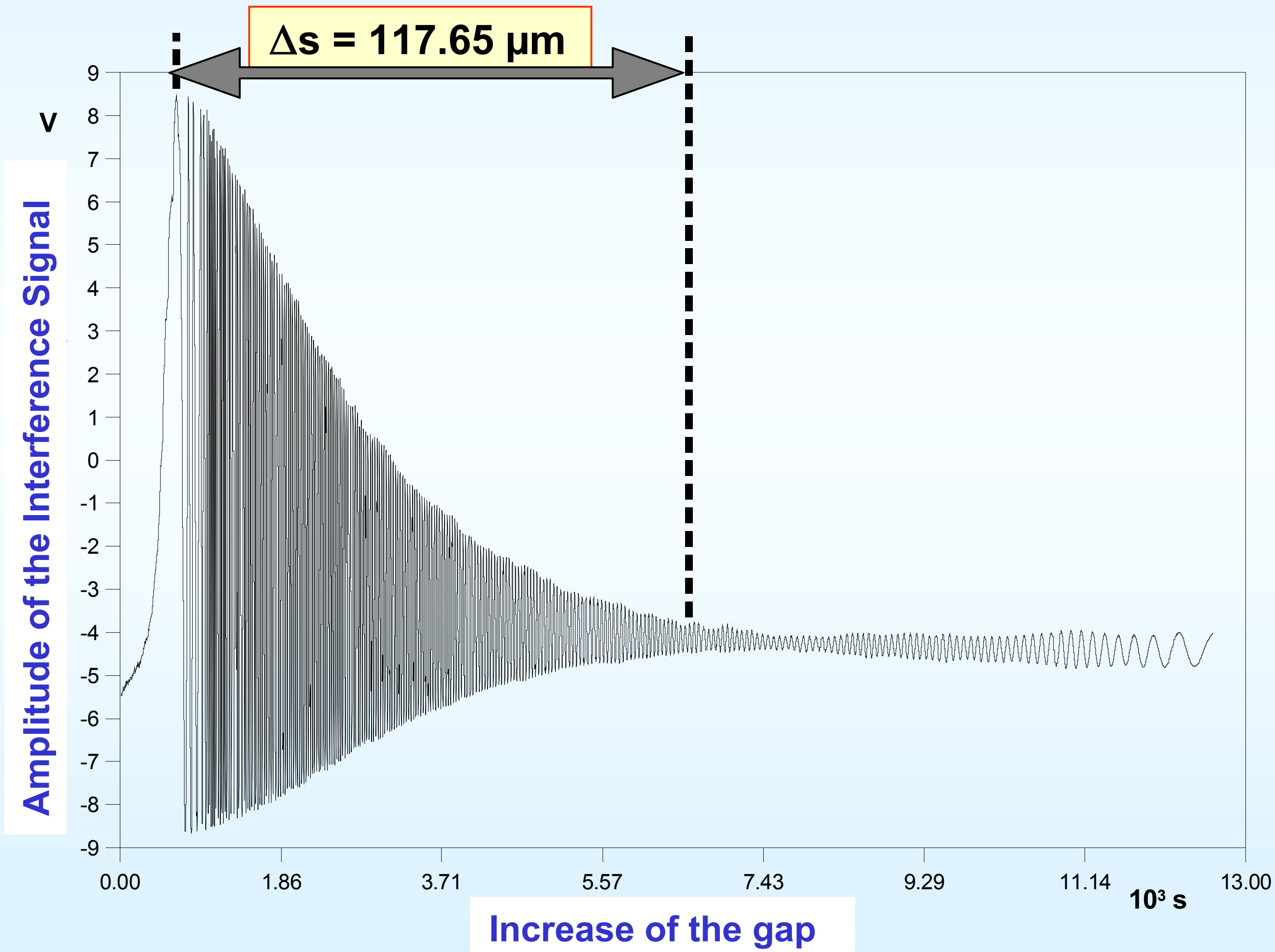
- **Use of a special sensor design** (twin-fibre structure or mechanical design)

Two-wavelength scanning of strain changes



What does fibre Fabry-Pérot sensor (FFPI) mean?

5. Limited increase of the gap



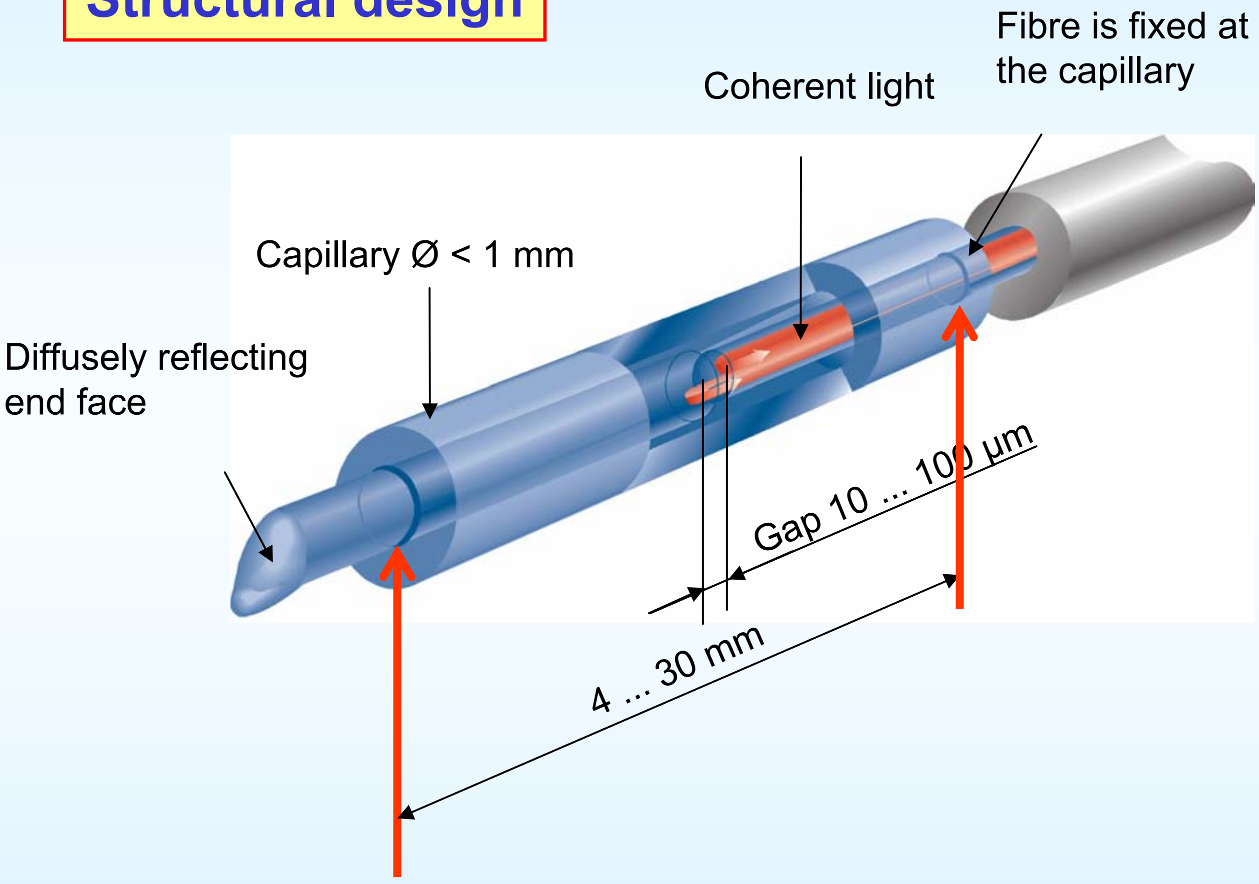
Summarizing the characteristic features

Characteristic data:

Gauge length:	**5 mm to 20 mm** (extension to 70 mm possible)
Measurement range:	**- 20,000 µstrain to +25,000 µstrain** (-2 % contraction; 2.5 % strain)
Resolution:	**0.1 µstrain (10^{-7}) and better**
Dynamic resolution:	**up to MHz (depending on the device)**
Long-term reproducibility:	**defined by kind of application** (reference to zero-measurement is lost after switching off the power)
Temperature sensitivity:	**- 0.036 % / K**
Sensitivity to transverse strain:	**almost insensitive**

Fibre Fabry-Pérot interferometer sensor

Structural design



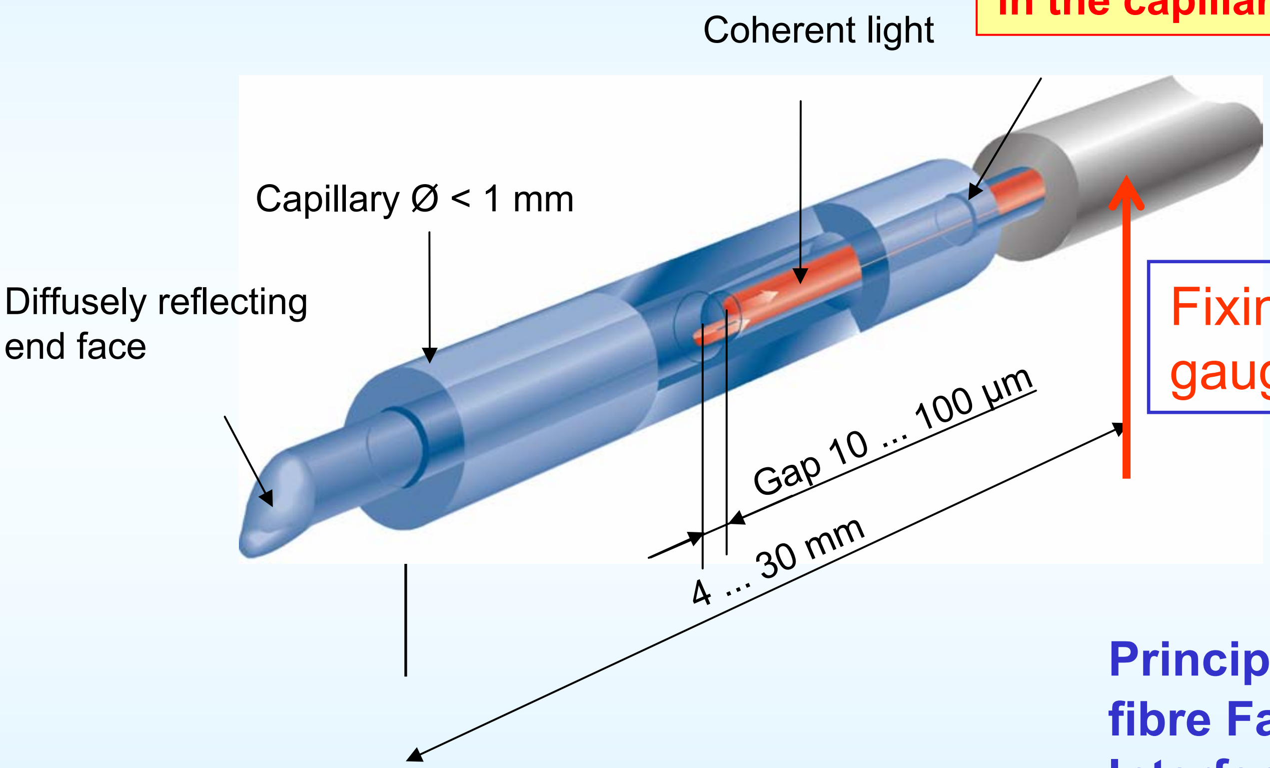
Principle of a stiff fibre Fabry-Pérot Interferometer sensor

Very important: Definition of the gauge length !

Fibre Fabry-Pérot interferometer sensor

Structural design

Leading fibre is sliding in the capillary



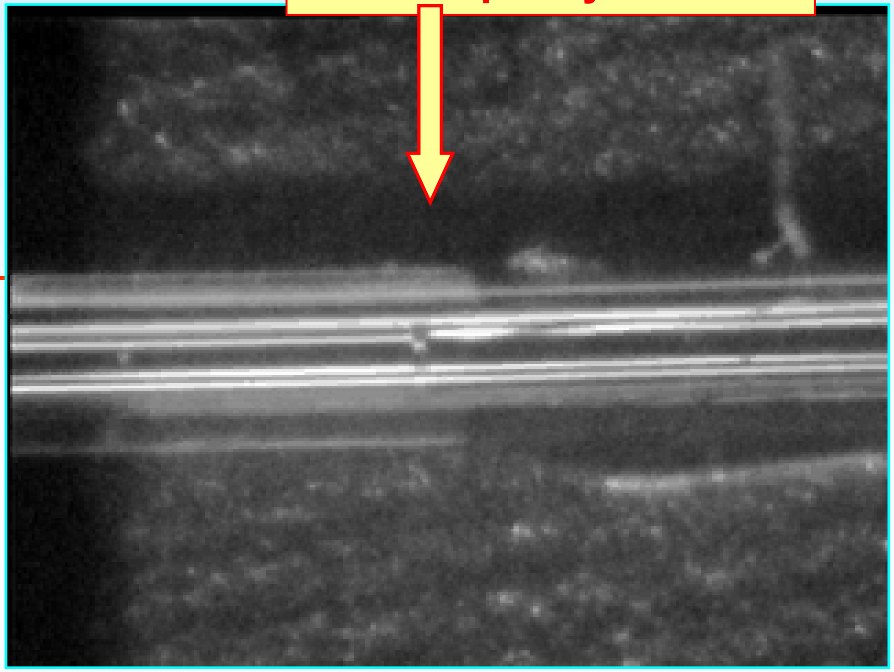
Fixing point =
gauge length

Principle of a flexible fibre Fabry-Pérot Interferometer sensor

Force threshold: 150 µN to 250 µN

Flexible fibre Fabry-Pérot interferometer sensor

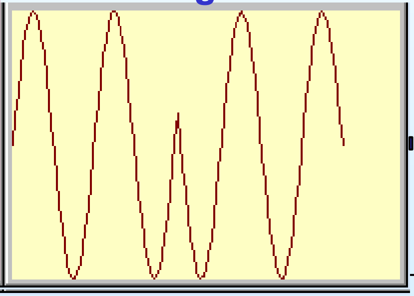
Leading fibre is sliding in the capillary



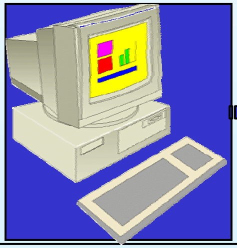
Design: D. Hofmann, BAM-S.1901

Gap variations (increase or decrease) lead to periodic signal changes:

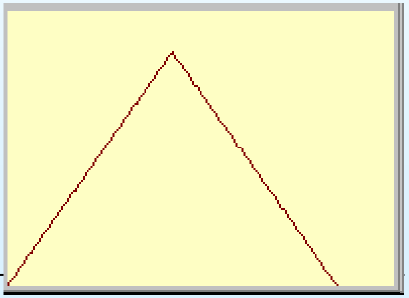
Interferometric signal



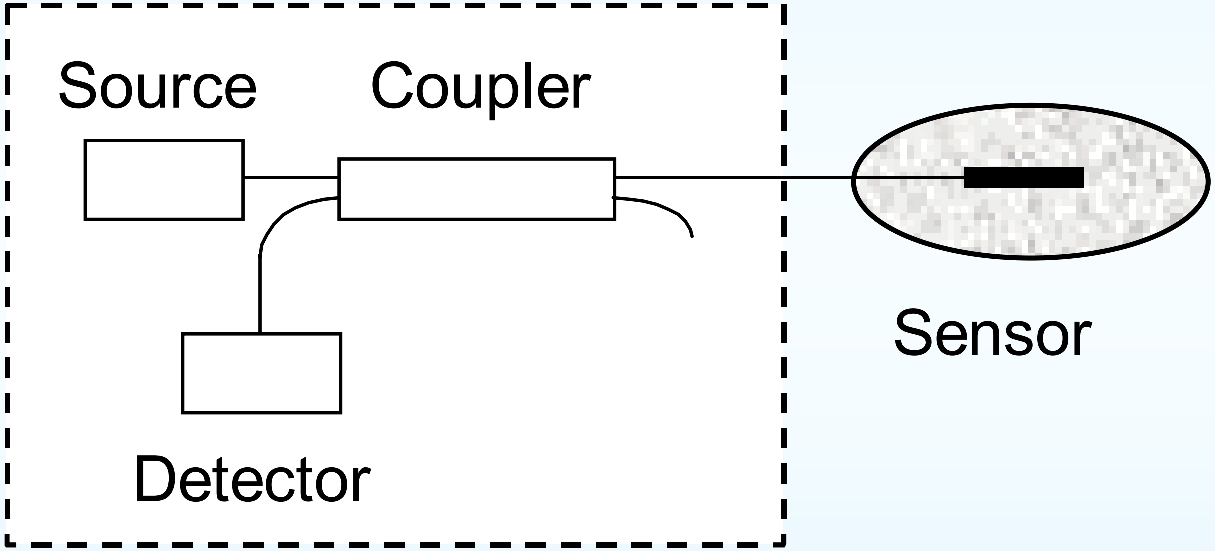
Data processing



Result (Strain, pressure, vibration ...)



