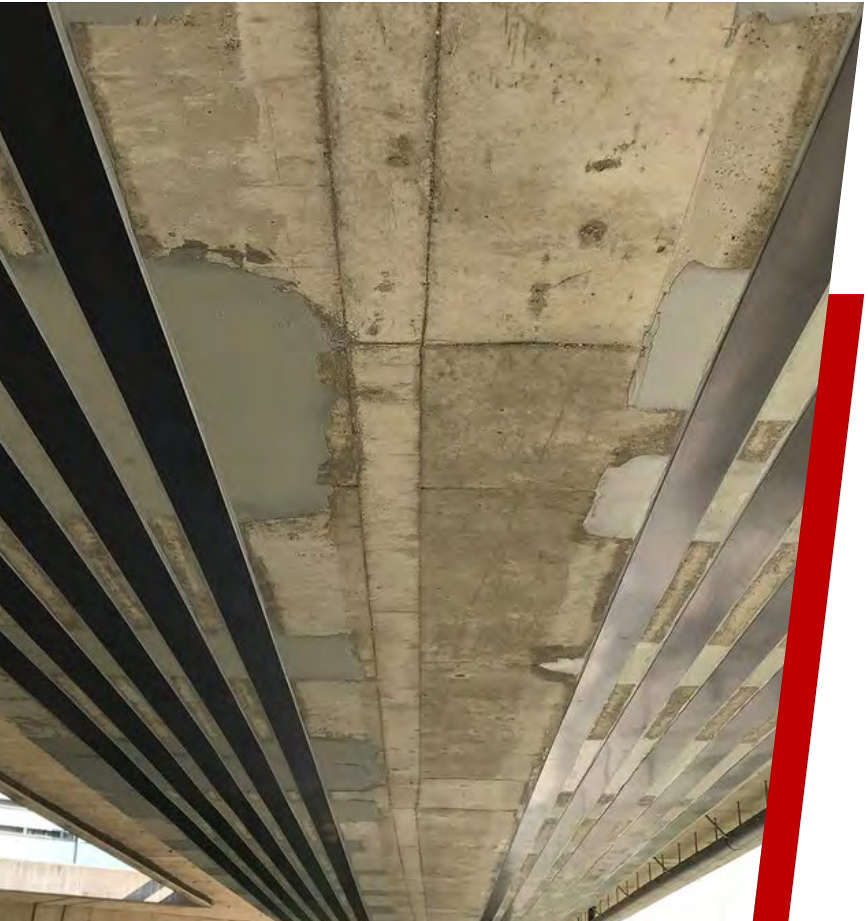

Empa
Materials Science and Technology

Structural Monitoring (CFRP strengthened Structures)

Fibre Composite Materials FS24

Matteo Breveglieri

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Swiss Federal Laboratories for Materials Science & Technology

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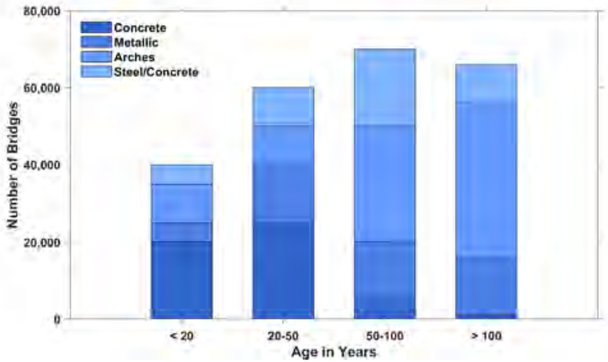
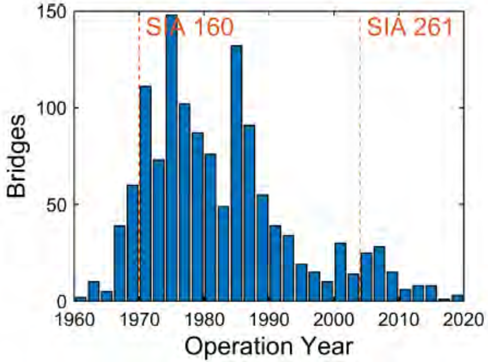
Introduction

- Many bridges worldwide are approaching or may have already reached the end of their designed lifespan



Age of railway bridges in Europe (2004)



Built year of road bridges in Switzerland (AGB 2017/004)

- Aging and deterioration of structures is a common problem in many Western countries. Most bridges have been built between 1960 and 1990 (approximately 35-65 years old).
- There is an important need to extend the service life of the existing structures to ensure safety, maintain functionality, and avoid costly replacements

Approaches to Extend Structural Service Life

The extension of the service life of a structure can be achieved through:

Inspection, and monitoring, testing	Strengthening and Maintenance (including timely repairs)
Identify potential issues before they become critical	Maintain or enhance the load-bearing capacity and overall resilience of the structure.

Monitoring provides quantitative information about bridge performance under operation conditions ⇨ input for bridge assessment

Inspection

- Very often visual inspections but increasingly instrumented inspections
- Periodic
- Non-destructive or locally destructive

  Acoustic emission
  Ultrasound
  Georadar
  Thermography
  Sclerometry [...]

Testing
Proof-load tests

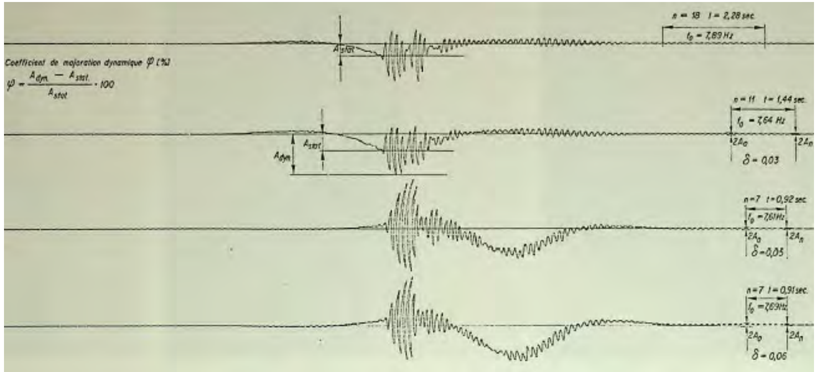
Fawad et al 2023

Fennis et al 2014

Lantsoght et al. 2018

Testing
Models validation

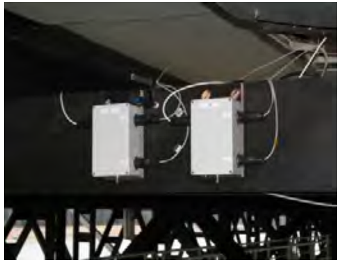


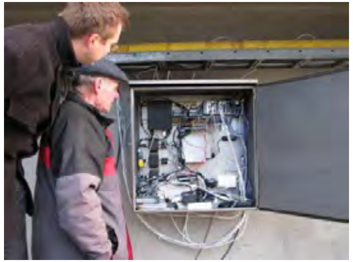


Empa report 41’002 - Load Test on Swiss a bridge (1979)

Paulsson et al 2010
(Sustainable Bridges EU Research Project)

Monitoring





Long term deployment (weeks, months, years)

Unsupervised or remote supervision deployment

Information about operation conditions

Type of sensor used in bridge monitoring

Surface-Mounted and Embeddable Sensors:

Accelerometer

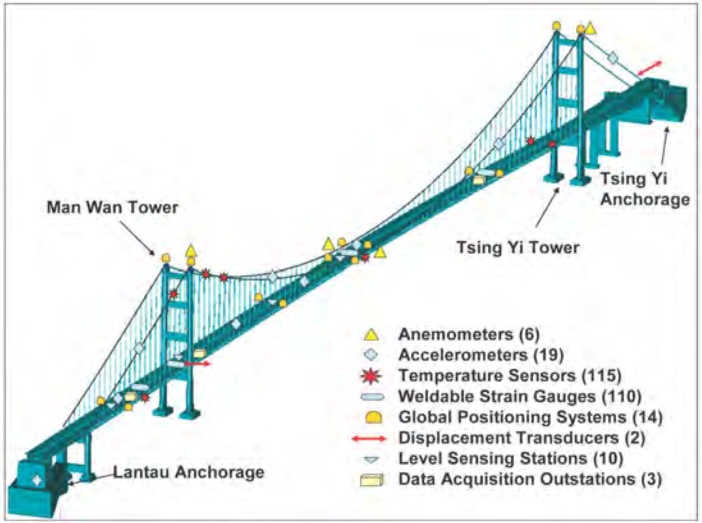
Strain sensors: (Strain Gauges, Fiber optic ...)

Tiltmeters

Corrosion Sensors

Crack Monitoring Sensor

Smart Aggregate



Wong K.Y 2007

Remote Sensing:

Total Station

Laser Scanner

Satellite navigation (GNSS)

Unmanned Aerial Vehicle (UAV)

Satellite interferometry

Radar Interferometer

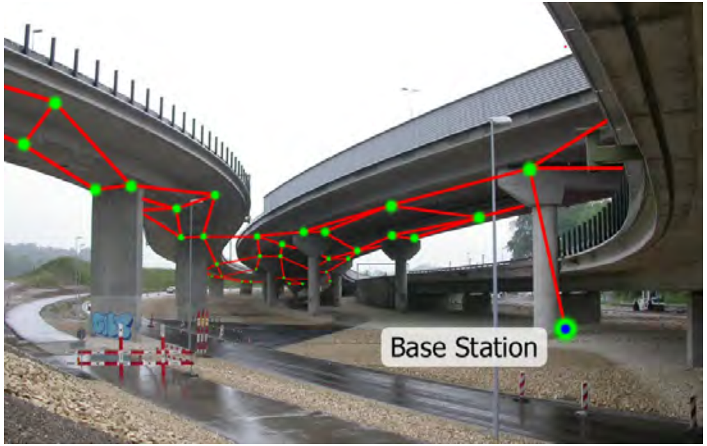
Weather Station

Temperature, Wind, Humidity

Traditional wired installation

https://www.youtube.com/watch?v=oO7E2G2WfL4

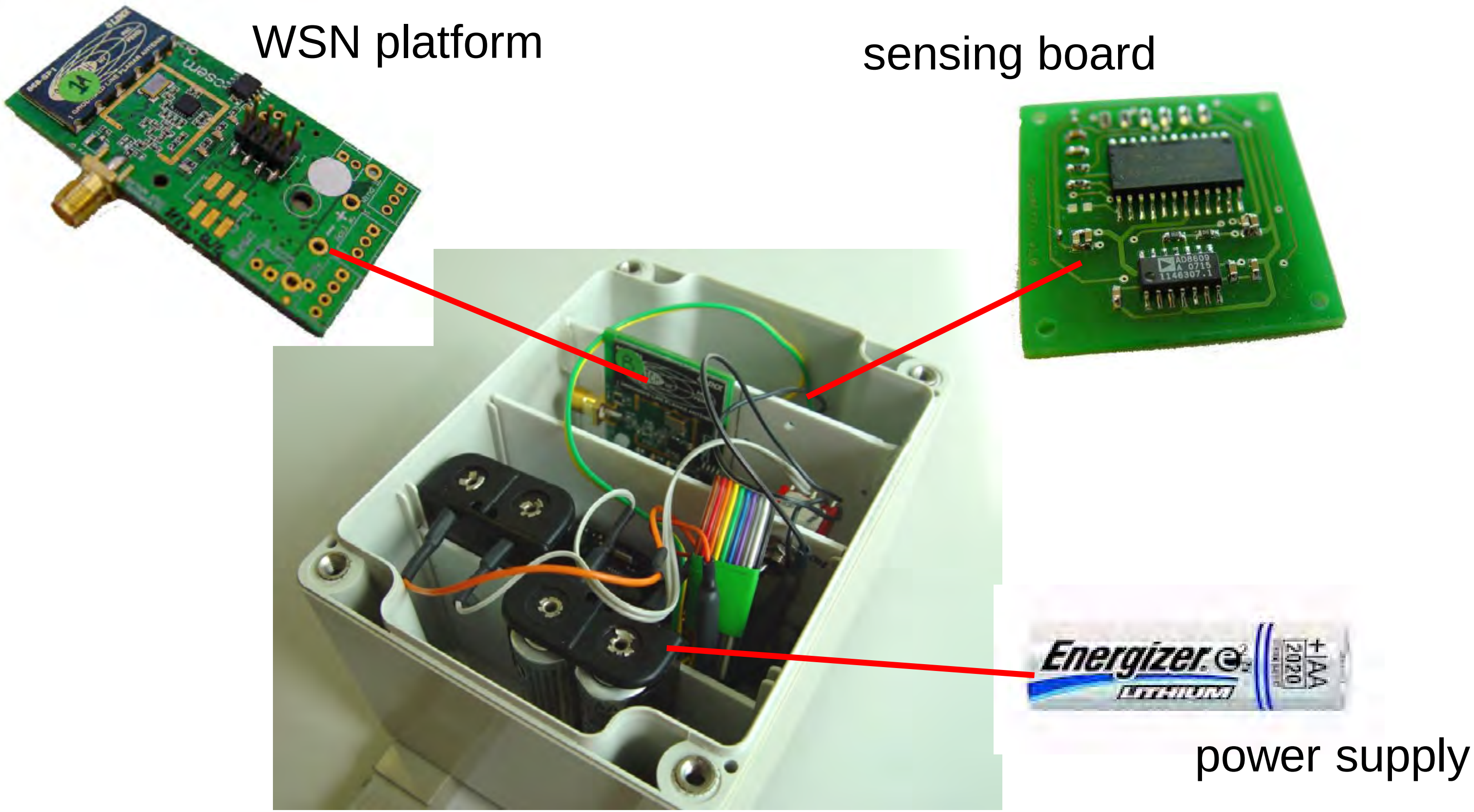
Wireless sensor networks (WSN)



Main characteristics:

- Network of tiny computers linked to sensors
- Wireless communication (radio waves)
- Self organizing (ad-hoc networks)
- Time synchronized

WSN node: Hardware



WSN node: Hardware architecture and software

Low performance hardware

- CPU speed: 16 MHz
- Memory: 8kB RAM, 126kB Flash
- Analog digital converter: 8 – 12 bit
- Bandwidth: 50 kbps

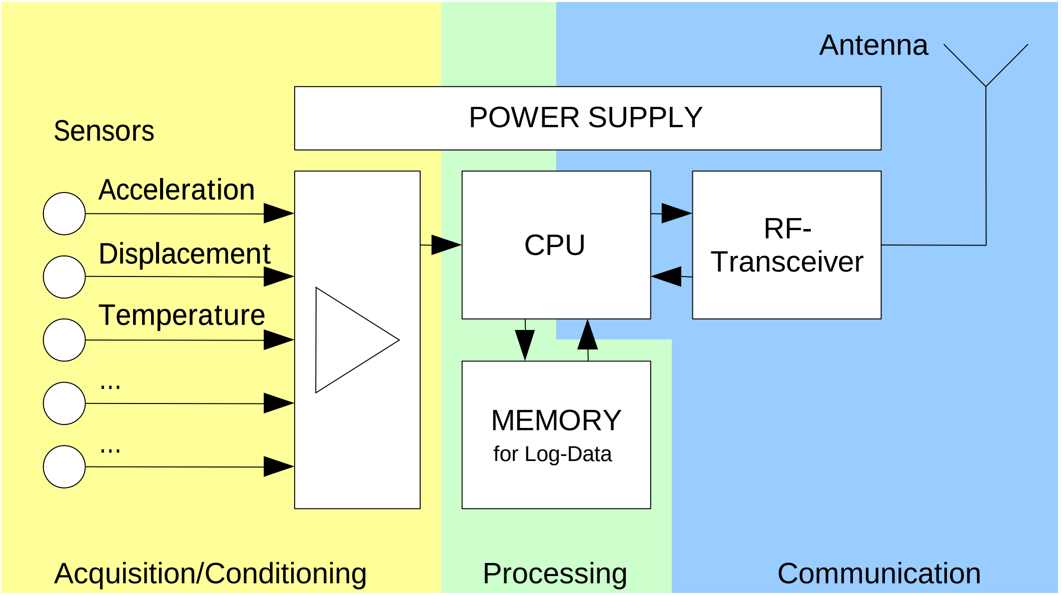
Software Functionality:

Self-organization, communication, time synchronization

Node configuration und remote maintenance

Scheduling of measurement tasks

Data acquisition and processing



Advantages/Disadvantages

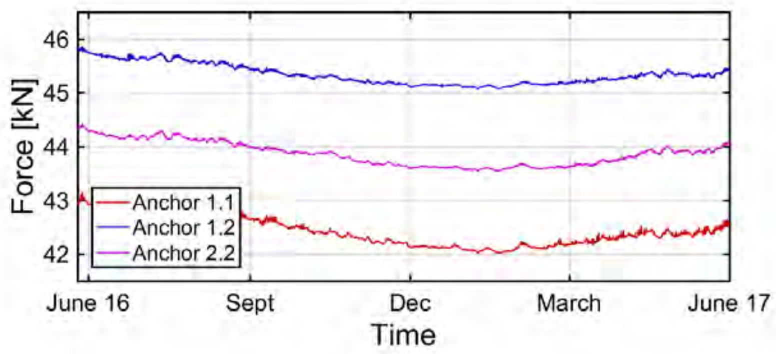
- Advantages
  - Rapid deployment
  - High flexibility
  - Noninvasive
- Disadvantages
  - Limited energy resources

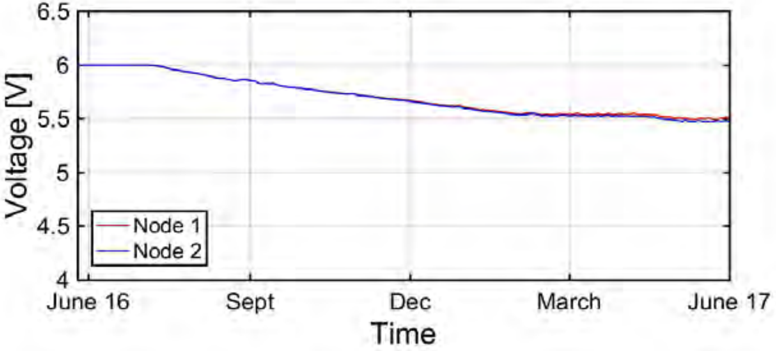
(battery powered)

Severe restriction for long term deployments with high data rates (maintenance costs)

Practice Wireless Monitoring

Monitoring of quasi-static processes (low data rates)





Energy consumption

Low power hardware

- Sensor node platform
  - Energy consumption: **50** mW (radio on), 5 mW (radio off)
- Sensors
  - MEMS-accelerometer (3 mW)
  - MEMS-Temperature/Humidity sensor (0.08 mW)
  - Electrical resistance strain gages (≈ **50** mW)

Low power communication protocols (Swisscom LoRaWAN)

Multi-hop networks

Embedded data processing

Event driven monitoring (switch hardware on only when required)

Embedded data processing

- Communicate information and not raw data (reduce redundancy)
- Communication dissipates more energy than computation/signal processing/compression (factor 10 to 100)
- Distributed (decentralized) data processing

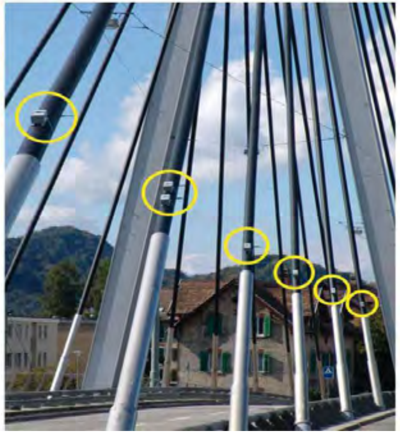
- Much less data to communicate
- Increases life time of batteries and reduces data loss
- Very efficient when monitoring dynamic processes

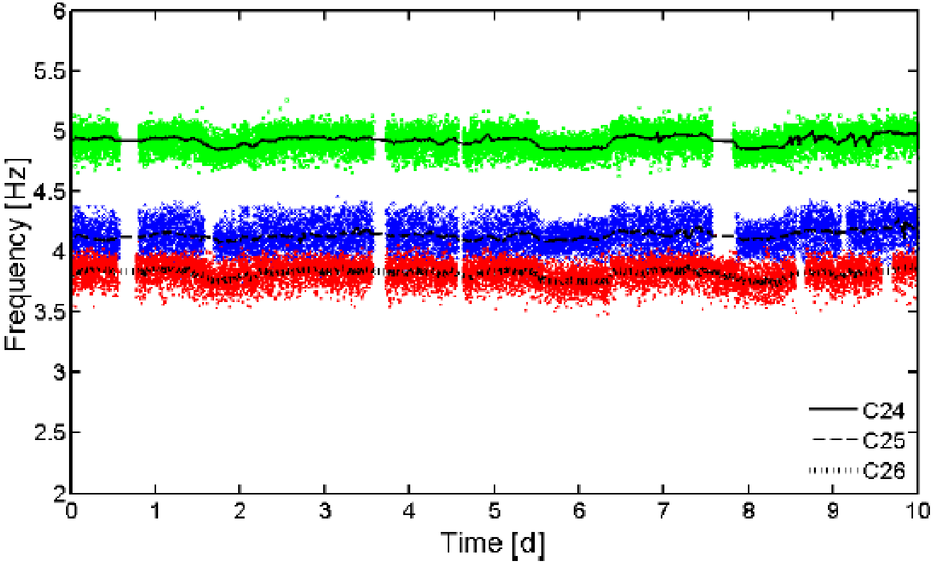
- Problem: Tiny computational resources (16MHz CPU, 8kB RAM)

Monitoring of the Storchen Bridge with WSN (2006)

Network with 7 nodes for stay cable frequency identification via ambient vibration

Verification of the performance in the field.





Vibration monitoring of a footbridge

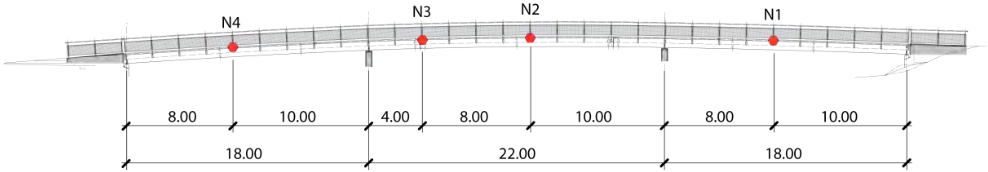
Timber bridge with three spans

Mastic asphalt pavement (protection against humidity and wear)