Measurement Scheme



Commercially available systems

e. g. from FISO, Canada (www.fiso.com)

- Strain gauges
- Pressure sensors
- Displacement transducers
- Temperature probes

- One-channel portable field instrument
- Multichannel instrument with multiplexing capability

Commercially available systems

BAM

FOE - FIBER-OPTIC EXTENSOMETER *MC-00068R1*

APPLICATIONS

The Fiber-Optic Extensometer, model n° FOE, from Fiso Technologies is designed for long term and accurate monitoring of displacements and axial deformations between two points inside or at the surface of man-made fill as found in dams, bridges, buildings, etc. The base length, the distance between the two end flanges (or anchors) is variable and is generally from 100 to 3000 mm.

To monitor very large-spread deformations or movements, several FOE are assembled together in series. The in-line assembly allows the deformation gradient to be measured over the whole length of the profile.

DESCRIPTION

The Fiber-Optic Extensometer is comprised of (see drawing on next page):

- an outer protective telescopic housing fitted with two end flanges (other type of anchors are available)
- an inner co-axial stainless steel rod. The rod is fixed at one extremity to an end flange (or other type of anchor) and has a fiber-optic linear position & displacement FOD transducer fastened to its other extremity.
- a robust Kevlar® reinforced fiber-optic cable linking the transducer to the fiber-optic signal conditioner.

The heart of the FOE is composed of the fiber-optic linear position & displacement transducer FOD which provides high precision measurement of positions and displacements. (For more information on the FOD itself, see Fiso Technologies' *Fiber-Optic Product Guide*). The FOD can be seen as the fiber-optic version of the popular Linear Variable Differential Transformer (LVDT) but unlike it, the FOD does not require any energizing AC voltage or driving signal with the associated messy wiring. The FOD is completely immune to EMI and RFI, and is not affected by lightning, humidity and corrosive environment. The FOD carries no risk of current leakage and no risk of ignition. It can be safely used in hazardous environments such as those containing explosive materials. Its very low temperature dependence ensure virtually no thermal shift of the sensitivity and the zero, either on short term and long term measurements. Moreover, the FOE can be designed as to produces thermal compensation for the structures to be measured. The rod and telescopic housing can be provided with PVC casing for more protection.

The signal conditioner can be configured to give an output either in absolute displacement (mm or inch) or in relative displacement such as % or microstrain $\mu\varepsilon$. The latter being the absolute displacement divided by the base length of the transducer (= $\Delta L / L$.)

The transducer signal can be transmitted through the fiber-optic cable over a distance of 1 km (and up to 5 km on special request) to the conditioner without the need of line amplifiers.

These above characteristics make the Fiber-Optic Extensometer well suited for long term and accurate monitoring of axial deformations over long base lengths.

FEATURES:

⇒ **LONG TERM AND ACCURATE MEASUREMENT OF DISPLACEMENTS AND AXIAL DEFORMATIONS OVER LONG BASE LENGTHS**

⇒ **MEASURING FIBER-OPTIC PRINCIPLE PROVIDES VIRTUALLY NO THERMAL SHIFT OF THE SENSITIVITY AND THE ZERO**

⇒ **POSSIBILITY TO PROVIDE THERMAL COMPENSATION FOR THE STRUCTURES TO BE MEASURED**

⇒ **RUGGED DESIGN OF THE TRANSDUCER AND THE FIBER-OPTIC CABLE**

⇒ **SIGNAL FROM THE TRANSDUCER CAN BE TRANSMITTED OVER LONG DISTANCE TO THE CONDITIONER WITHOUT THE NEED OF LINE AMPLIFIERS**

⇒ **EASY INSTALLATION AND MAINTENANCE WITH NO ENERGIZING AC VOLTAGE OR DRIVING SIGNAL REQUIRED.**

FIBER OPTIC SENSORS

product datasheet

UMI Signal Conditioner

The UMI is a tabletop, universal fiber-optic signal conditioner ideally suited to performing multi-point temperature, pressure, strain, and displacement measurements in applications that are hostile to non-fiber-optic transducers.

Key features

- 4 or 8 channels
- ± 5 V Analog output
- RS-232 and USB 1.1 communication ports
- Up to 20 Hz sampling rate
- Large VFD Display
- Compatible with all of FISO's fiber optic transducers

Applications

- Microwave food processing
- Medical applications (thermotherapy, NMR)
- Other microwave and RF related applications
- High temperature pressure measurements
- High temperature displacement measurement
- Multi-purpose laboratory applications
- In-situ process monitoring
- Civil engineering
- New material research
- Hazardous environments

FISO's fiber-optic temperature, pressure, strain and displacement transducers feature complete immunity to microwave and RF radiation with high temperature operating capability, intrinsic safety, and non-invasive use. The UMI conditioner is designed to perform accurate multi-channel measurements. The system can scan through all the channels in use with a switching time of 0.15 s, or sample one specific channel at a rate of 20 Hz. All operational parameters are easily programmable using the front panel interface or through RS-232 remote control. A 7-digit gage factor affixed on the connector of each transducer allows the UMI conditioner to easily recognize the transducer type and calibration.

Through the use of a white-light cross-correlator (U.S. Patents 5,392,117 and 5,202,939), the UMI conditioner is capable of measuring the absolute cavity length of FISO Technologies' Fabry-Perot fiber-optic transducers with astonishing accuracy, providing highly accurate and reliable measurements. The UMI has a 0.01% FS resolution (without averaging) and 0.025% FS precision.

The UMI conditioner has a non-volatile memory buffer that can store up to 50 000 data samples. Data-logging sequences, duration and other operational parameters are easily programmable using the front panel interface or through RS-232 remote control. Each channel has a dedicated ±5 V adjustable analog output. The use of a Flash EEPROM allows the customer to easily upgrade the firmware.

Application Examples

1. Optimization of the shrinkage behaviour of cementitious materials at very early ages

(Measurement of autogenous deformations at very ages)

Research project in cooperation with TU of Berlin, Civil Engg.

Objectives:

- Minimising cement paste shrinkage to avoid micro crack initiation

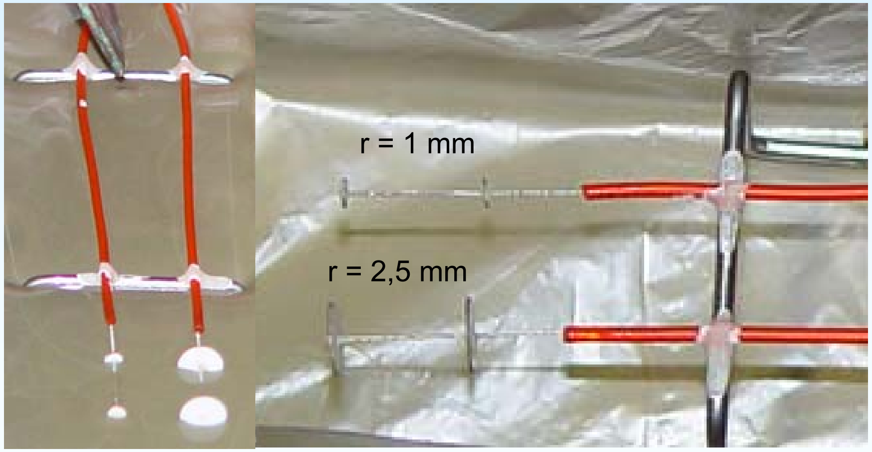
- **Measurement of deformations of different hydrating cementitious materials already at the beginning of settlement process**
  (in fluid cement suspension)

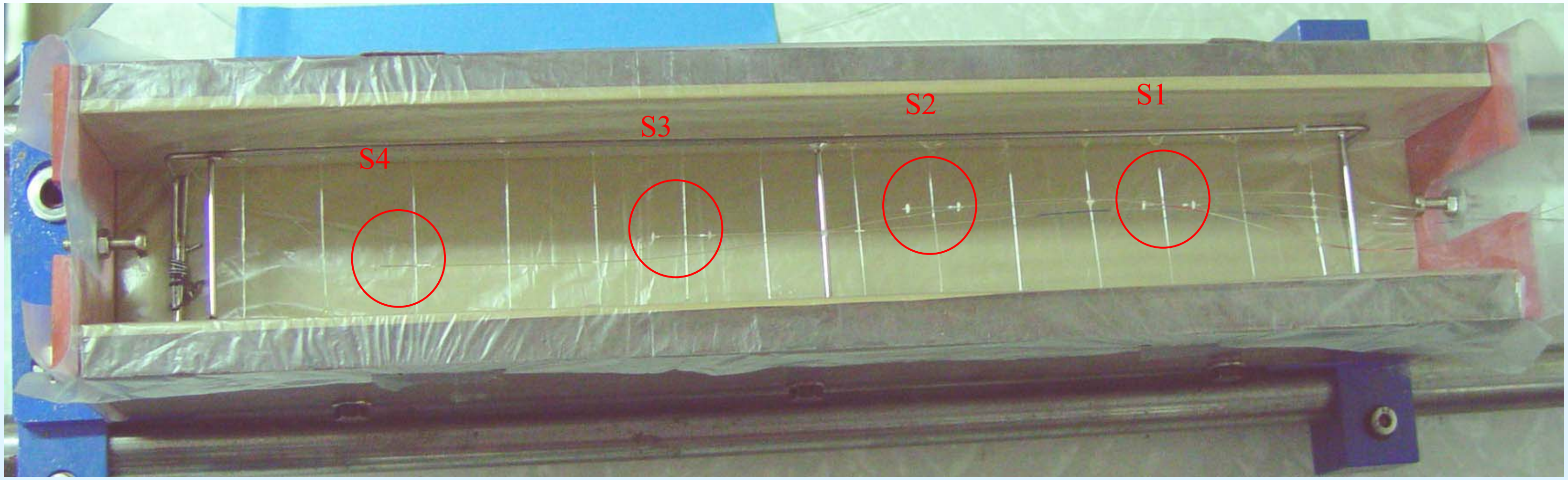
- **Optimising the behaviour of grout deformation and self-compacting concrete mixtures**

Solution:

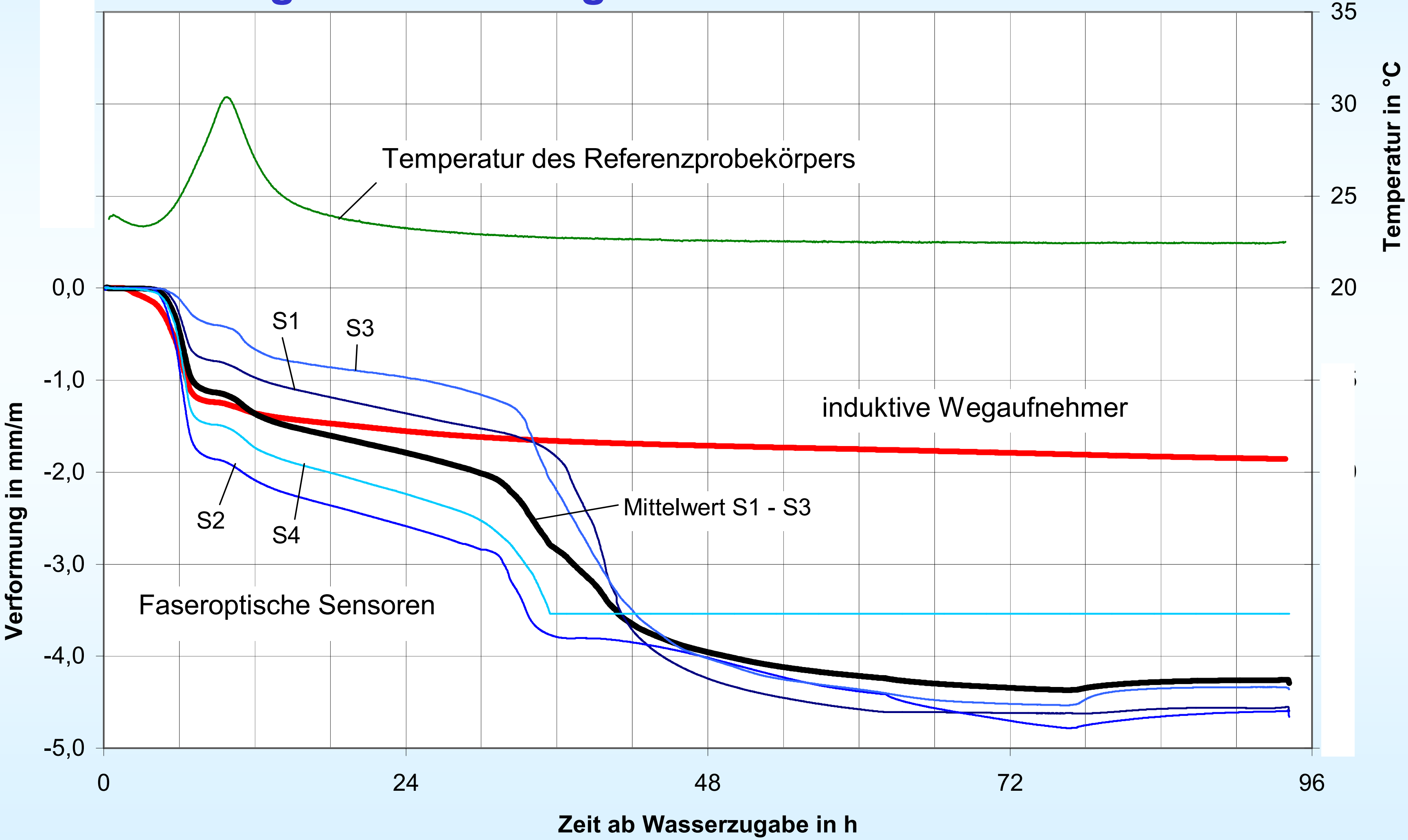
Using movable FFPI

Preparation of the test specimen

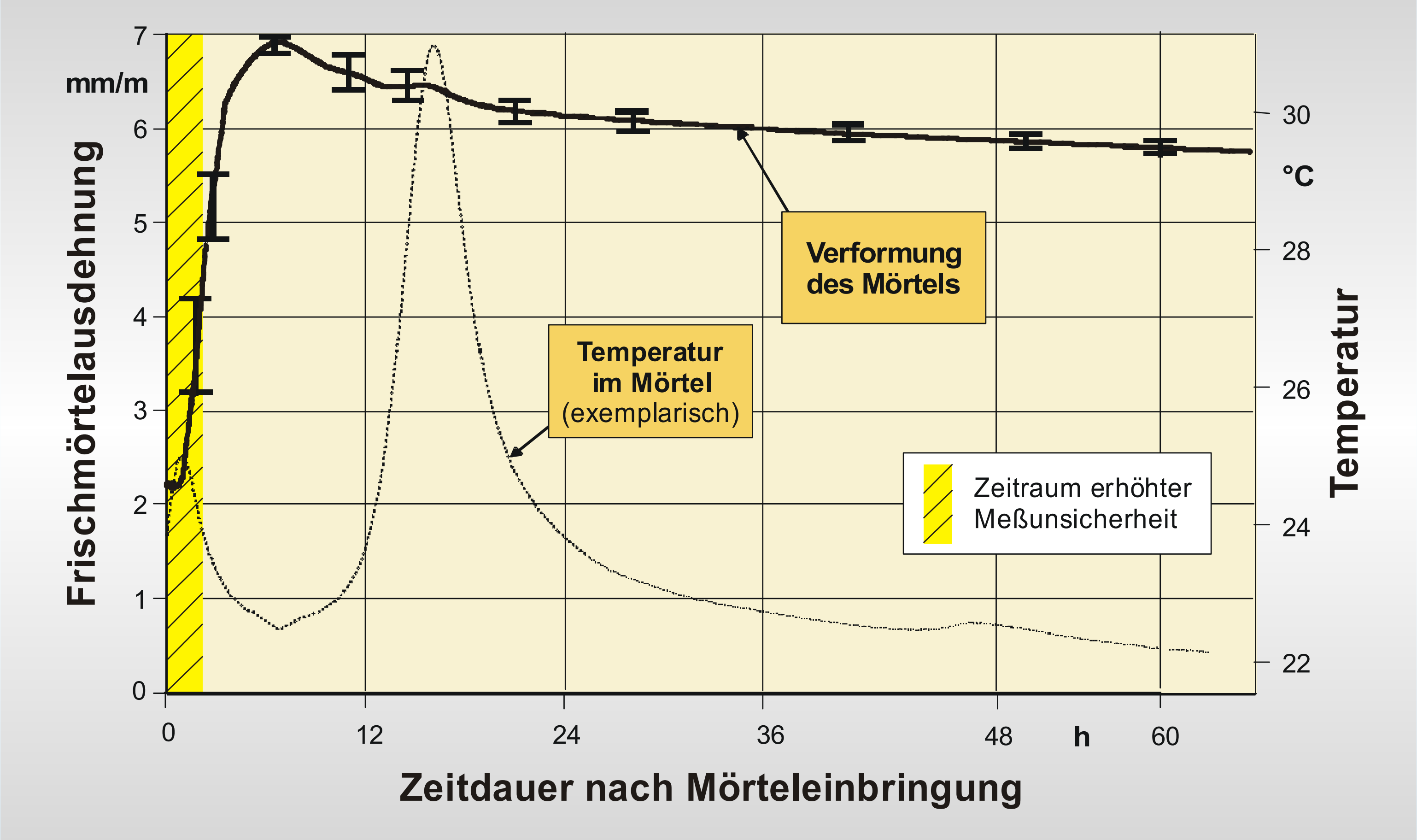




Use of fibre Fabry-Pérot interferometer sensors to optimise the swelling behaviour of grouts



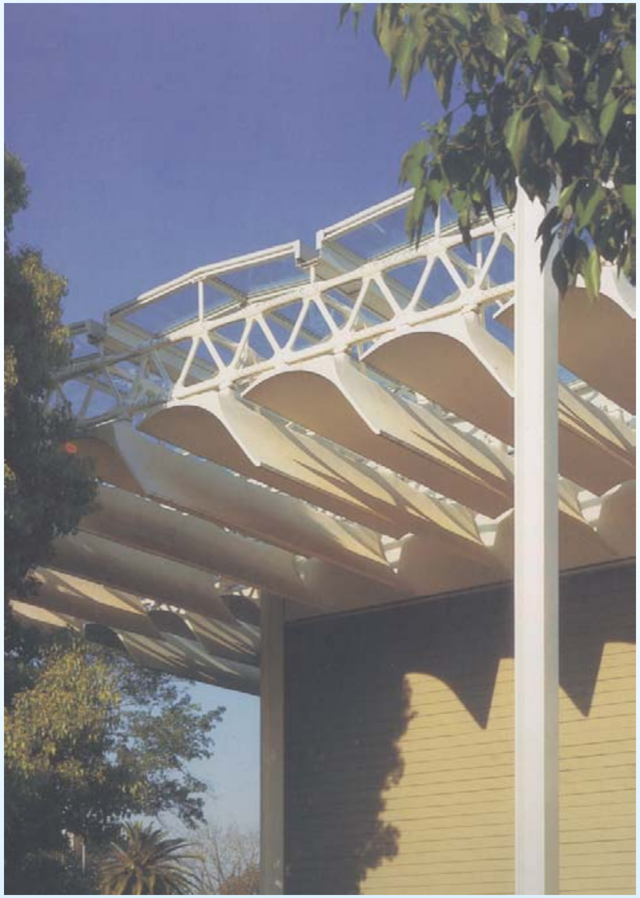
Use of fibre Fabry-Pérot interferometer sensors to optimise the swelling behaviour of grouts

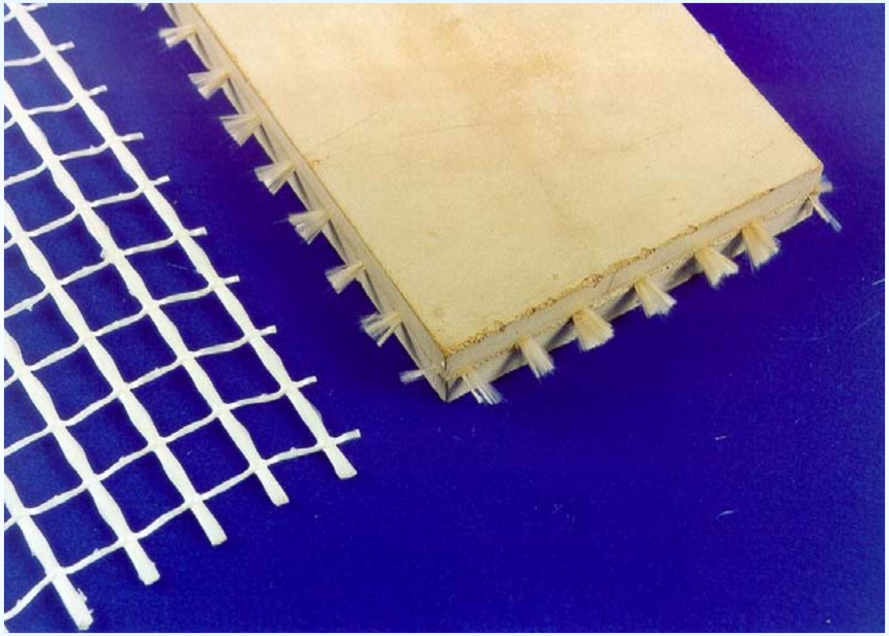


Source: Proc. of the 11th ASCE Conf. „Engineering Mechanics“ in Fort Lauderdale/USA 1996. vol. 1, 355-358. ISBN 0-7844-0172-1

Application Examples

2. Investigation of textile-reinforced concrete components





Research cooperation with TU of Aachen, Civil Engg.

Application Examples

Objectives:

- Investigation of the bonding behaviour of textiles in concrete
- Measurement of deformation strands embedded in the concrete matrix when concrete member is deformed
- Evaluation of the strain distribution between outer (sleeve) and inner (core) filaments in the concrete matrix
- Estimation of load-bearing capacity of newly developed textile-reinforced components

Solution:

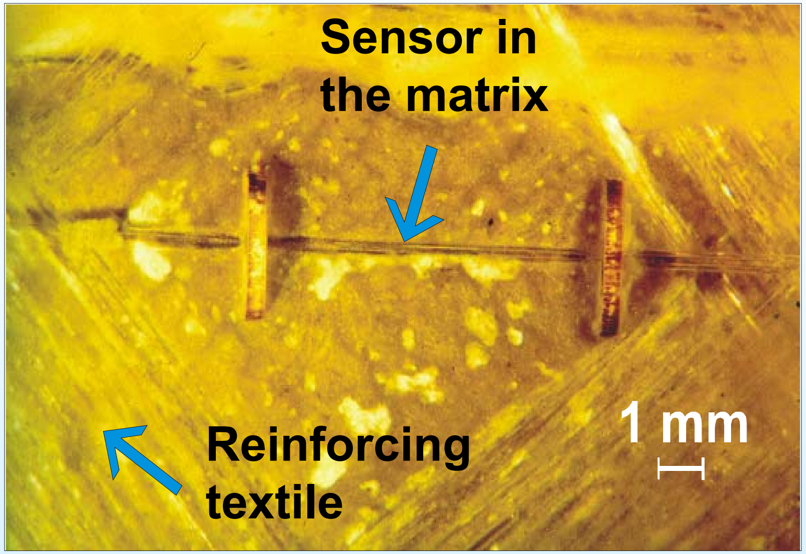
Using movable FFPI

Embedment of flexible (movable) micro strain sensors into the textile reinforcement

Benefit of movable Fabry-Pérot sensors ?

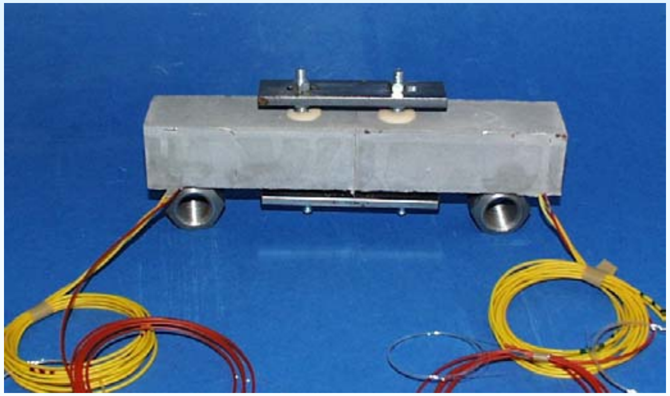
Movable sensors do not hinder the measuring object