Monitoring system

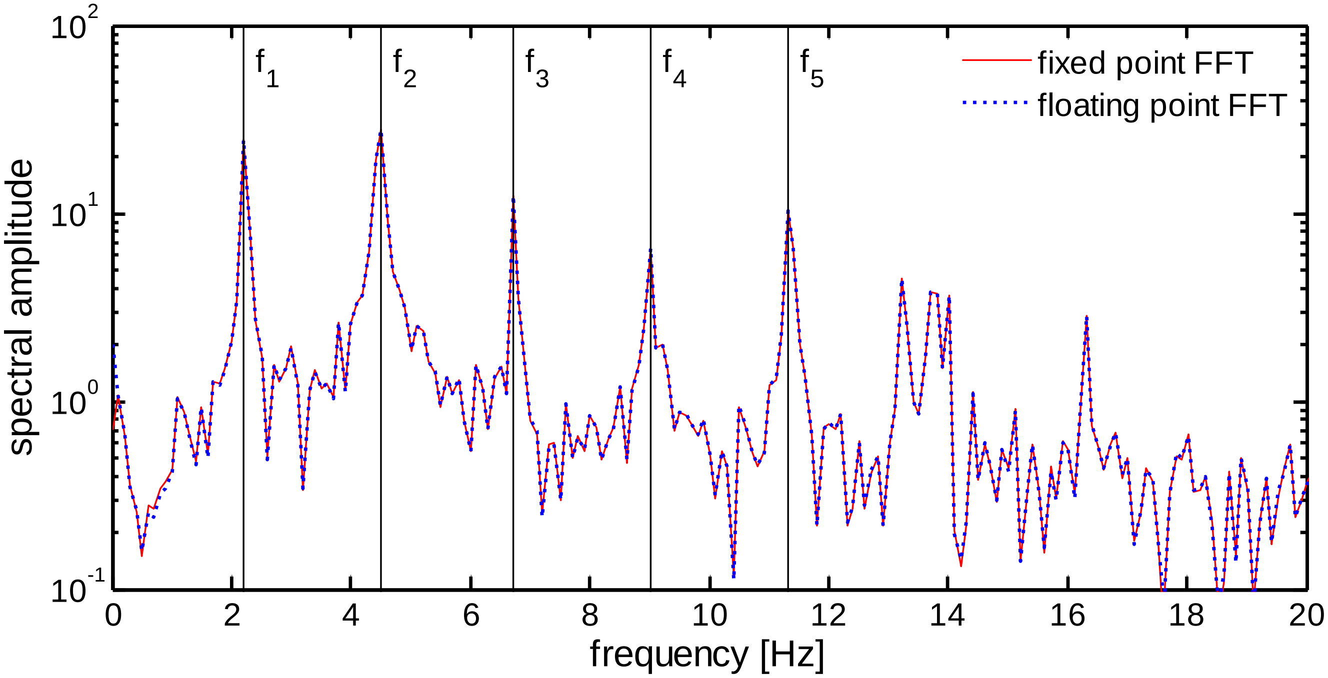
Investigate the effect of asphalt pavement on natural frequencies

4 sensor nodes and 1 relay node Acceleration and temperature



Computation of frequency spectrum

Fast Fourier-Transform computed using fixed point operations
(10 times faster than floating point operations)
Computing time: 1 s (1024 samples)



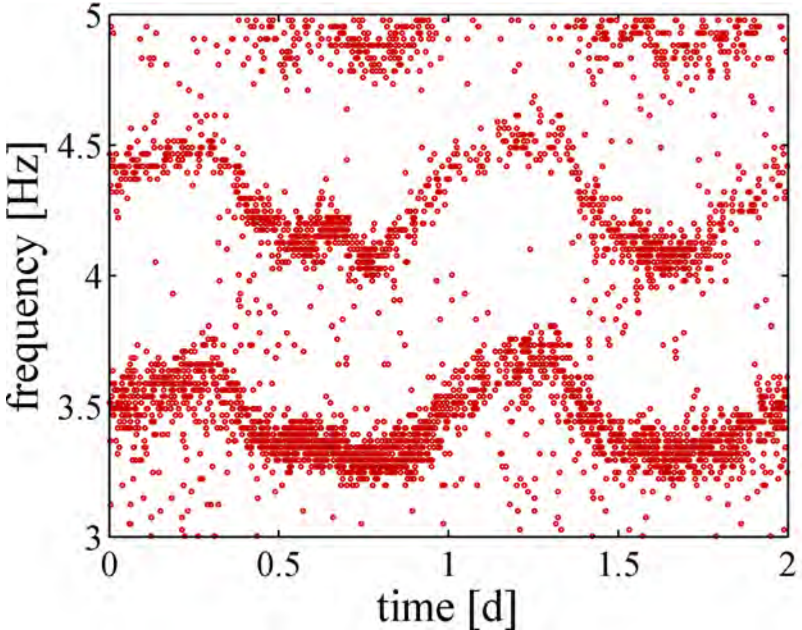
Recording of natural frequencies

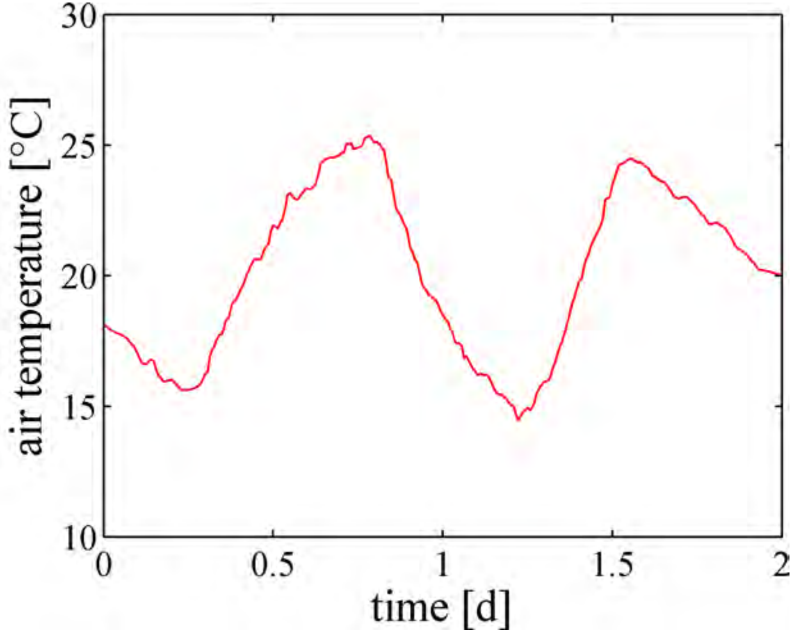
Permanent data acquisition with sampling rate of 50 Hz (2048 samples)

Scaling ⇨ FFT ⇨ abs ⇨ scaling ⇨ peak picking

Computing time: 1.8 s

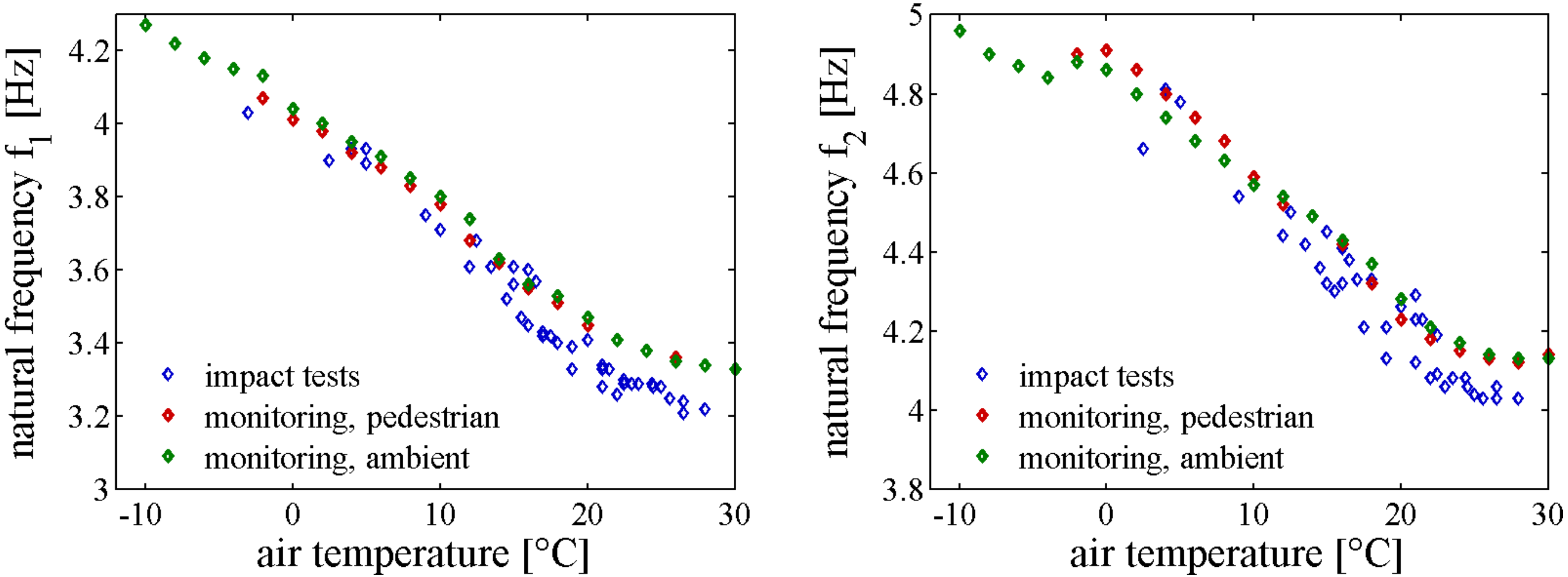
2048 raw data points ⇨ 8 frequencies & 8 spectral amplitudes (0.8%)





Results natural frequencies

Comparison monitoring results/test results (sensors with high sensitivity and resolution and 24 bit data acquisition device)

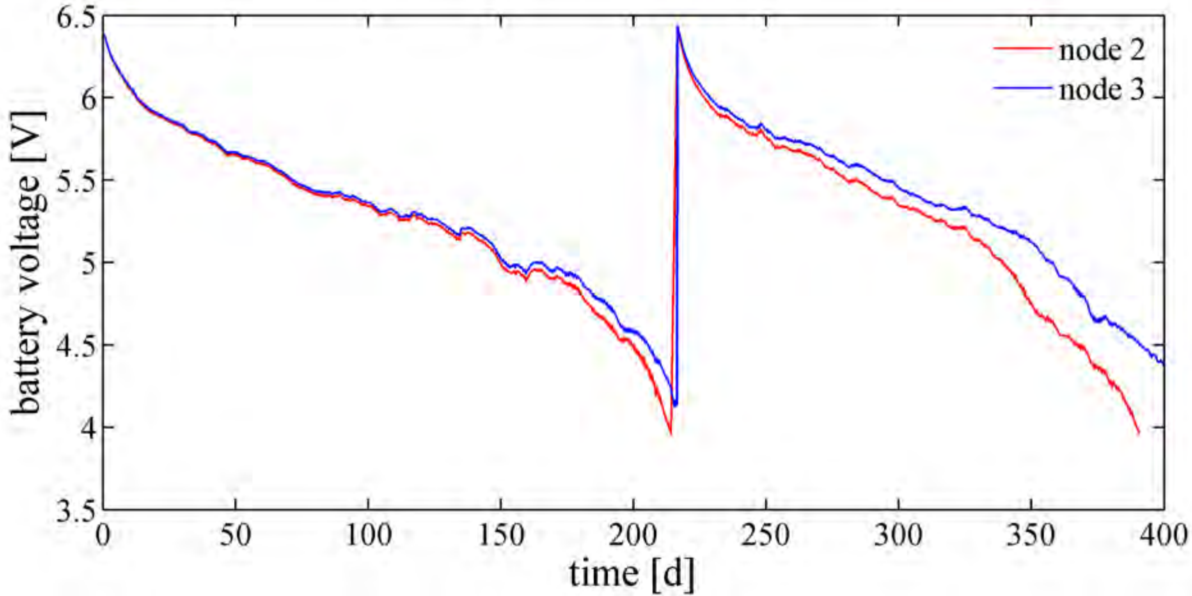


Life time of batteries

4 batteries @ 19’200 mAh

Lifetime ca. 200 days

1 battery replacement during deployment period



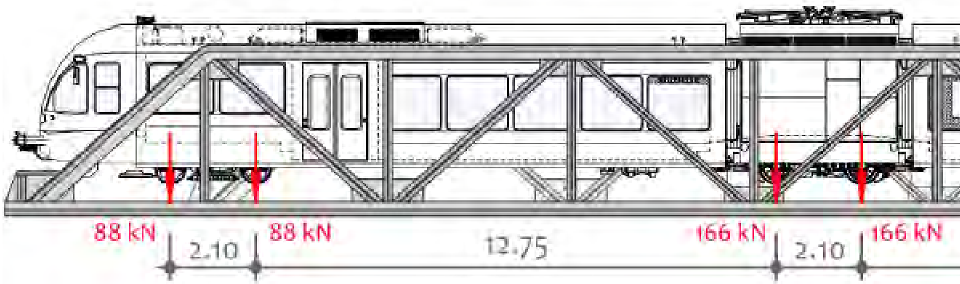
Strain monitoring on a steel bridge

Assessment of remaining lifetime of old railway bridges

Monitoring provides quantitative data about real stresses

More reliable assessment of remaining lifetime

Secondary structural elements are often critical (axle loads)

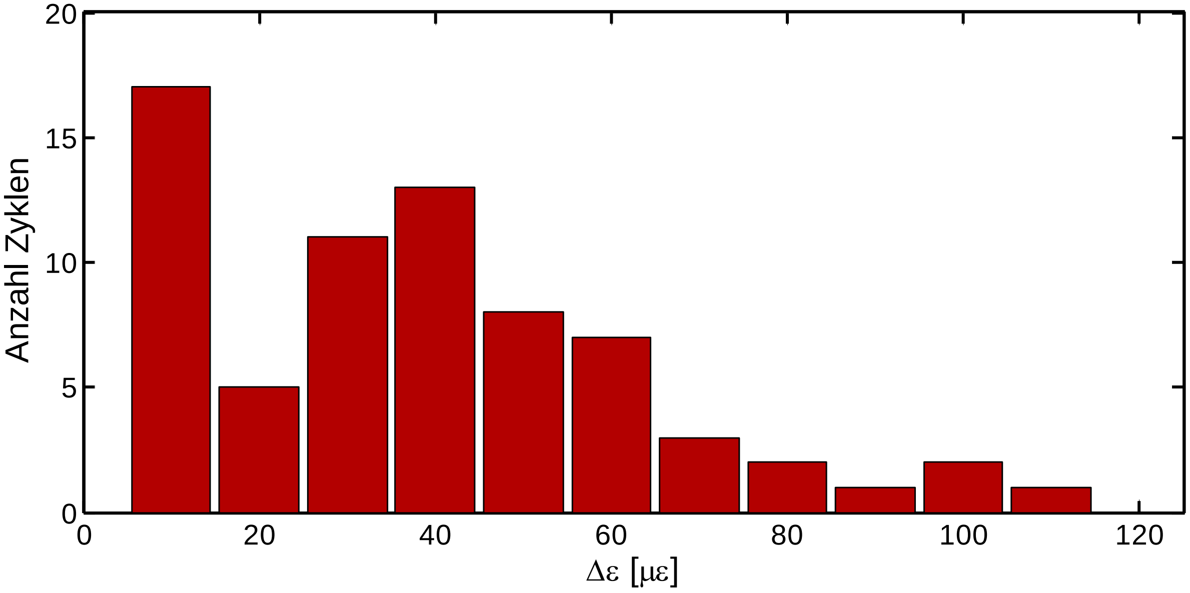


Statistics about strain cycles

Rainflow-Analysis

Histogram of strain (stress) cycles

Input data for fatigue remaining lifetime assessment



Strain sensing

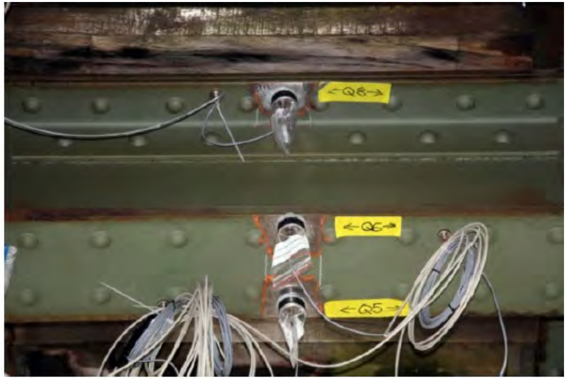
Reusable strain sensors based on electrical resistant strain gages (bond by friction, permanent magnet and spring)

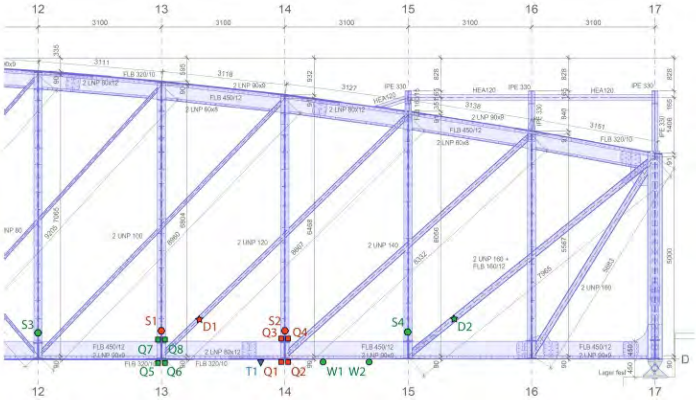
Fast deployment

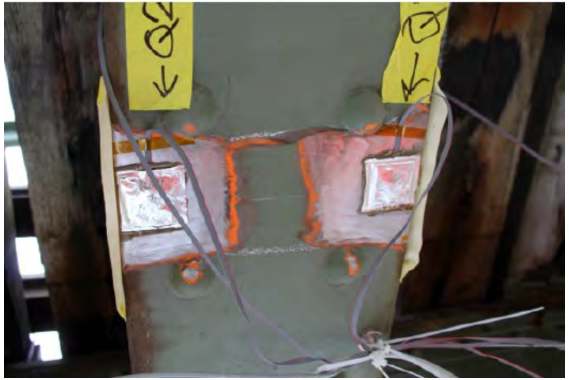
TOSSBRÜCKE WILA

Dux.U (2016)

Fachwerkbrücke (Sitterbrücke)







b)

Empa Prüfbericht Nr. 5214‘014‘720

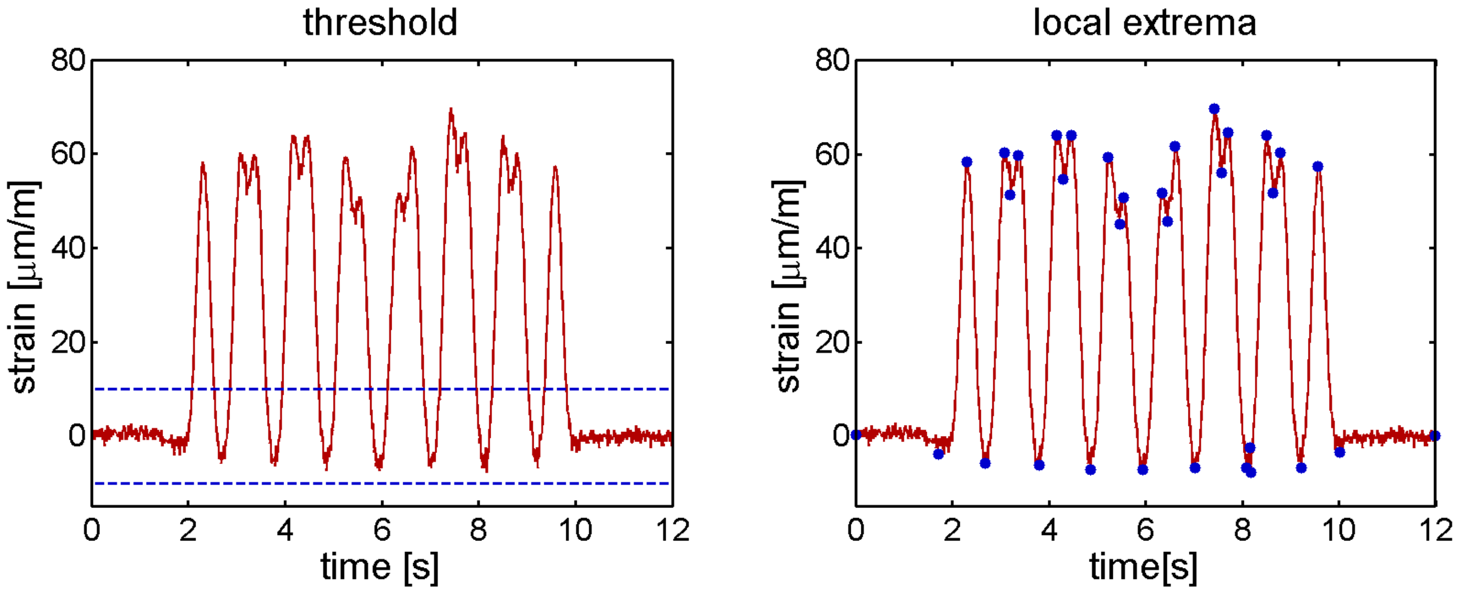
Embedded data processing

- Algorithm:

  Ignore data packets with data not exceeding a threshold

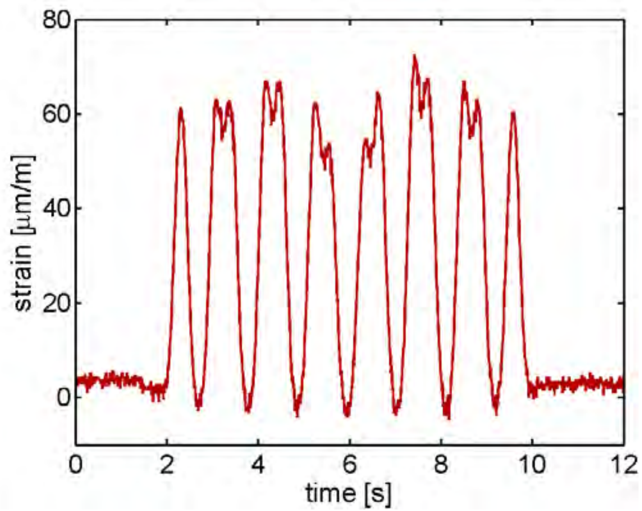
  Data reduction by picking out local extrema (cycle filtering)

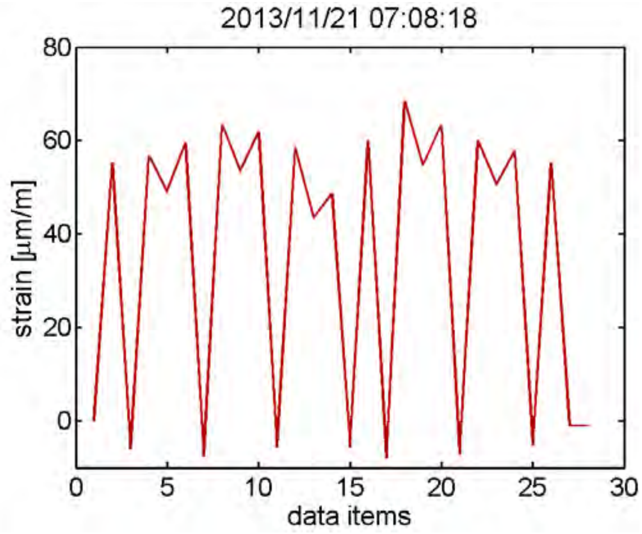
- Processing time: 0.2 s



Embedded data processing

Raw data: 1476 data points (12 s @ 123 Hz)
Processed data: 28 data points (1.9% of original data size