Tiny sensor dimension enable application onto the filaments



Tests

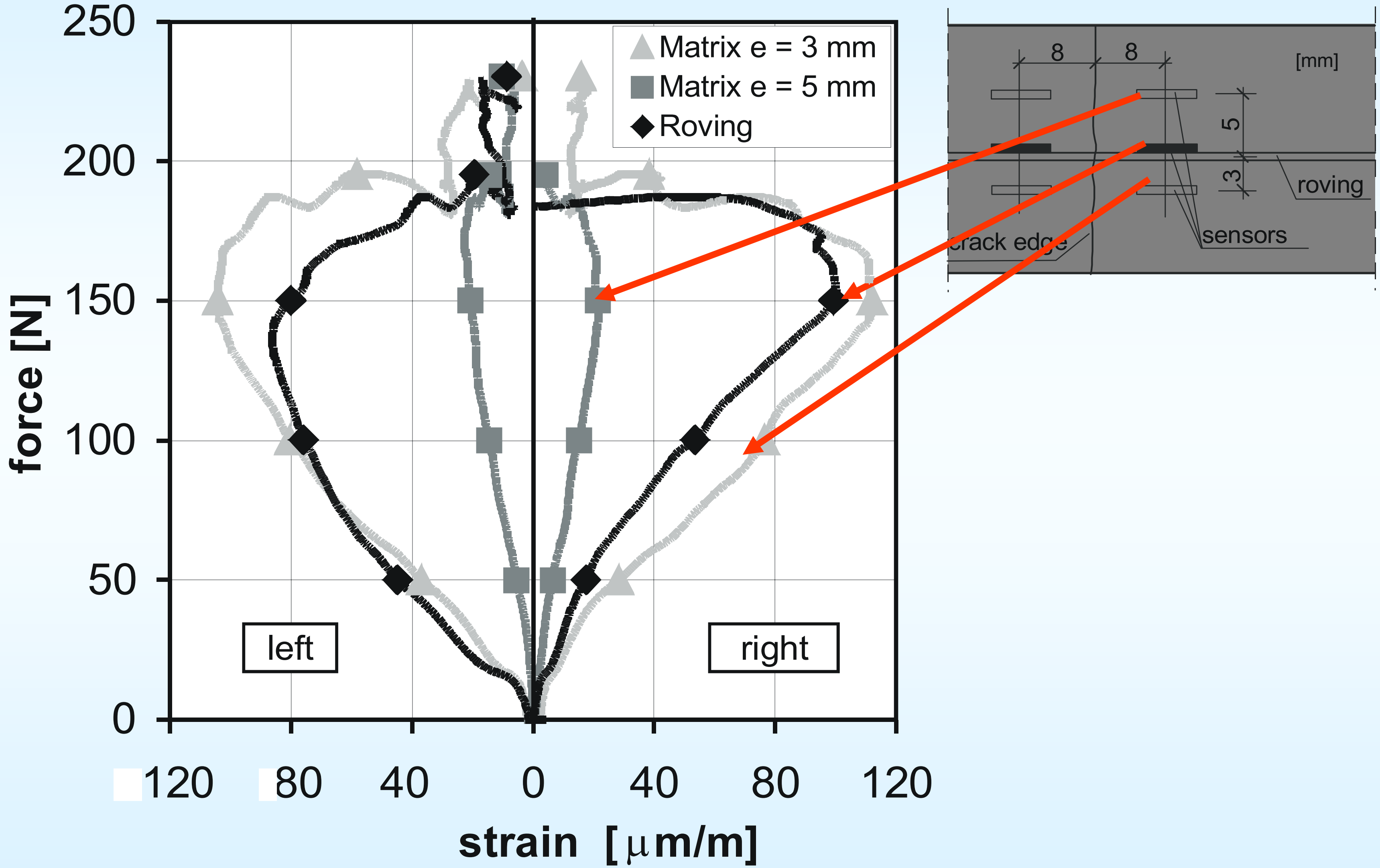
Test specimen



Data recording

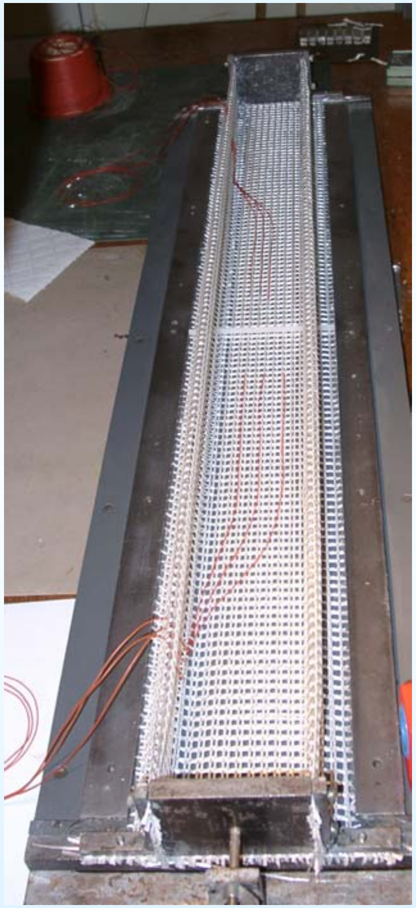
Tensile test

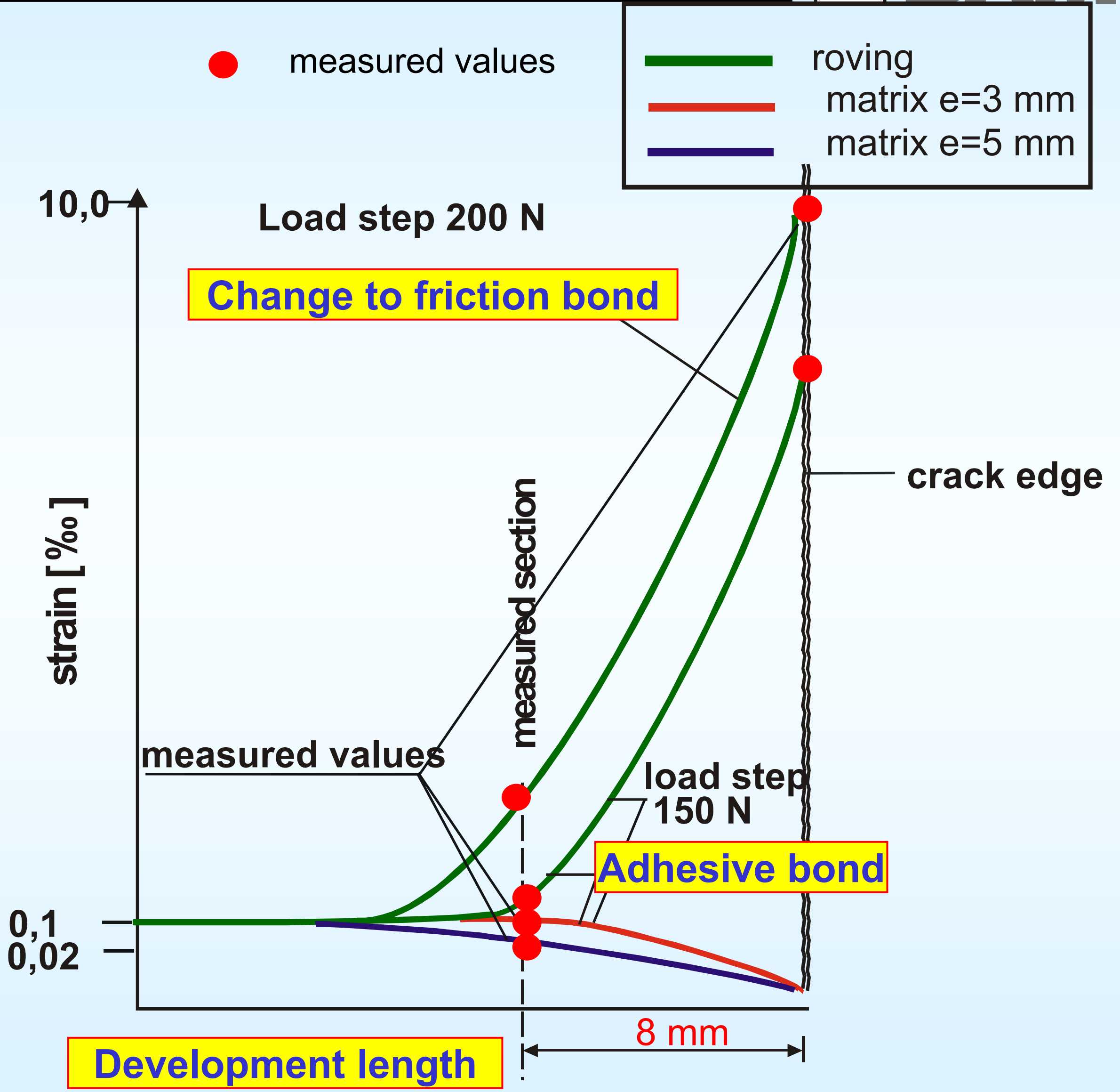
Test results



Source: Proc. of the SPIE vol. 4694(2002), 253-258.

Interpretation of the test results

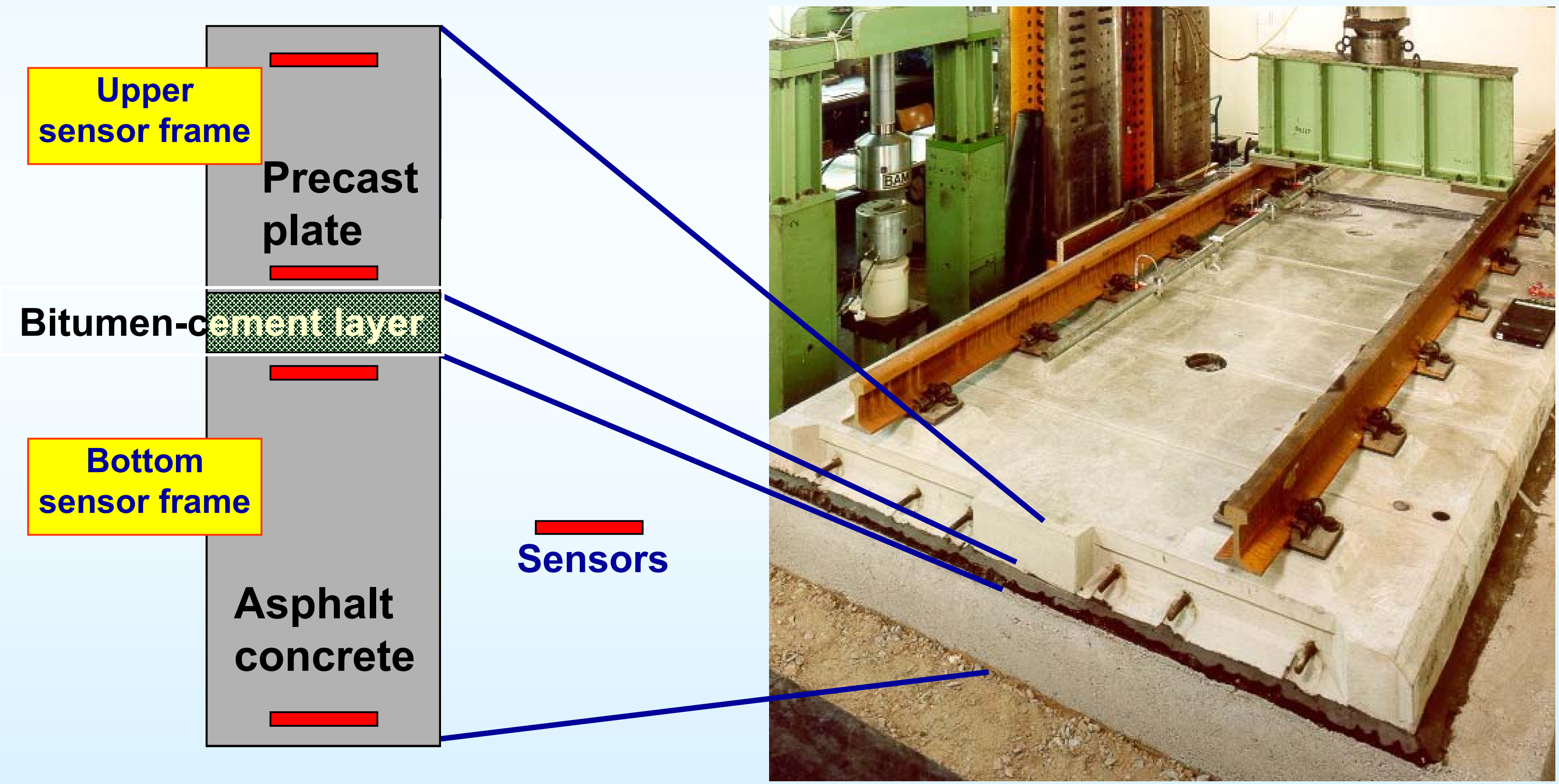




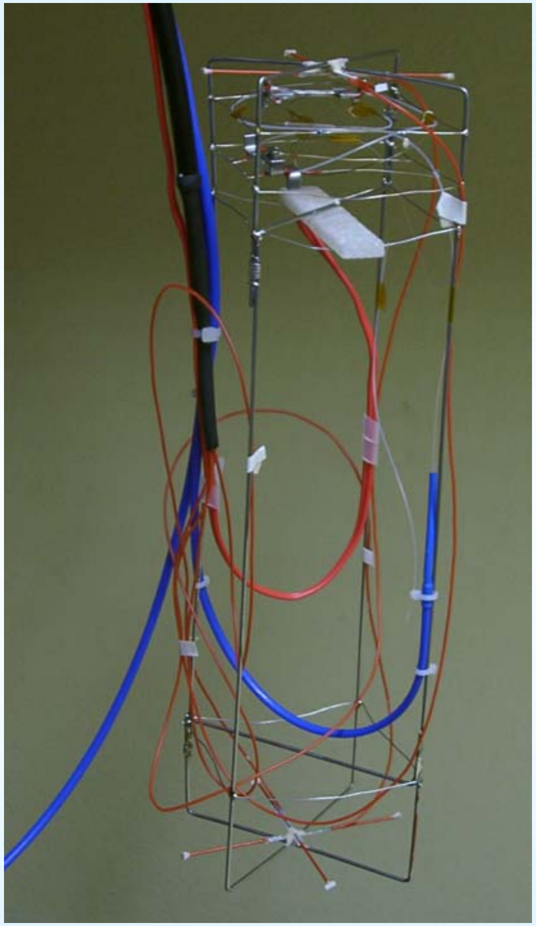
Application Examples

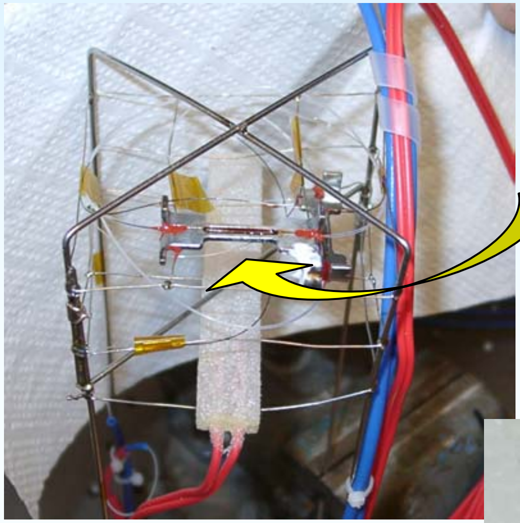
3. Investigation of the stability of a newly developed precast concrete track for high speed railway traffic

Research project in cooperation with Deutsche Bahn AG



Sensor Frame (inner view)