Event driven monitoring with sentinel nodes

Perform measurements only if something interesting occurs

Sentinel nodes

Measures permanently

Analyses the data by embedded data processing for events

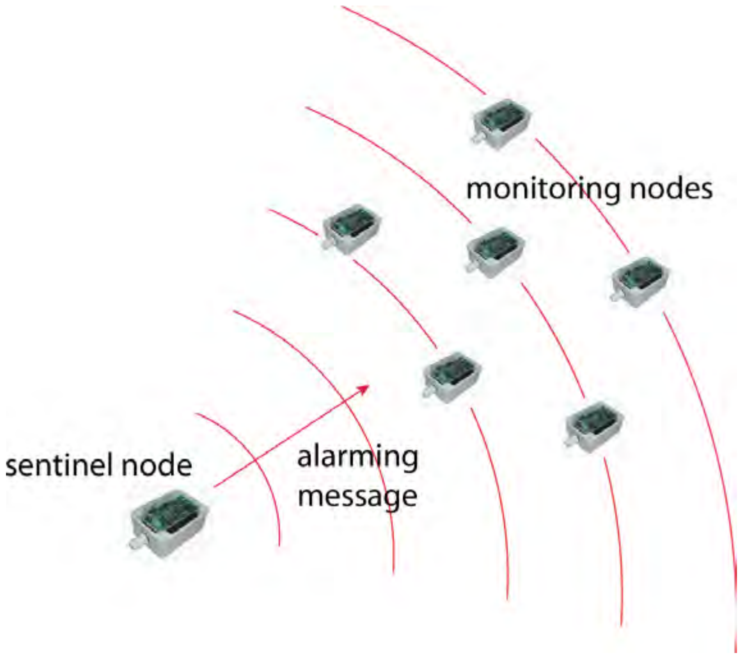
When an event occurs alarms monitoring nodes

Monitoring nodes

Sleep and periodically wake up and listen for an alarm

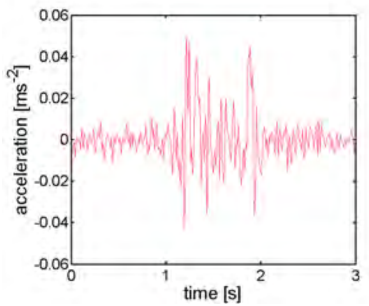
Go sleeping if no alarm

Start measurement if sentinel node is alarming



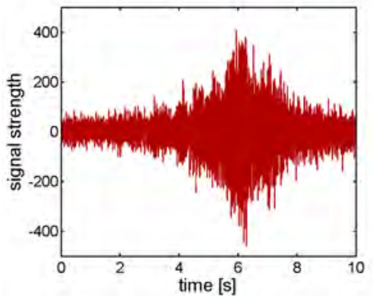
“Lightweight” sentinel nodes

vibrations



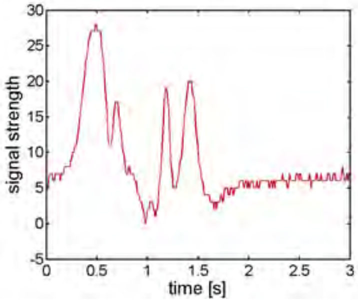
P = 0.6 mW

noise



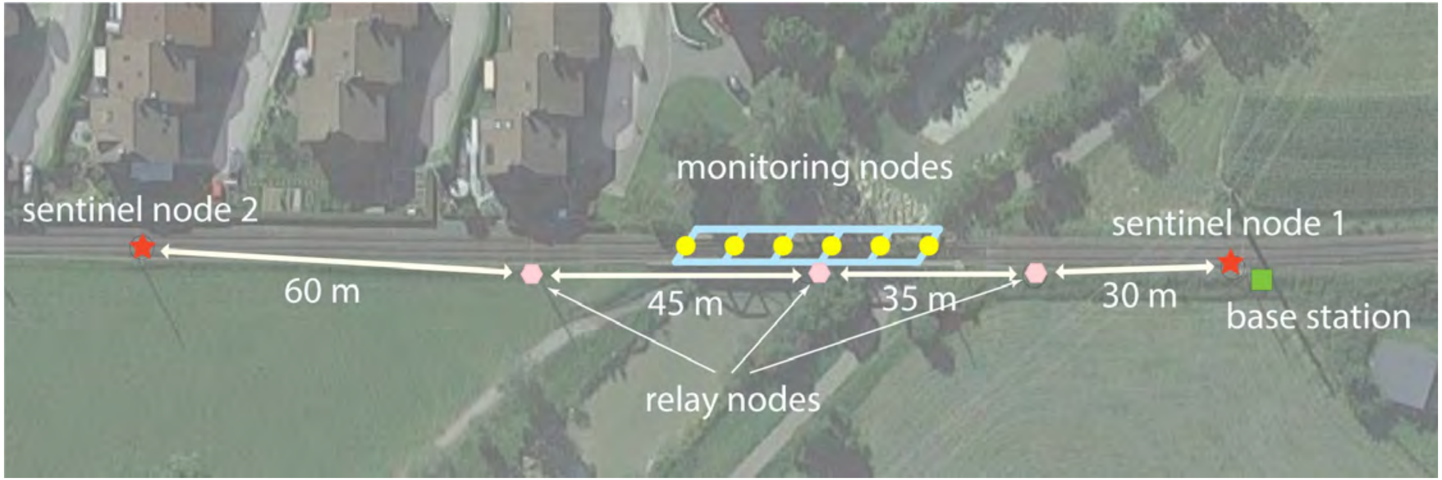
P = 2.1 mW

magnetic field

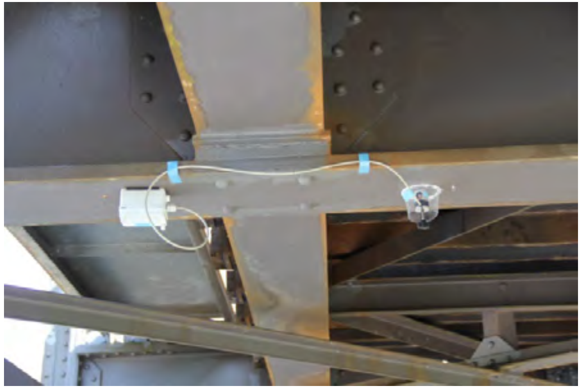


P = 1.9 mW

Railway bridge deployment



- Sentinel node (2) monitors rail vibrations
- Monitoring nodes (6) record strains
- Relay nodes (3) improve communication between sentinel and monitoring nodes
- Base station (1) links WSN to data server

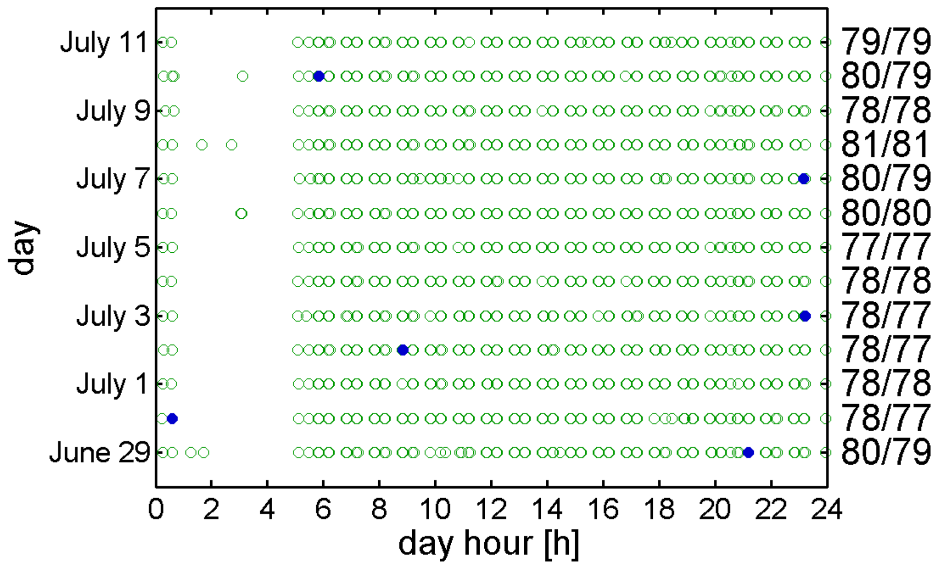


Sentinel nodes

- Monitoring of rail vibrations (5 mW)
- Permanent recording
- Data processing checks for threshold exceedance

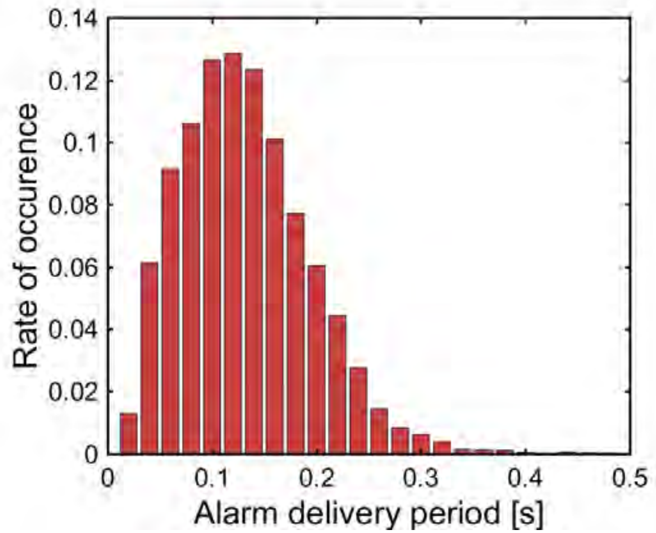
Event hit rate

- Total 3728 trains (events)
- 11 events – no information (0.3%)
- 39 events received by less than 6 nodes
- 98.6 % events received by 6 nodes



Reaction time to alarm

- Elapsed time period between sending and receiving the alarm message
- Quantiles: 0.13 s (50%), 0.45 s (99.9%)



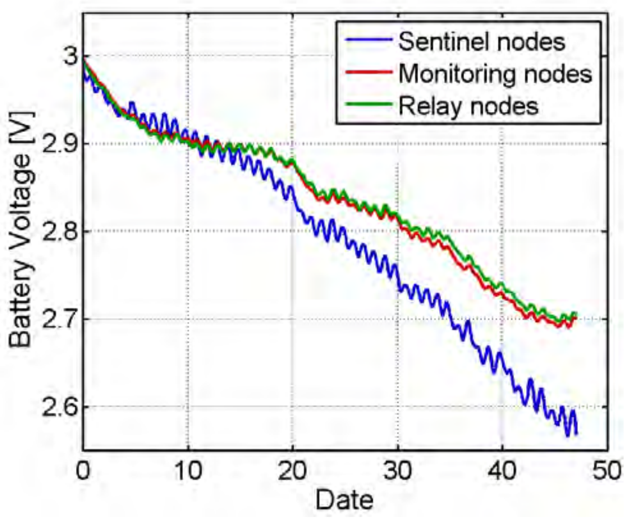
Power consumption

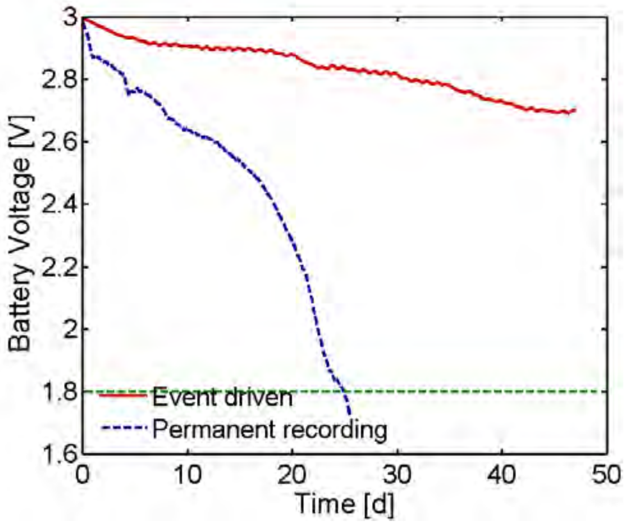
Sentinel nodes most power consuming

Monitoring nodes:

Lifetime permanent recording: max. 25 days

Lifetime event driven with sentinel nodes: ca. 100 days





Decentlab

PRODUCTS LoRaWAN SERVICES SUPPORT NEWS ABOUT

Decentlab is a Swiss company providing wireless sensor devices and services for distributed, cost-effective monitoring solutions.

The sensor devices communicate wirelessly over LoRaWAN® and are designed for ultra low power consumption, capable of operating on batteries for several years. The devices are built for industrial applications and are ready to be deployed in any harsh indoor or outdoor environment.

The service framework provides convenient access to measurement data and enables seamless integration into existing monitoring and control systems.

Application areas are environmental and air quality monitoring, hydrological measurements, smart agriculture and smart cities.

APPLICATIONS

ECOPHYSIOLOGY

TreeNet project - The biological drought and growth indicator network.

Read more

GROUNDWATER LEVEL MONITORING

Field test in 20-meter deep groundwater monitoring well in Finland.

Read more

INDOOR AIR QUALITY

The Swiss measuring device DL-IAM from Decentlab reliably measures indoor air quality.

Read more

GROUNDWATER MEASUREMENTS

Groundwater measurements that provide real-time data and visual representation.

Read more

INTERNET OF WATER

Smart sensors for Internet of Water Flanders and our partner VITO.

Read more

URBAN HEAT ISLAND

To monitor the urban heat island, our DL-SHT35 sensors are deployed at various locations in the city.

Read more

SMART AGRICULTURE

Smart agriculture with DL-TBRG for farmers in the outback of Australia.

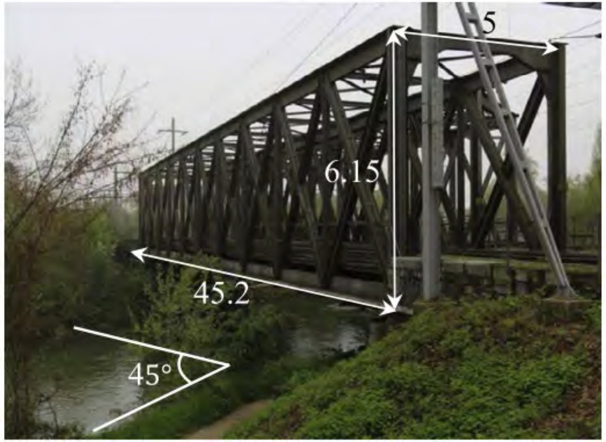
Read more

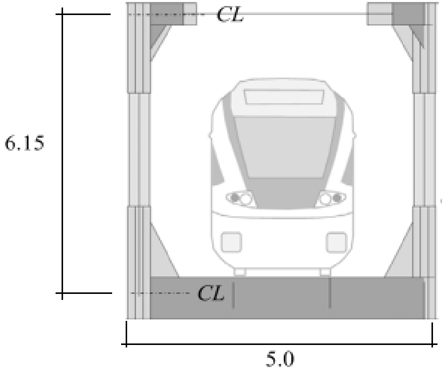
FLOOD MONITORING

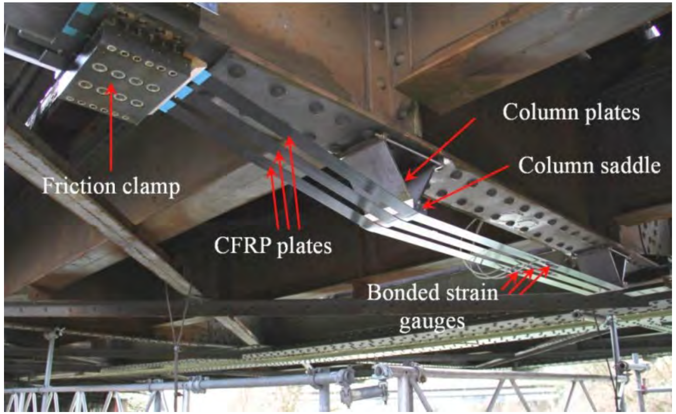
River flood monitoring with DL-MBX in the Game Reserve in Africa.

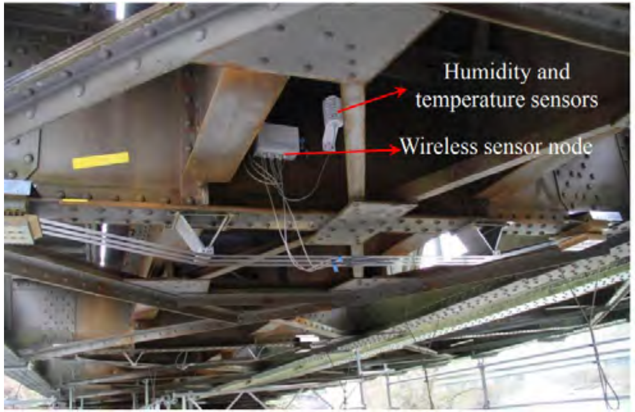
Read more

Monitoring and strengtheningg of the Münchenstein bridge

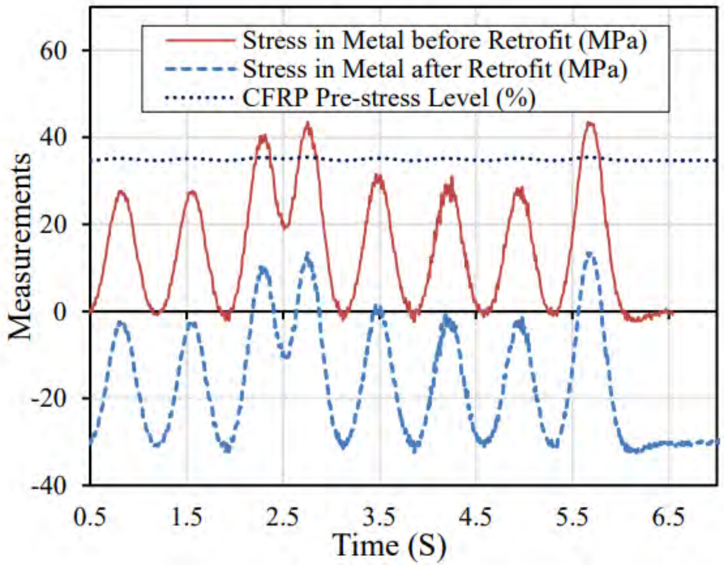


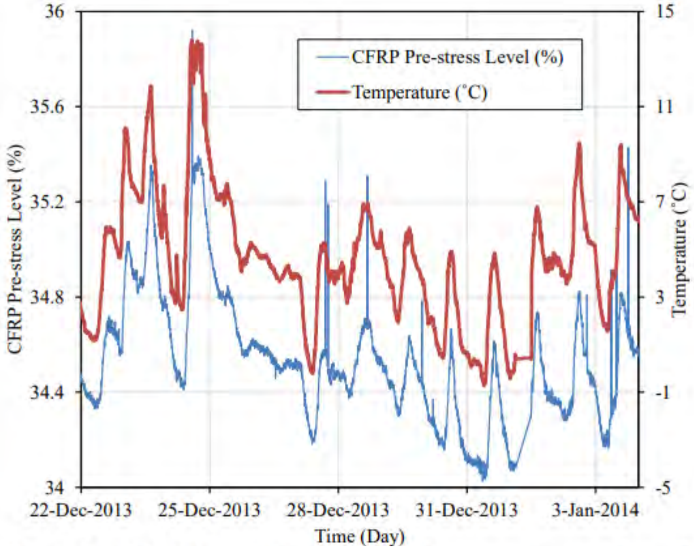






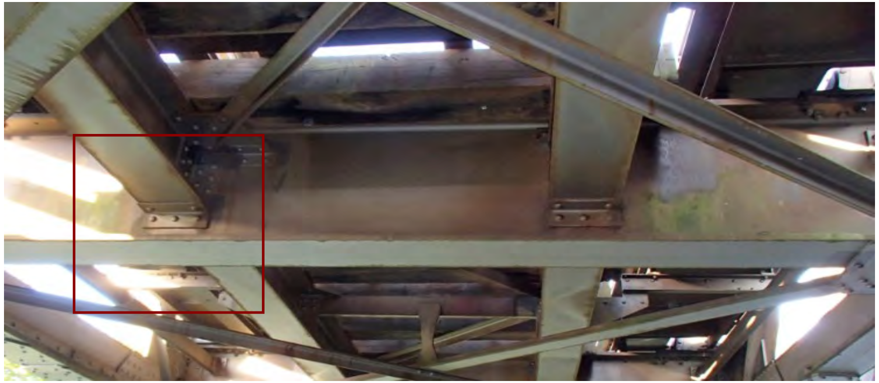
Monitoring and strengtheningg of the Münchenstein bridge

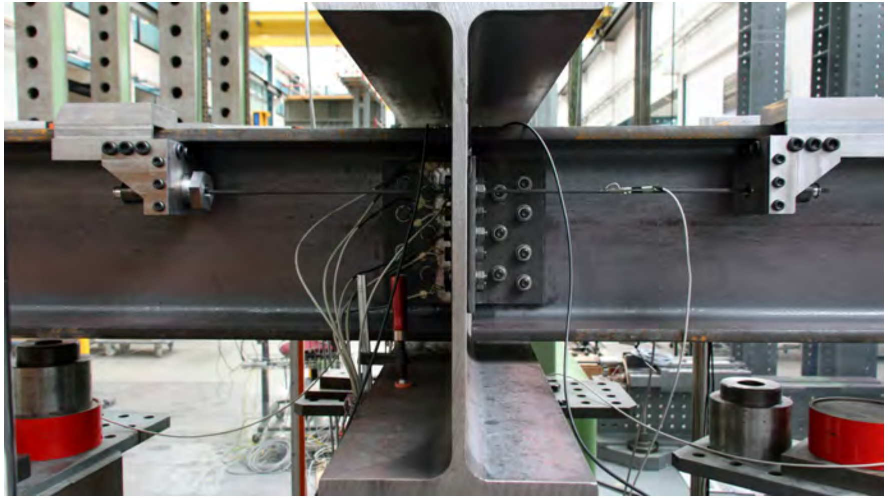




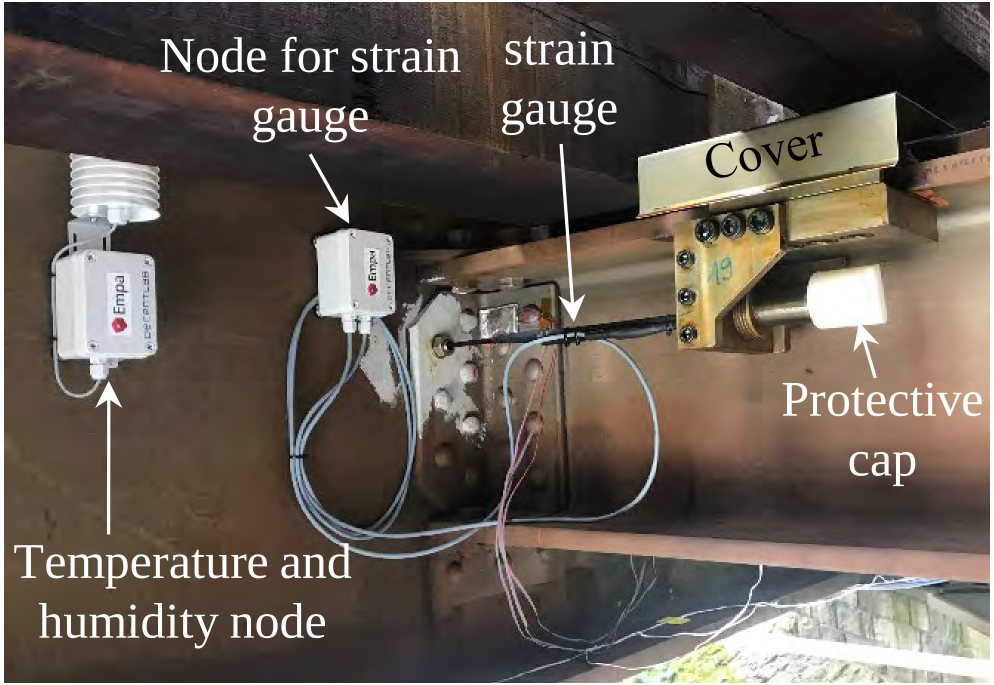
Long-term measurements of strains in the CFRP rods in Aabach Bridge