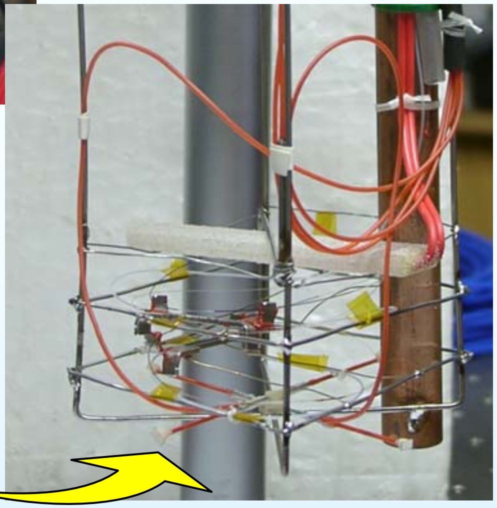




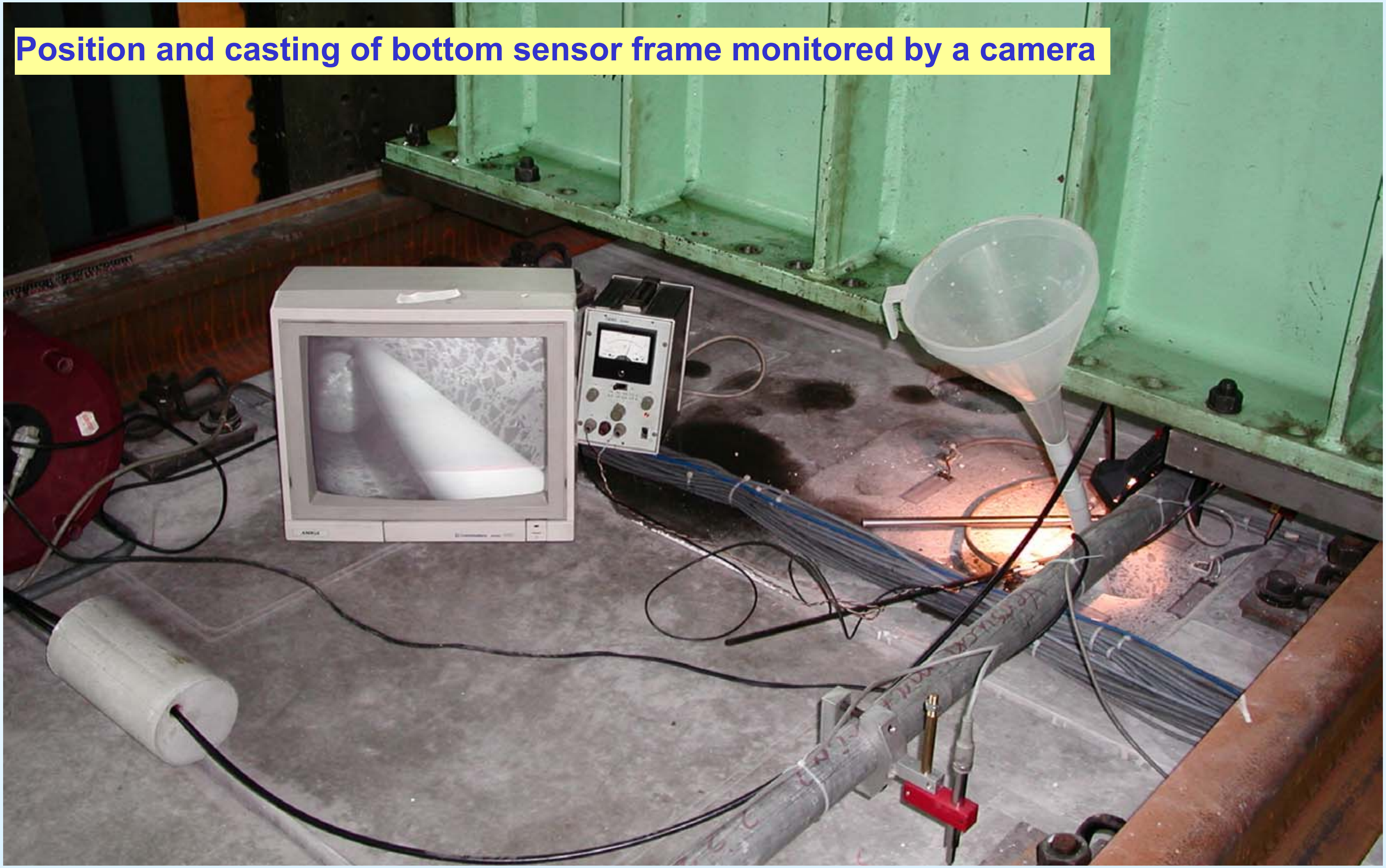
Details

Application of the Bragg grating sensors on tiny clips

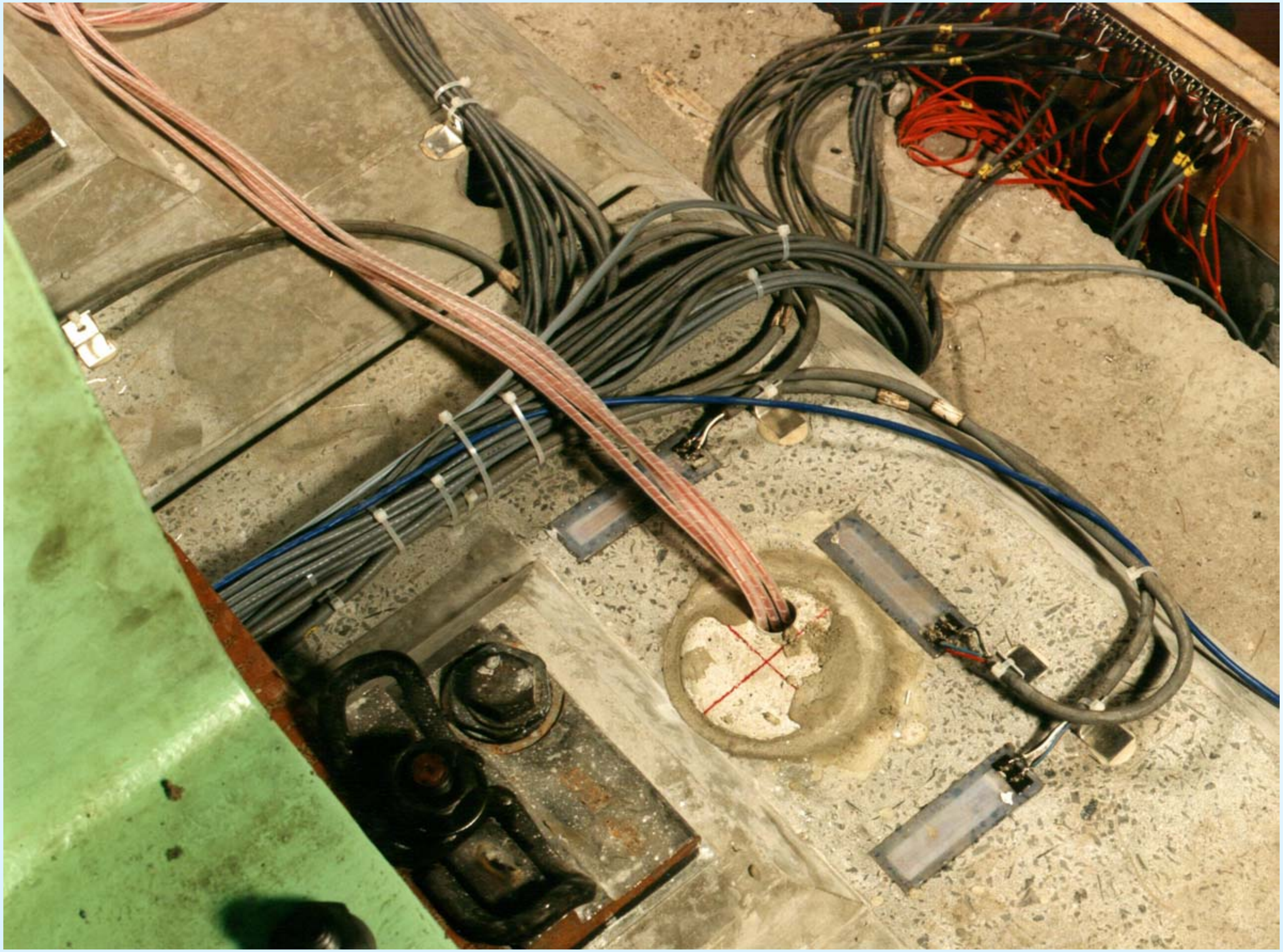
Application of the EFPI sensors



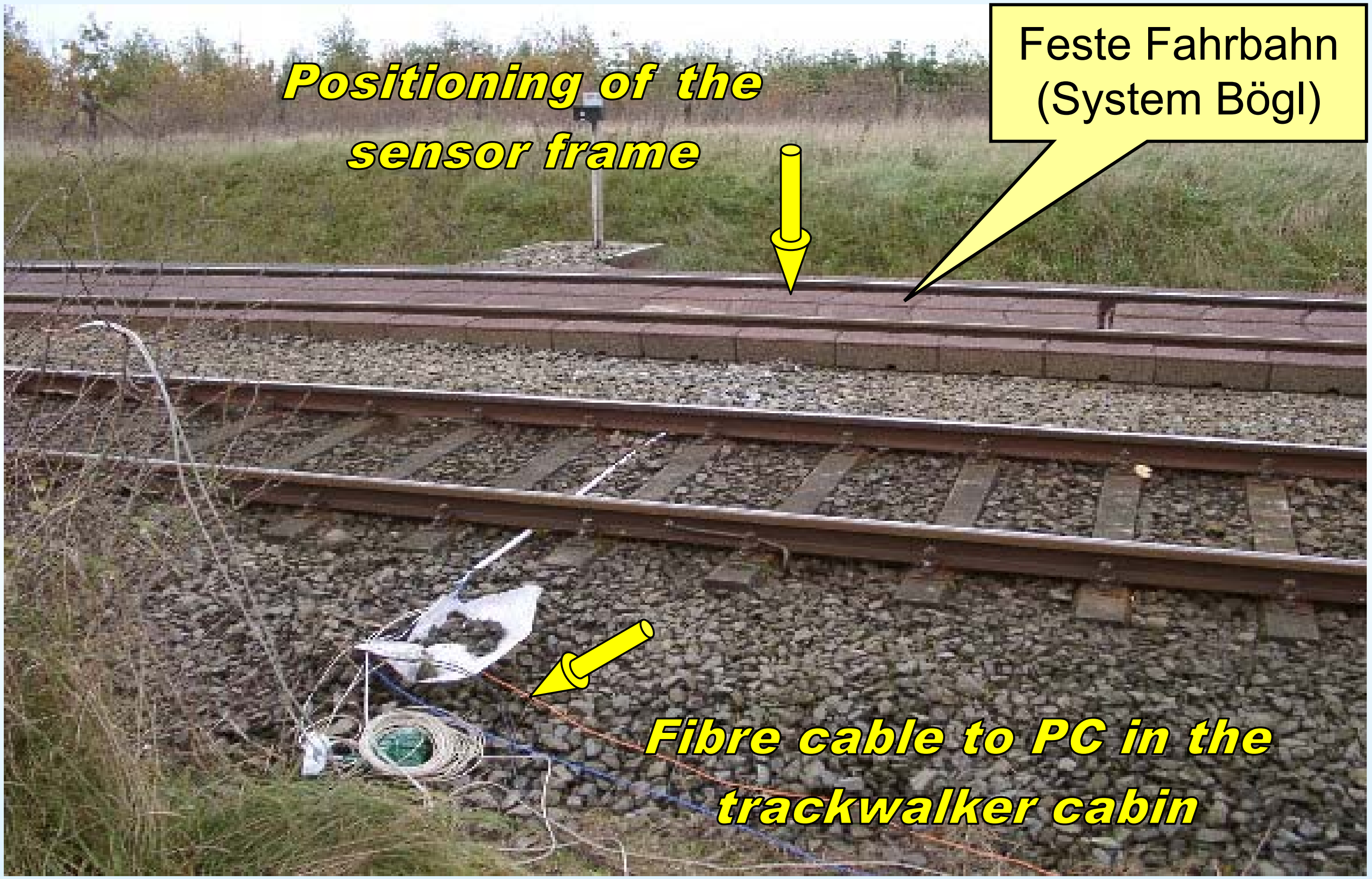
Installation of the Sensor Frame



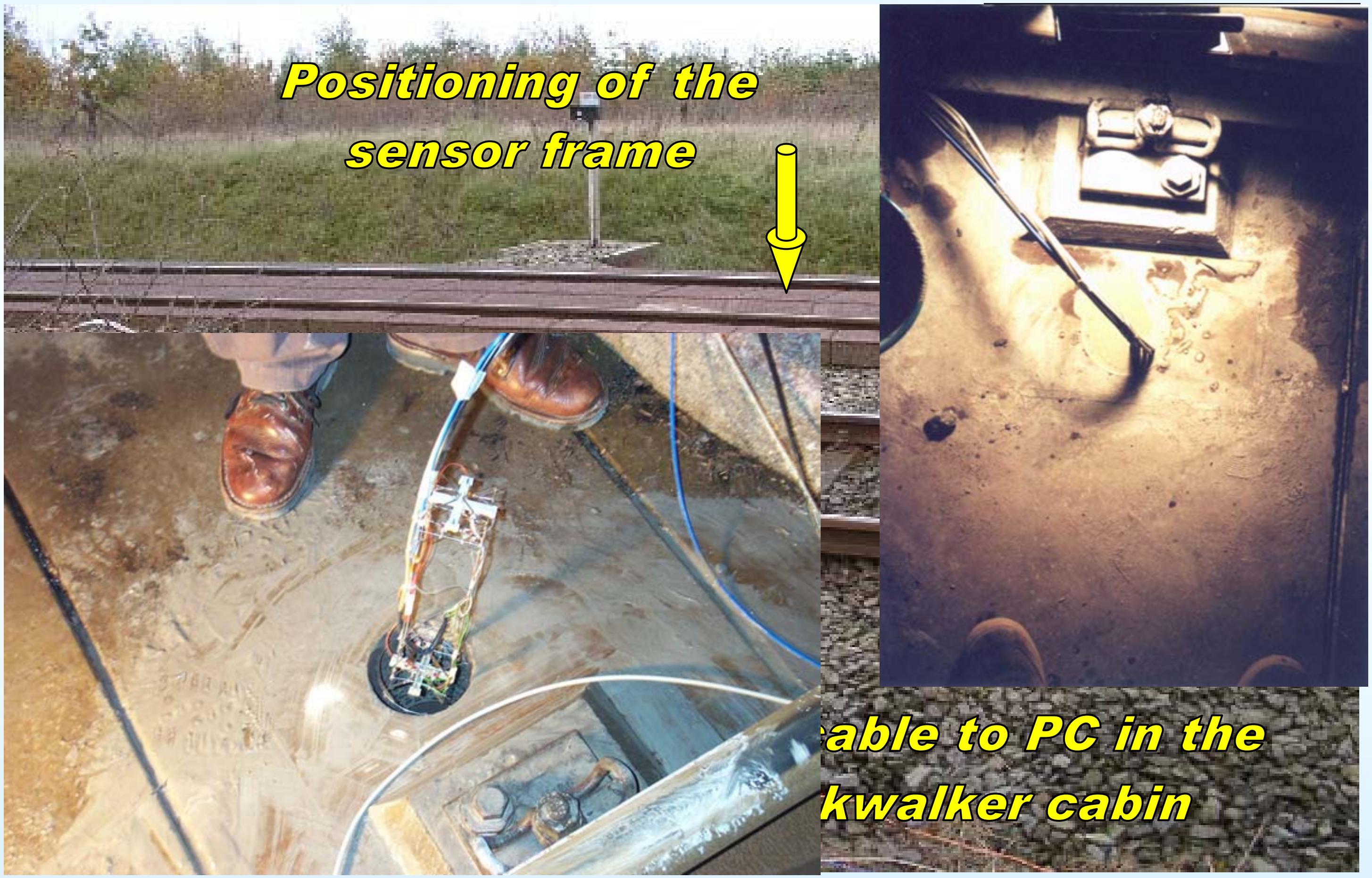
Installation of the Sensor Frame



Measurements at the IC-rail (Husum-Niebüll)



Measurements at the IC-rail (Husum-Niebüll)