Aabach Railway Bridge, Lachen (90-year-old)

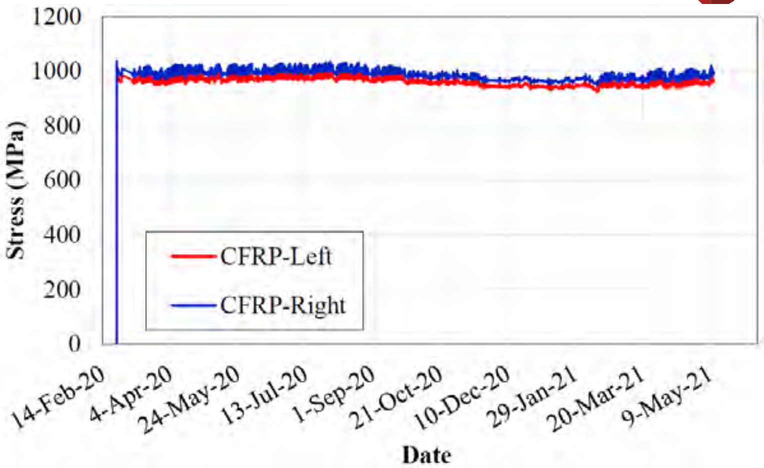


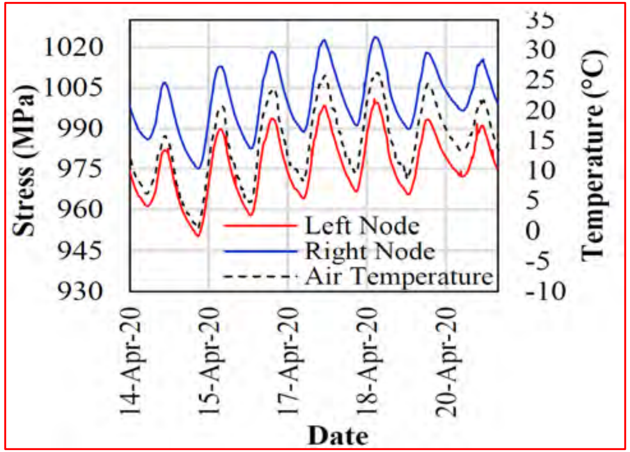


Stress history of the CFRP rods

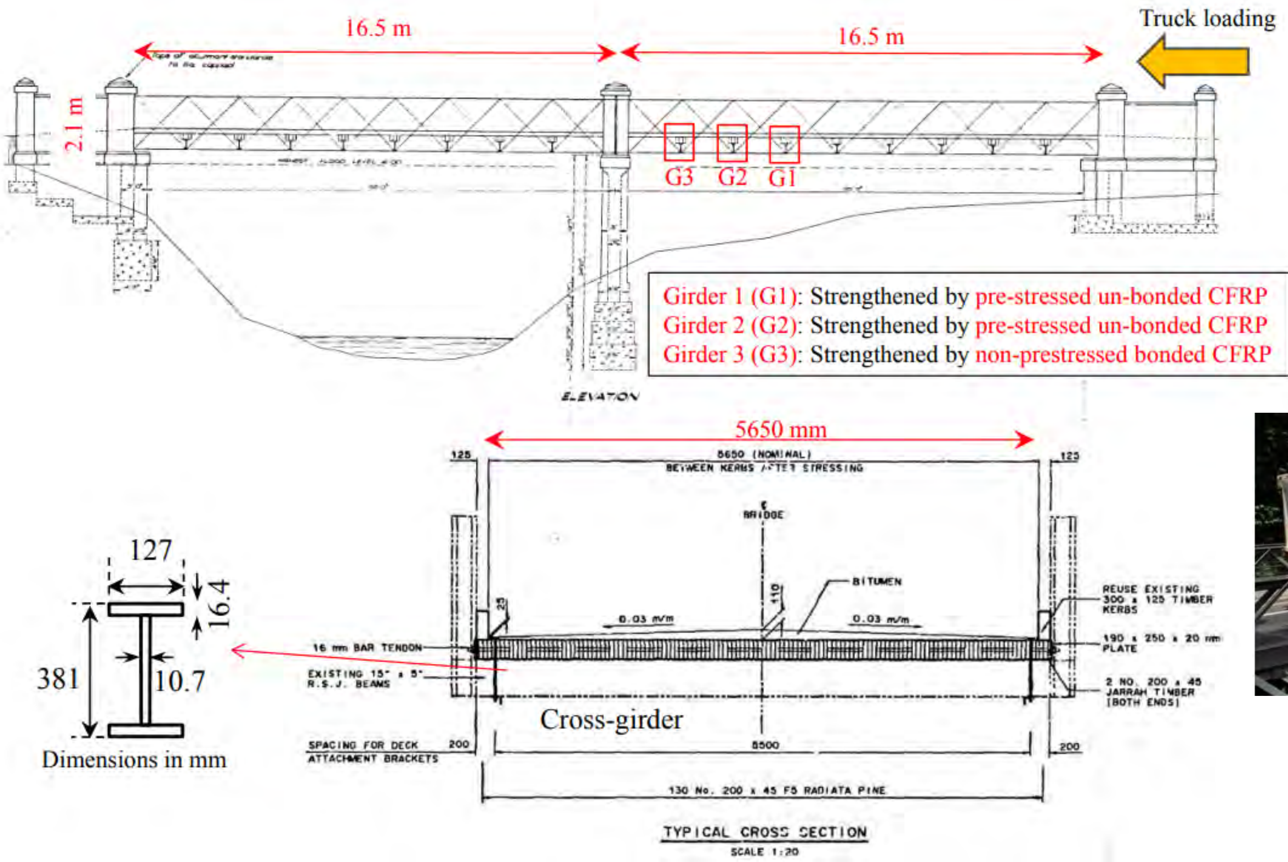


No prestressing loss occurred in the CFRP rods since the installation.



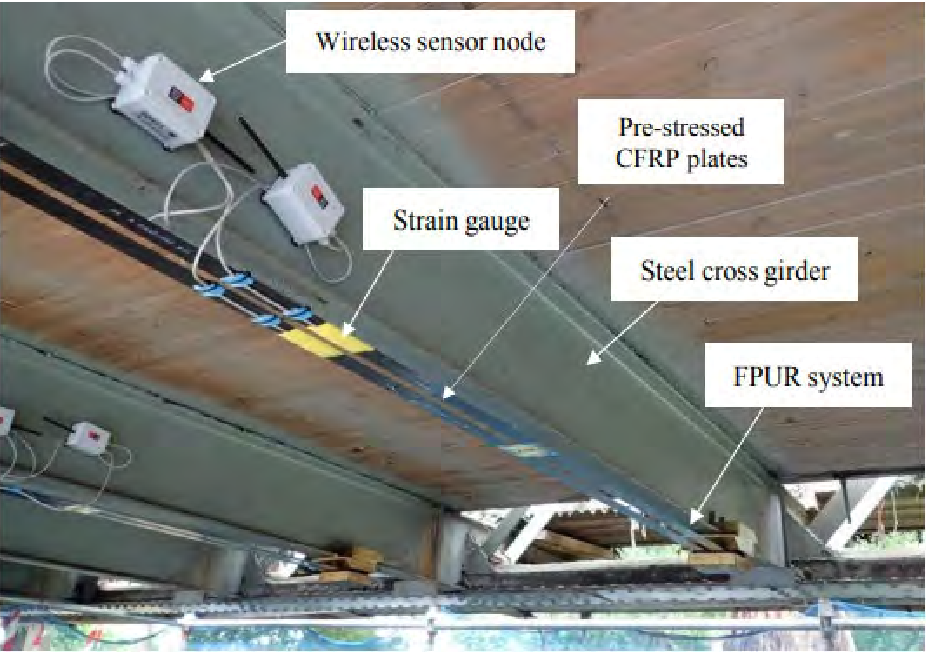


Strengthening Diamond-Creek bridge AUSTRALIA



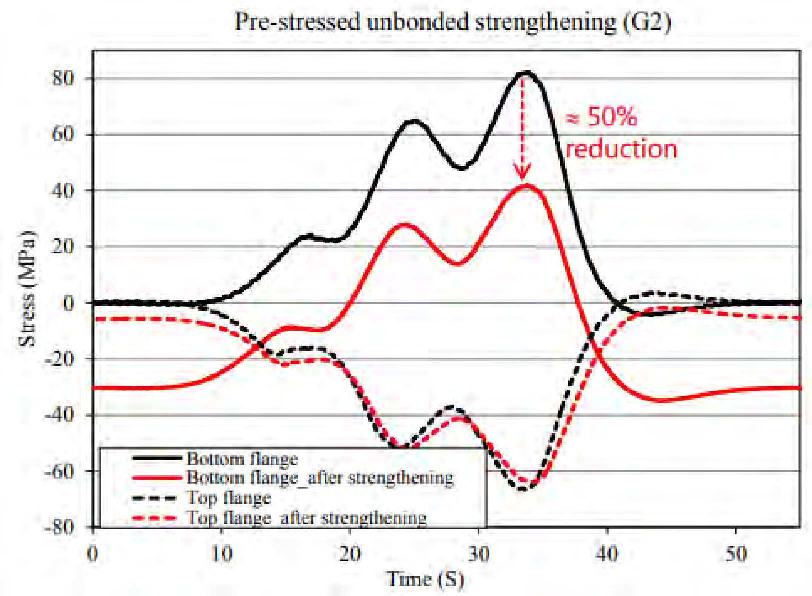
Girder 1 (G1): Strengthened by pre-stressed un-bonded CFRP
Girder 2 (G2): Strengthened by pre-stressed un-bonded CFRP
Girder 3 (G3): Strengthened by non-prestressed bonded CFRP

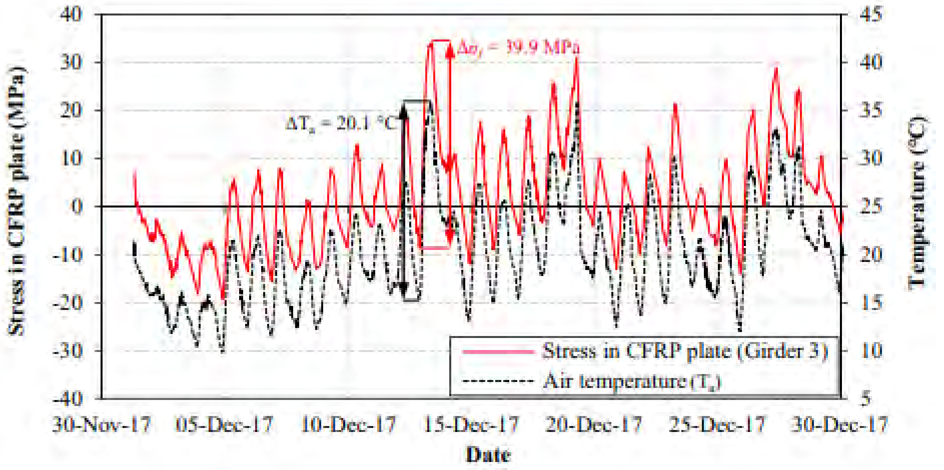
Ghafoori et al 2018


Wireless sensor node
Pre-stressed CFRP plates
Strain gauge
Steel cross girder
FPUR system