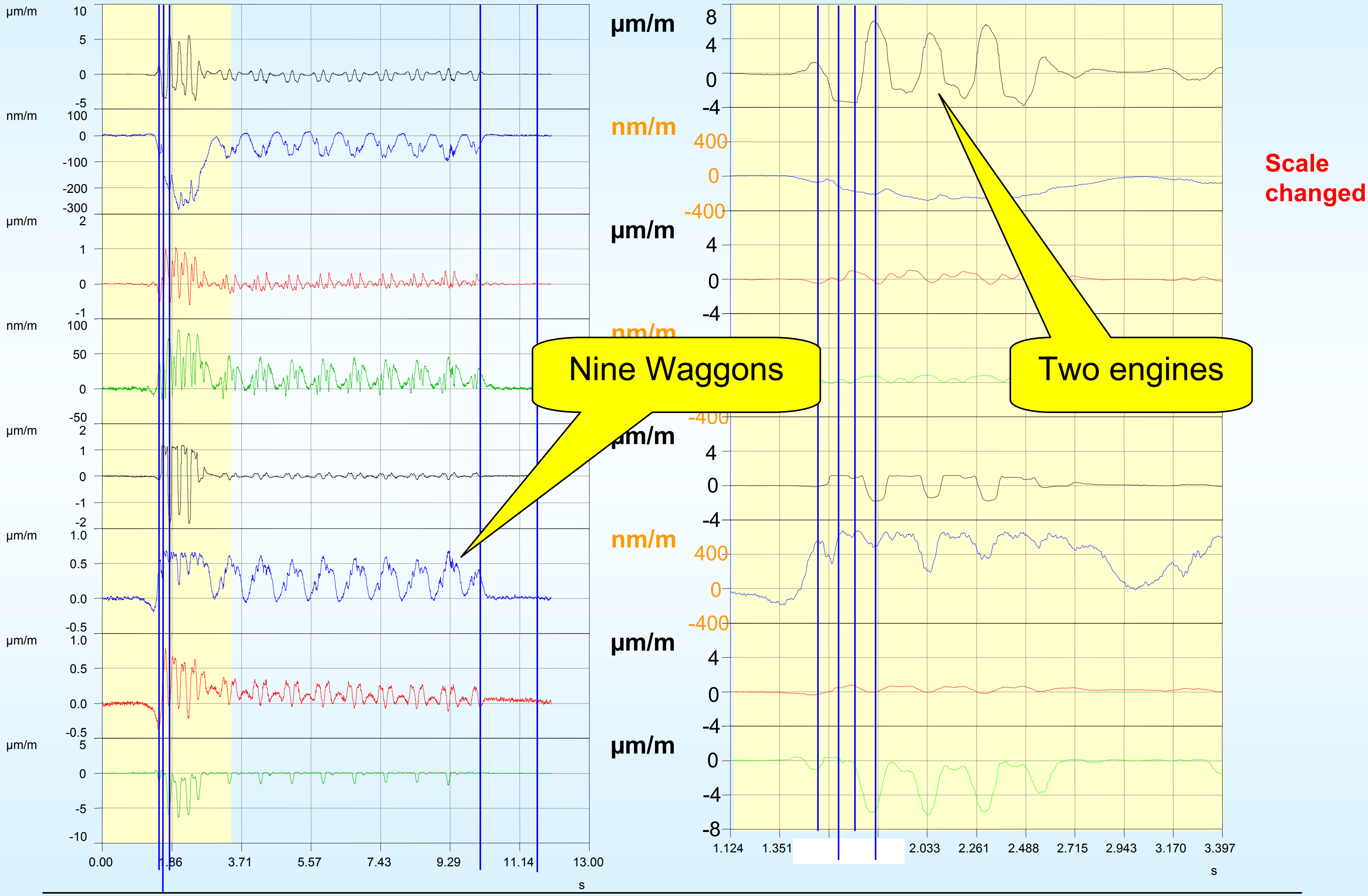


Measurements at the IC-rail (Husum-Niebüll)

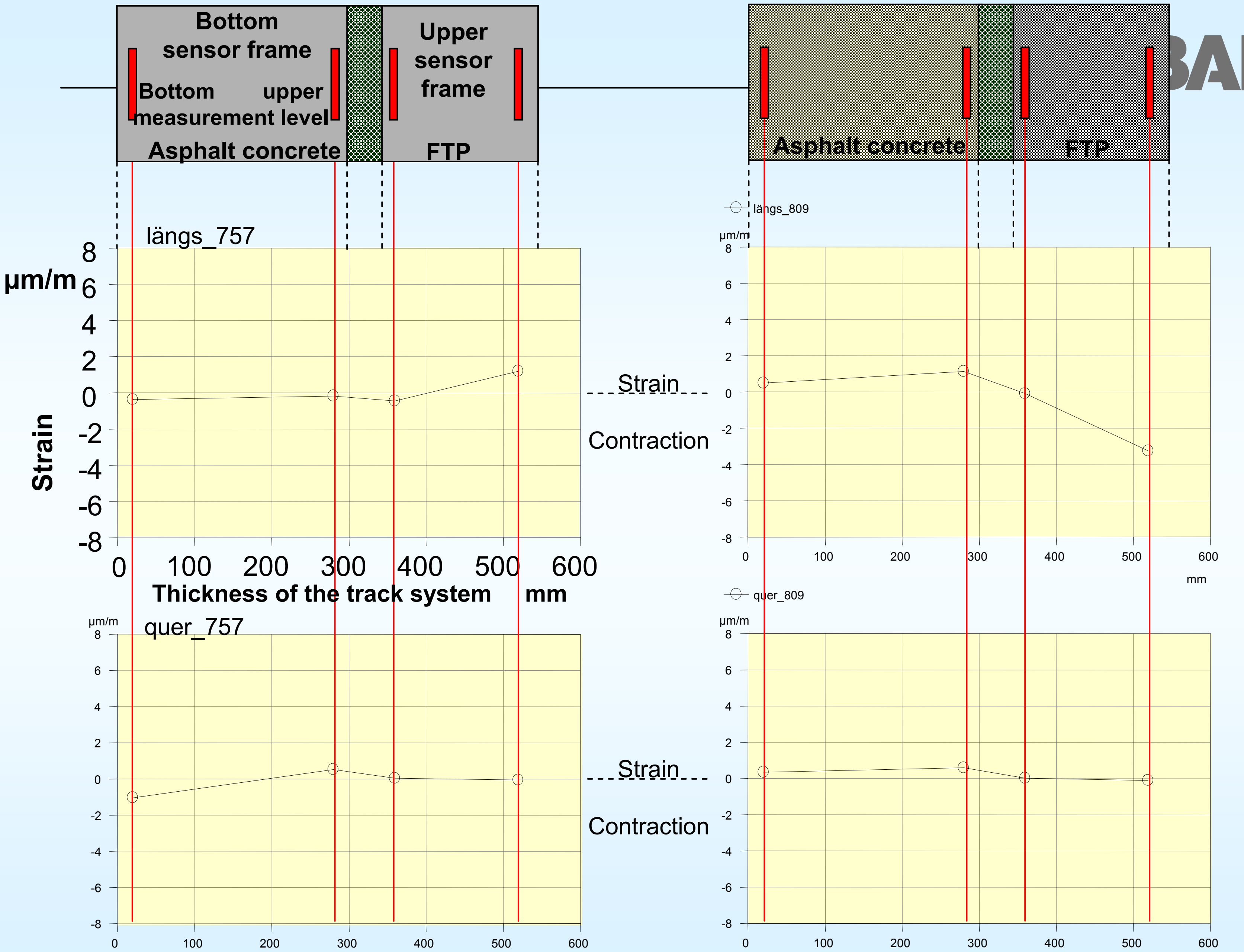
Loading: IC train with two engines and nine wagons
(service load: 80 t, axle load 20.3 t)

Train velocity: approx. 115 km/h

Temporary measurement facility in trackwalker cabin



Source: Proc. of the 3rd World Conf. on Structural Control in Como/Italy 2002. J. Wiley & Sons, vol. 2(2003), 903-908. ISBN 0-471-48980-8



Case 1: Engines did not reach meas. position

Case 2: 1. Rail couple of the 1. leading bogie (LB) is above the measurement position (MP)

BAM

4. Evaluation of strain distribution in the inner part of complex elastomeric components

Research project in cooperation with Bauhaus-Universität Weimar

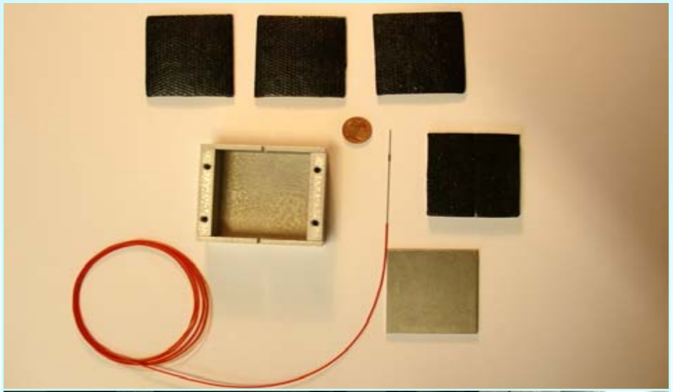
Objectives:

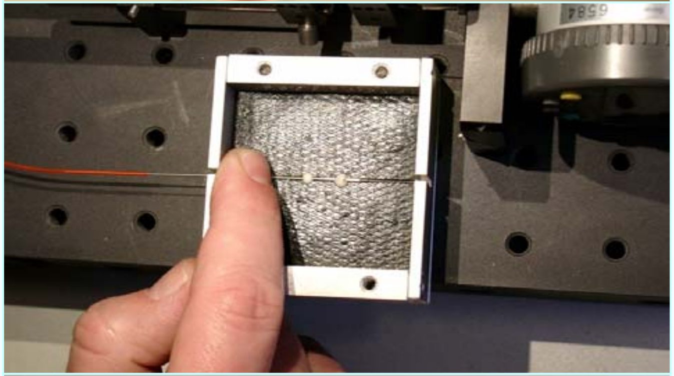
- Improvement of theoretical models by experimental investigations
- Improvement of design rules for elastomeric components for use in Civil Engineering

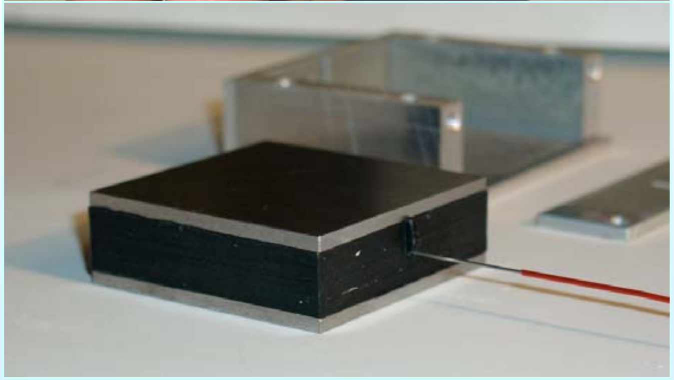
Solution:

Using movable FFPI

Investigation of elastomeric materials







Sensor

and steps to instrument the elastomeric body

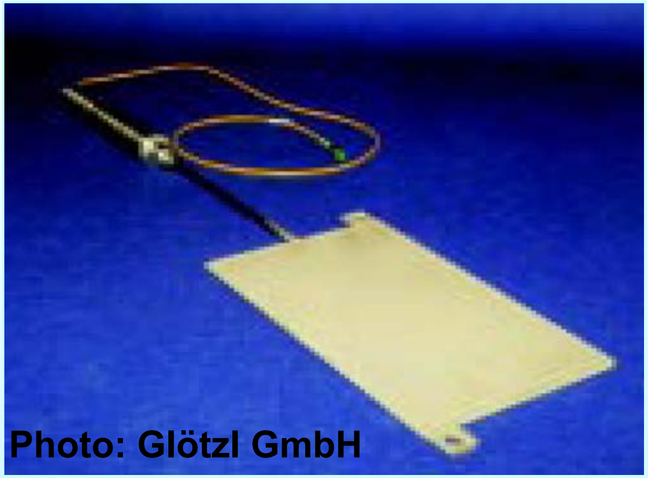
Application Examples

5. Fibre optic diaphragm gauge for pressure heads

In cooperation with Glötzl Gmbh, Rheinstetten/Germany

Objectives:

- Lightning-safe scanning of the deflection of a circular diaphragm inside a pressure head used for stress transducers in geotechnics



Stress transducer

Pressure head

Objectives:

- Lightning-safe scanning of the deflection of a circular diaphragm inside a pressure head used for stress transducers

- **No stress-induced reaction to the diaphragm**

- **Long-term reliable and precise measurement** (> 25 a)

- **Ability to calibrate the sensor after years**

- **Exclusively fibre optic data transmission from sensor to control station**

Solution:

Development of a highly resolvable scanning head with the possibility of pneumatic calibration

Requirements

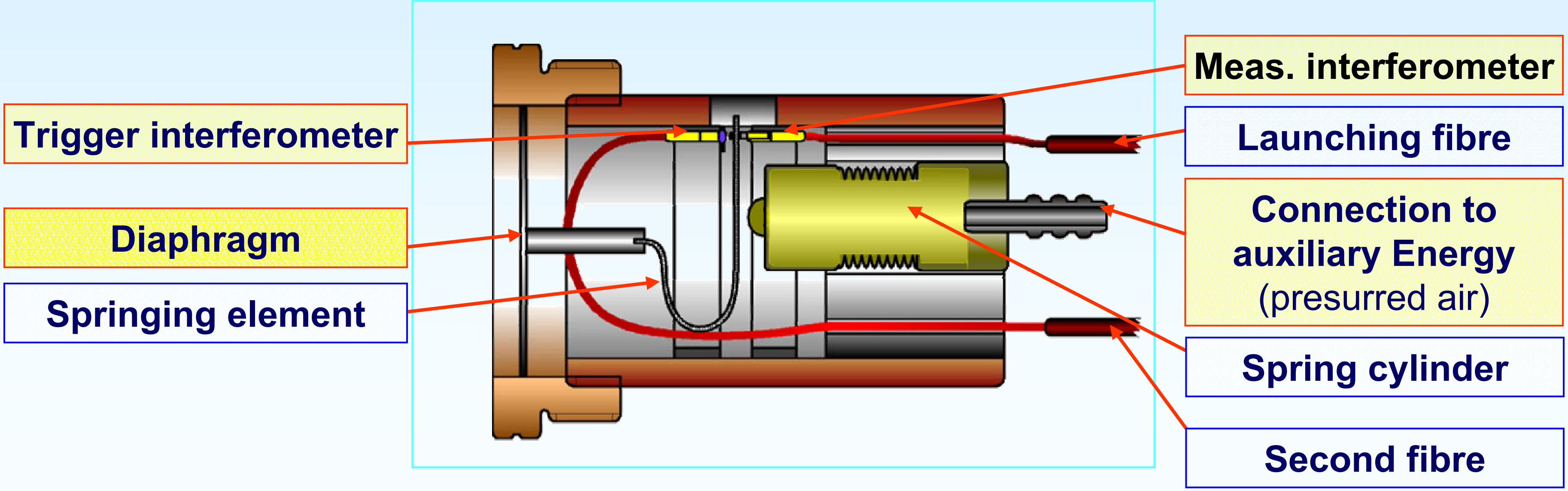
- **High resolution of diaphragm deflection** (≤ 1 µm)

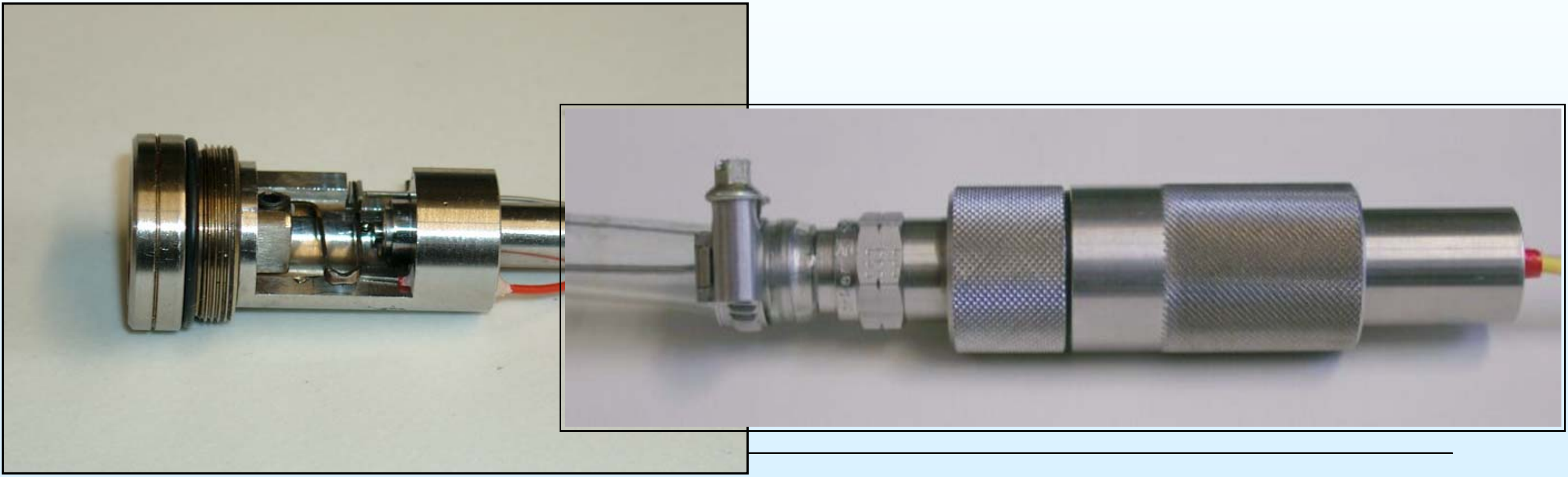
- **Reproducibility of measurement values better than 2 %**

- **Ability to calibrate the sensor after installation and after years of service**

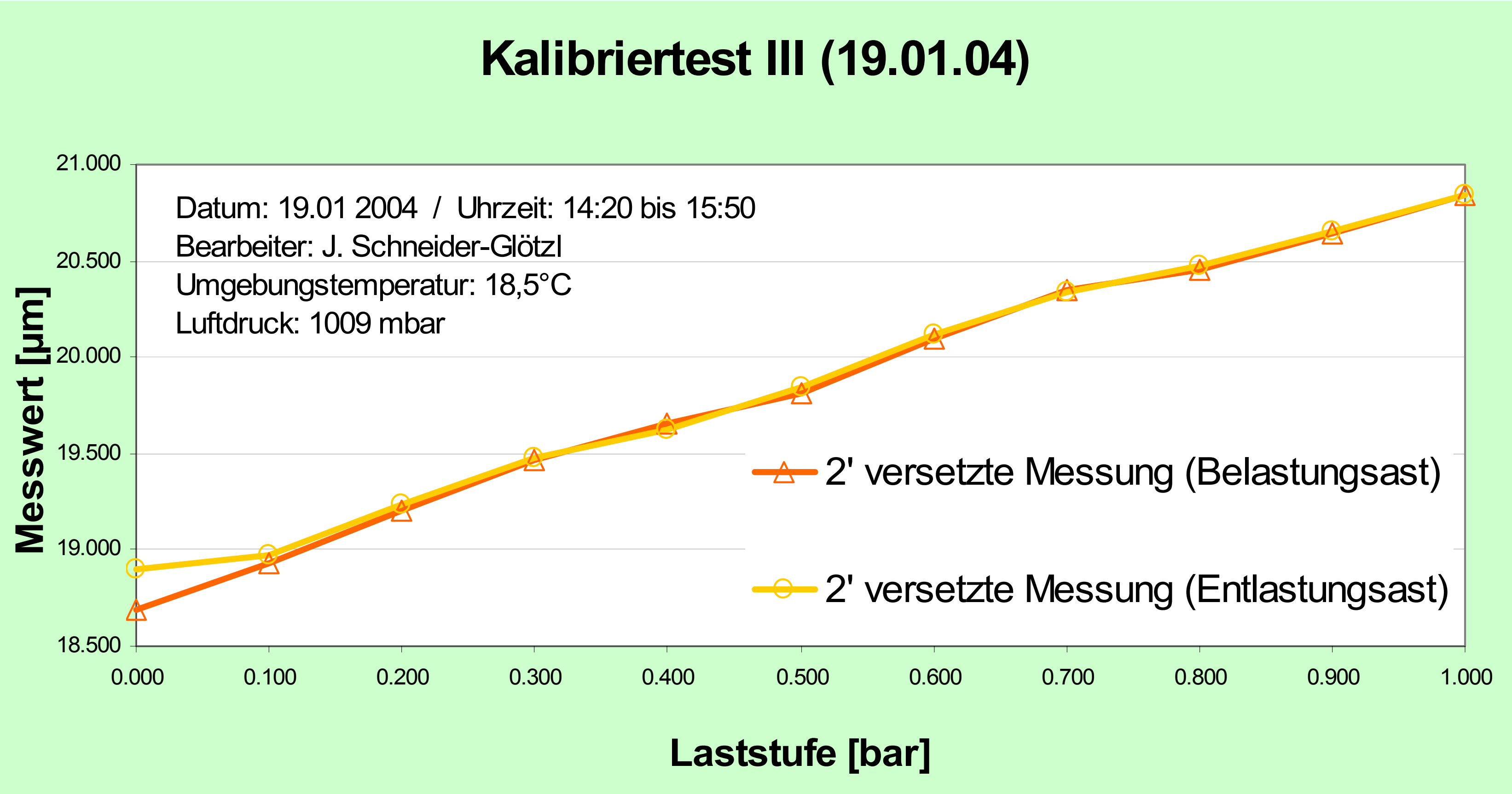
- **Referencing the measurement data to initial data**
  (to avoid a lost of zero-point reference, that means:
  mastery of drift, hysteresis, ageing, …)

Measuring head with zero-point detection

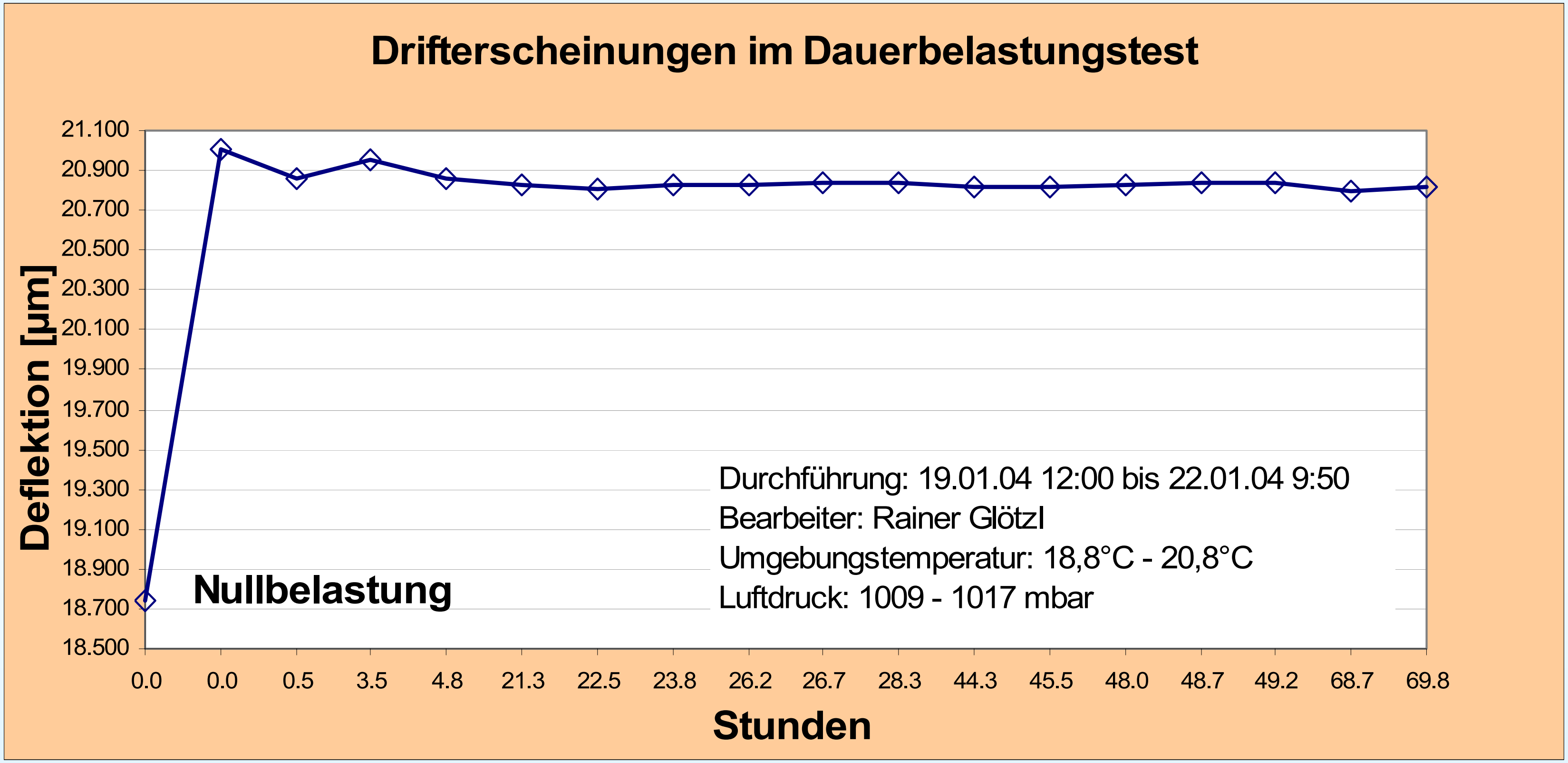




Calibration cycles



Long-term stability test under maximum pressure (1.000 bar)



Source: Proc. of the 2nd Europ. Workshop on Optical Fibre Sensors in Santander/Spain. SPIE vol. 5502(2004), 128-131.

Application Examples

BAM

6. Acoustic emission measurement on concrete tubes constructed from single segments

Research project in cooperation with TU of Berlin, Civil Engg., supported by DFG

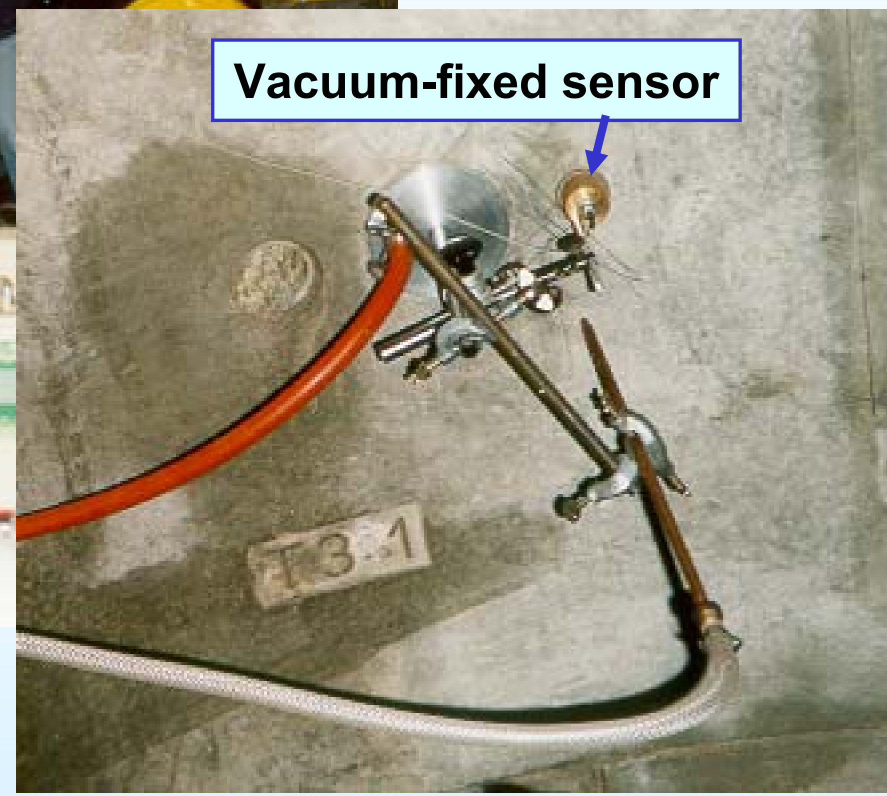
Objectives:

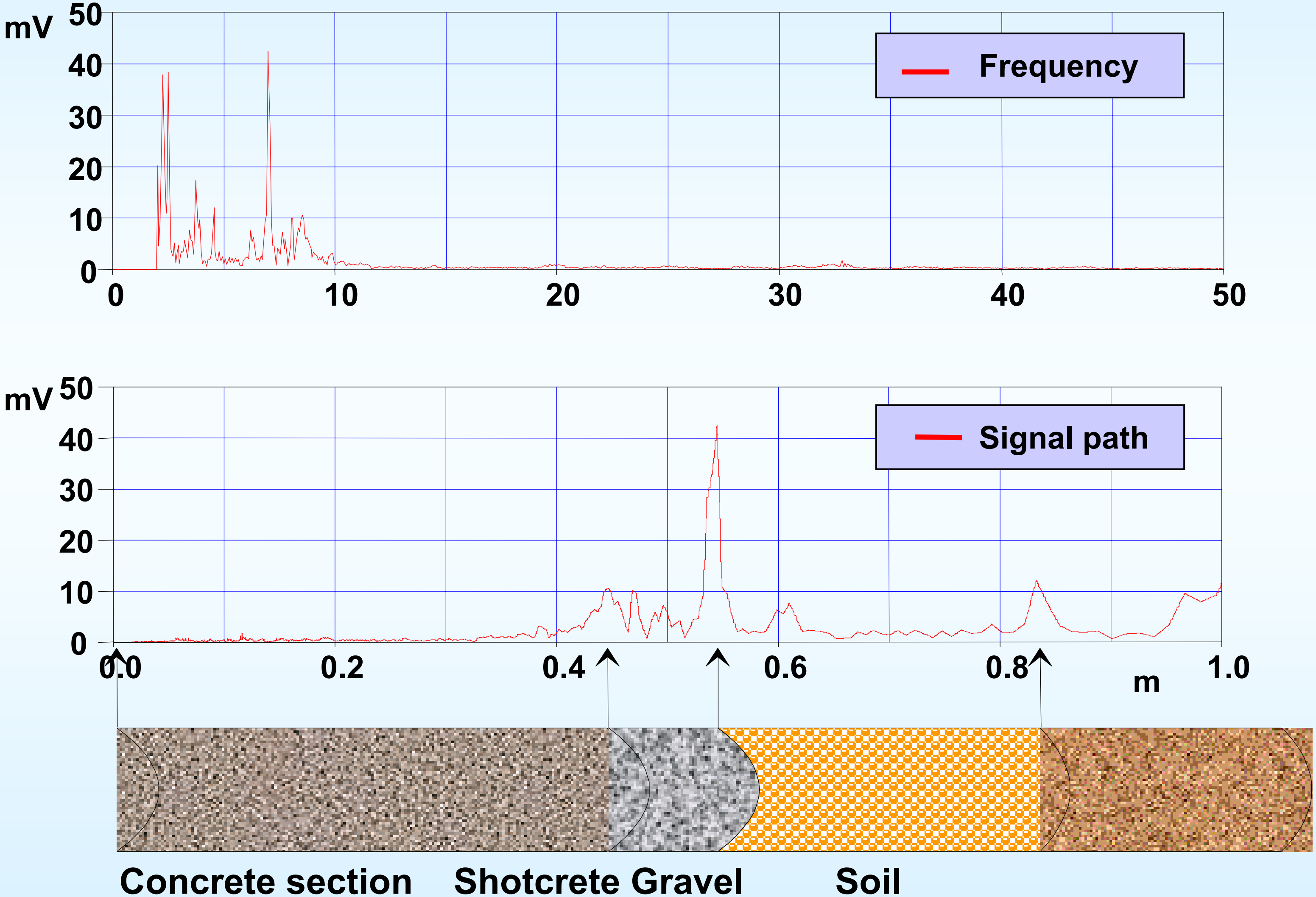
Detection of damage on the back of concrete elements

Solution:

Development of a highly sensitive acoustic detector (stethoscope) **based on a Fabry-Pérot cavity**

Subterranean concrete tube for high voltage power cables

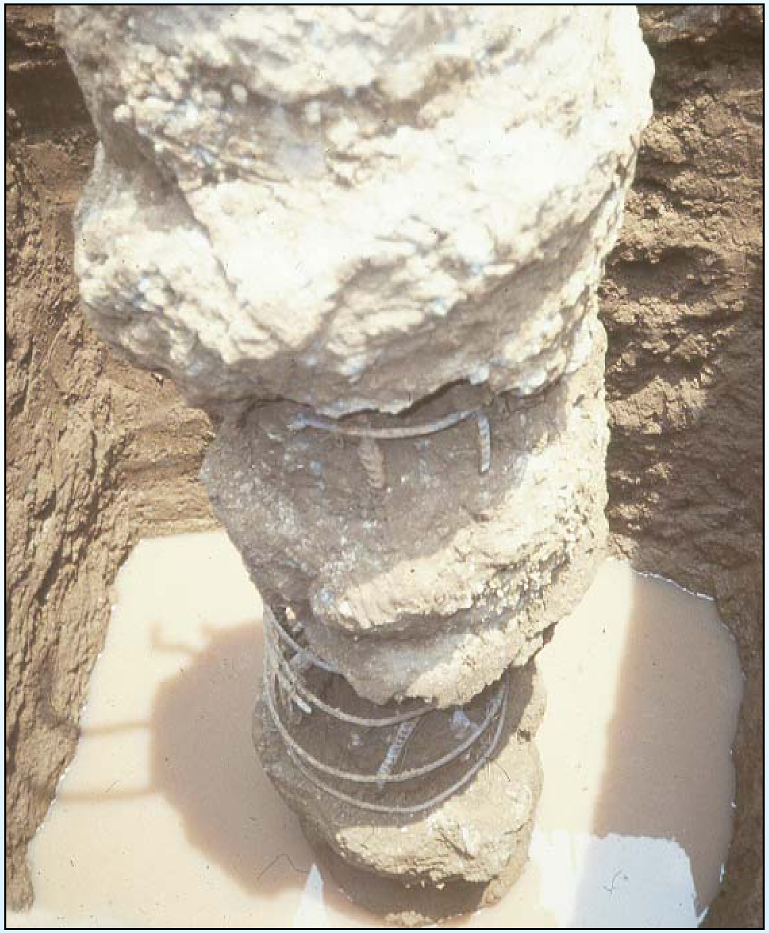



mV
50
40
30
20
10
0
0
10
20
30
40
50
Frequency
mV
50
40
30
20
10
0
0.0
0.2
0.4
0.6
0.8
1.0
m
Signal path
Concrete section
Shotcrete
Gravel
Soil

Application Examples

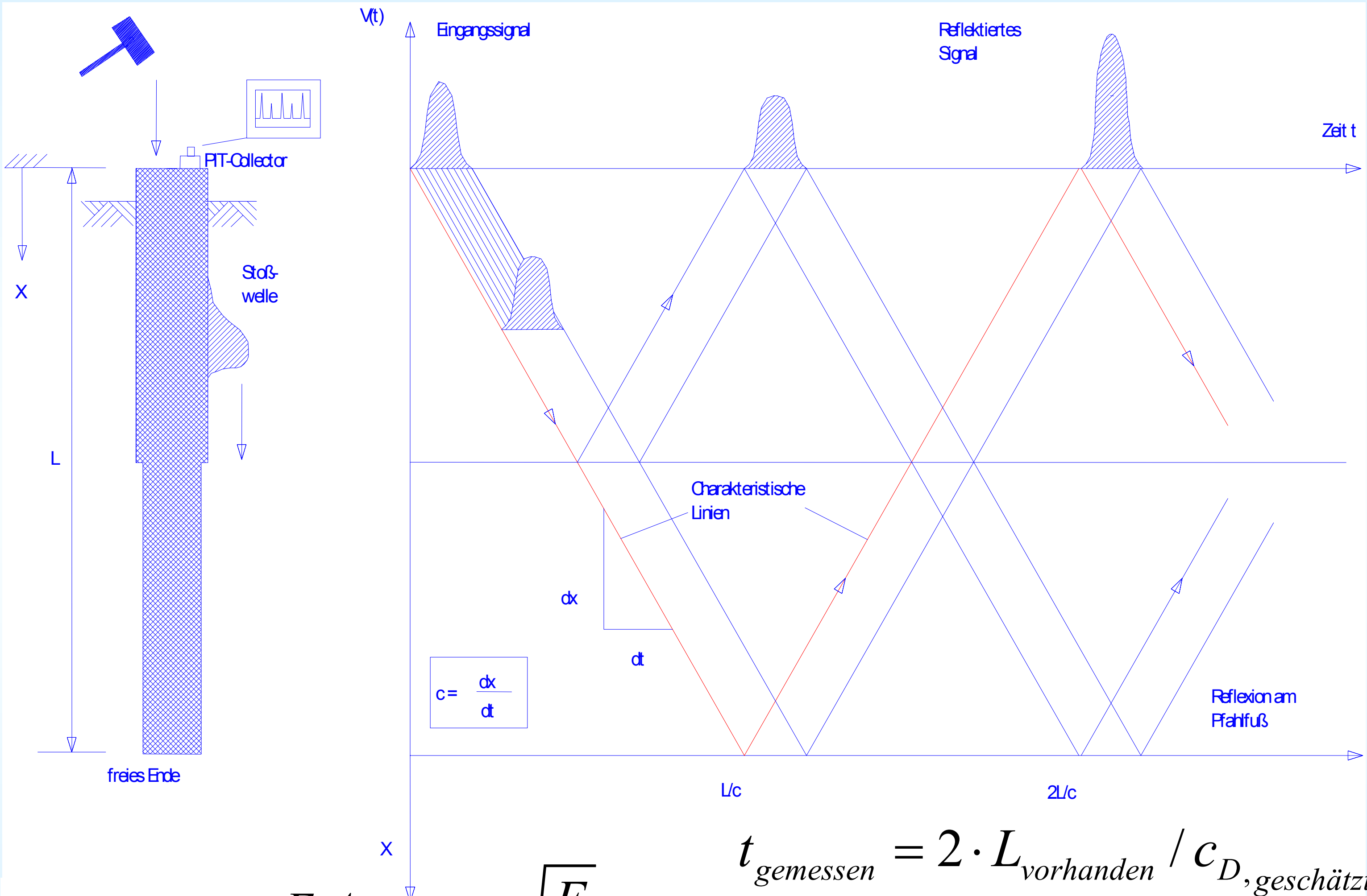
7. Acoustic emission measurement on concrete piles

Research project in cooperation with TU of Braunschweig, Soil Mechanics



Damage while pile is constructed

German research project (8 partners)



$$t_{gemessen} = 2 \cdot L_{vorhanden} / c_{D,geschätzt}$$

$$Z = A\sqrt{E\rho} = \frac{E\,A}{c_D}$$

$$c_D = \sqrt{\frac{E}{\rho}}$$

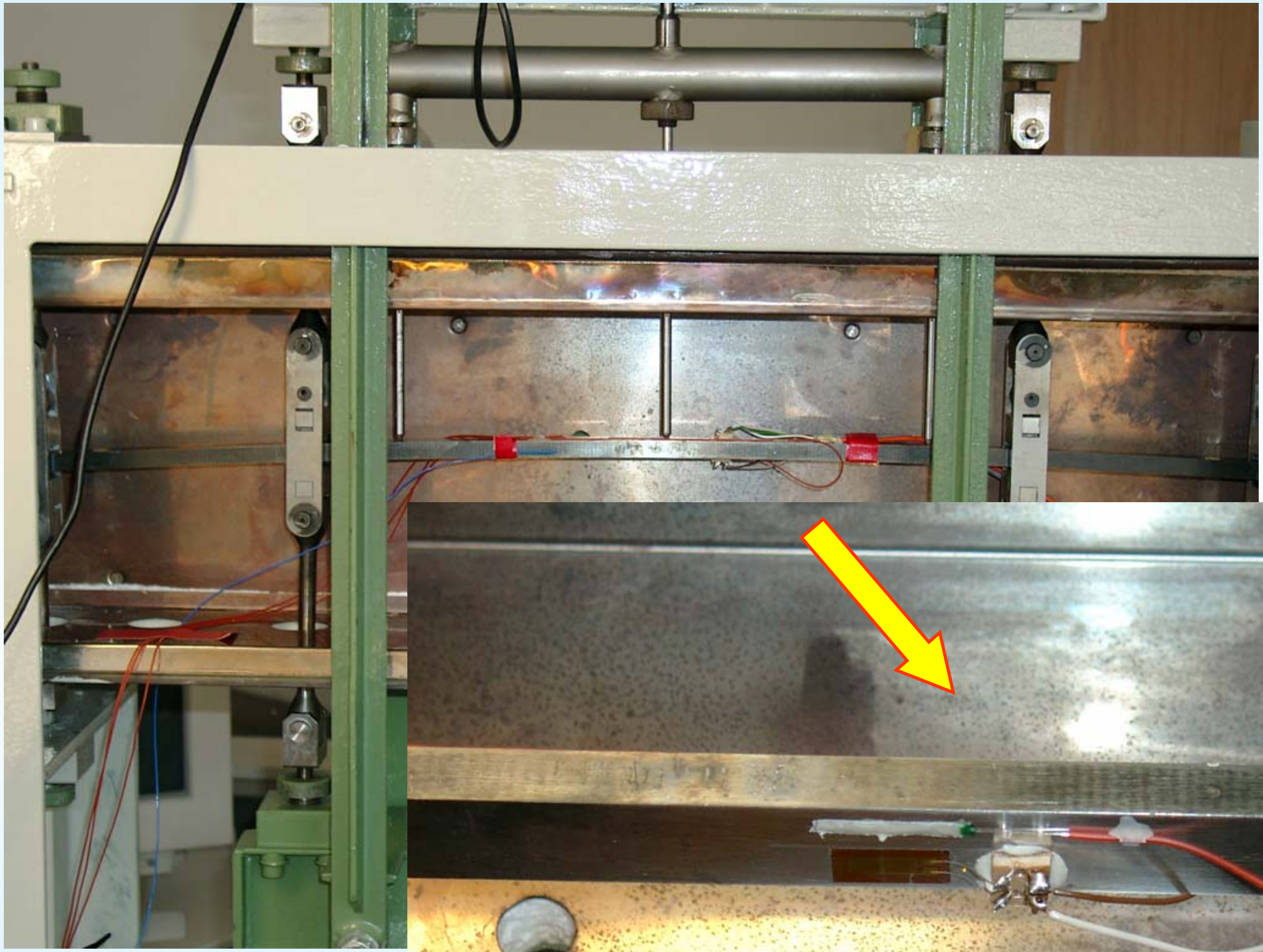
$$L_{vorhanden} = c_{D,geschätzt} \cdot t_{gemessen} / 2$$

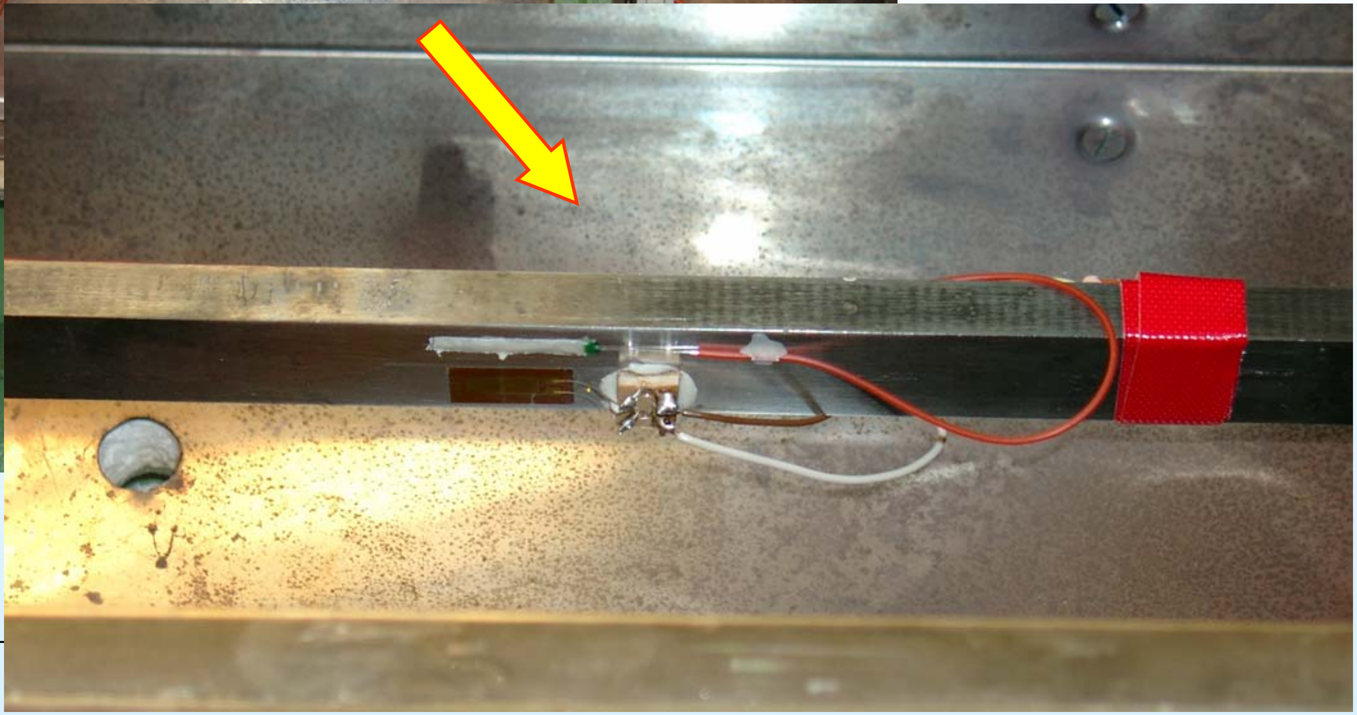
Reliability aspects

Facility for calibration of fiber optic strain gauges

Recommended Lit.: To be published in Proc. of the SPIE vol. 5384(2004) (Habel).

Facility for calibration of fiber optic strain gauges





Facility for calibration of strain gauges and deformation meters

Summary

- **FFPI sensors have excellent potential static and dynamic strain resolution**

- **Apparent strain induced by thermal influences is small;**
  FFPI sensors can be designed as temperature compensated ones
  (similar to resistive strain gauges)

- **FFPI sensors can be designed as movable micro strain sensors**
  (reaction-free measurement in materials with low Young's moduli and in boundary zones)

- **FFPI sensors are local sensors**

- **FFPI sensors are not intrinsically absolute sensors**