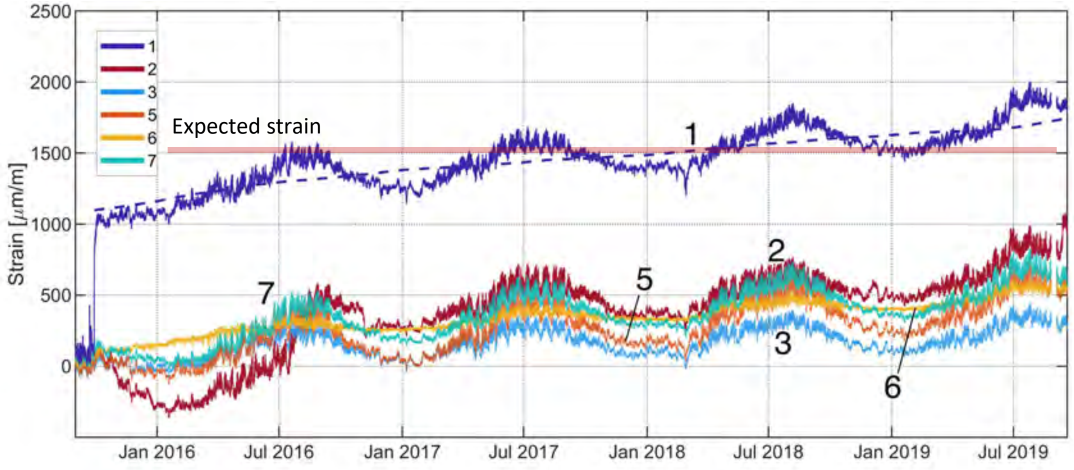

Girder 1

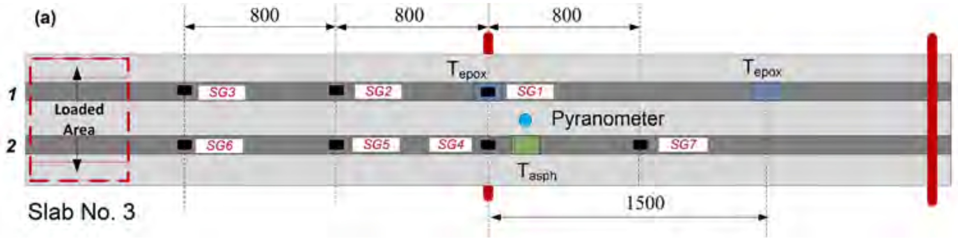
Stress reduction

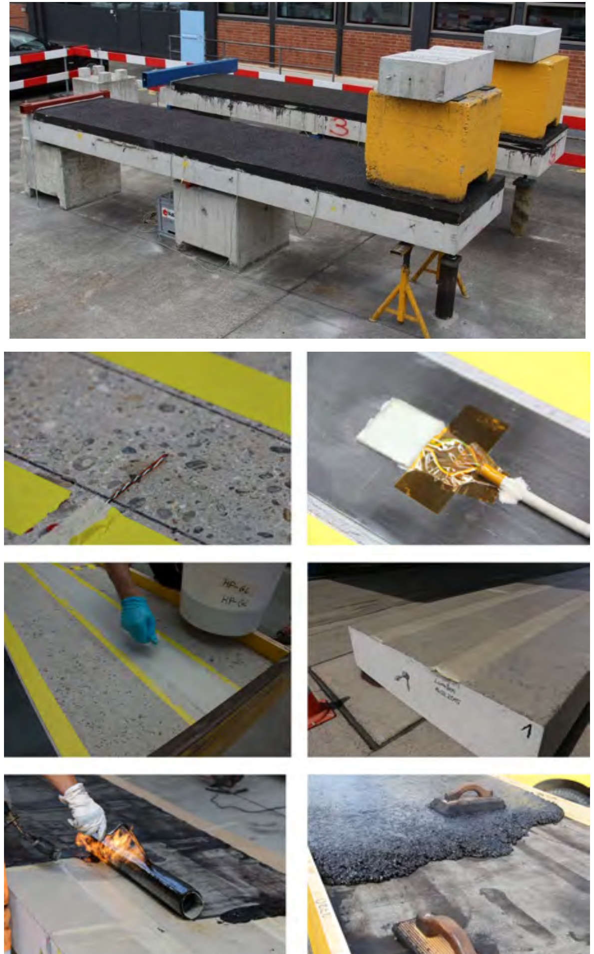




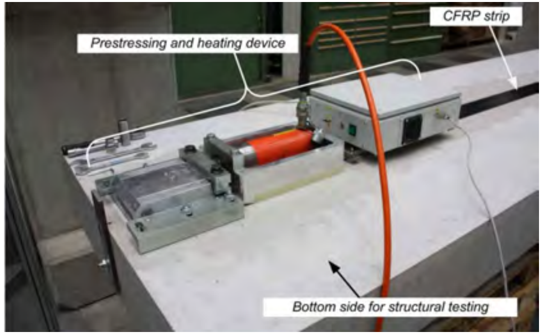
Monitoring of CFRP strengthened slabs Non-Prestressed strips



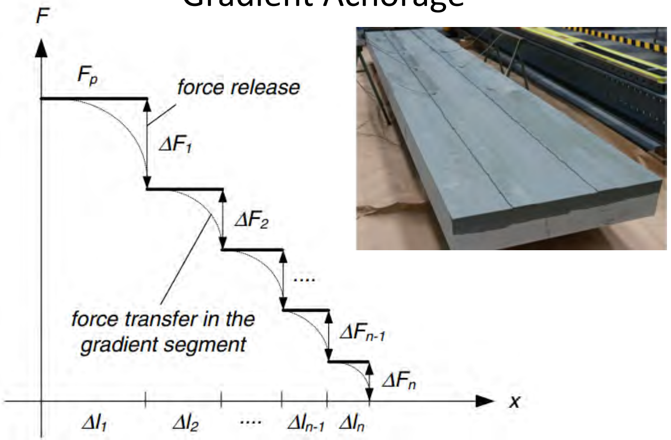




Monitoring of FRP strengthened slabs
Prestressed strips



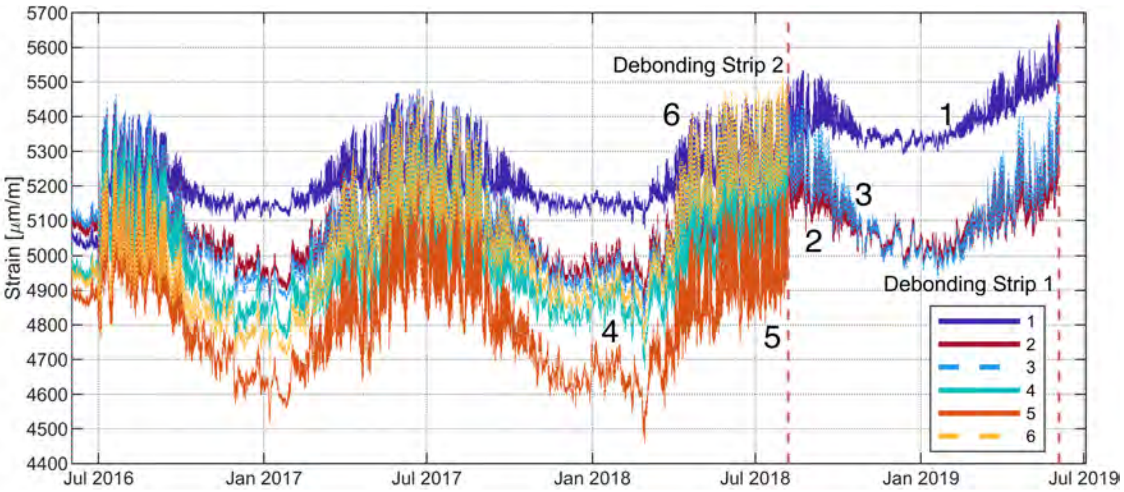
Gradient Achorage

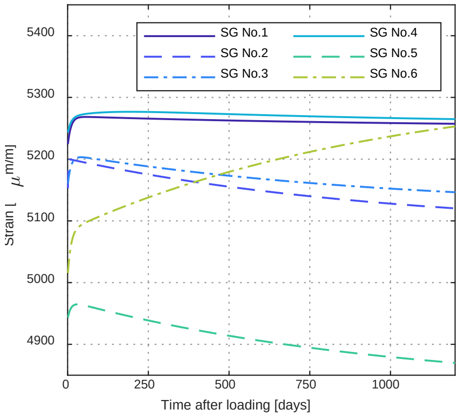


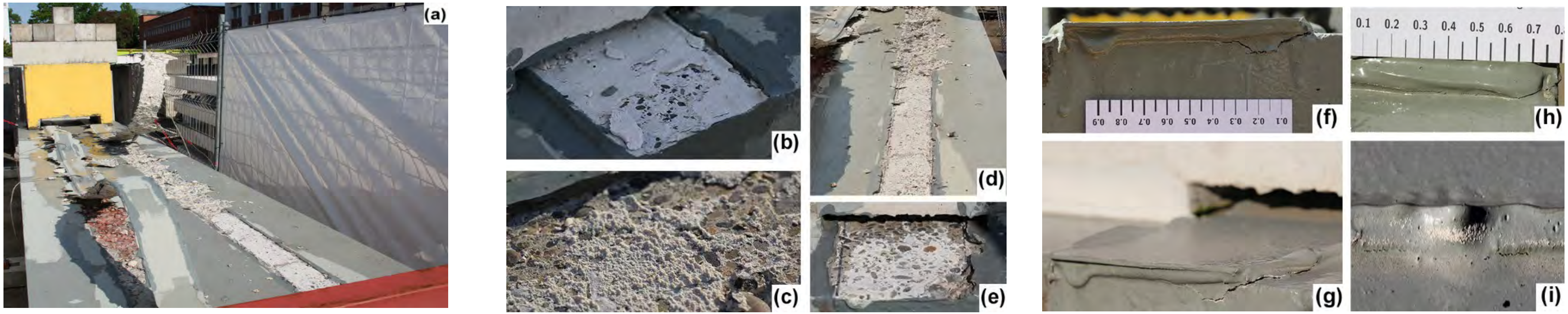
SlabNo.6

Prestressing Force 200 kN

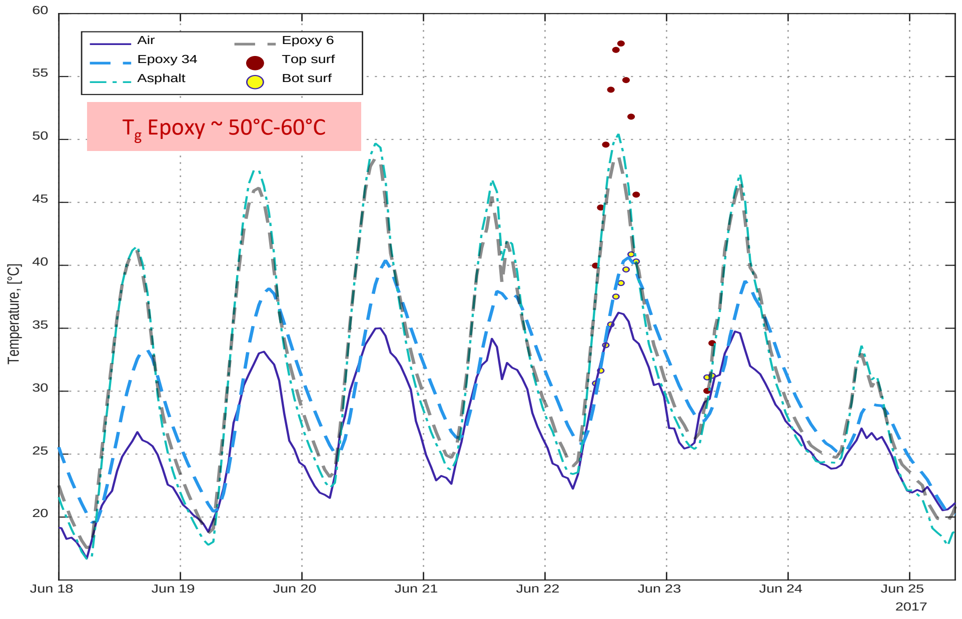
Strenghtening with prestressed FRP strip

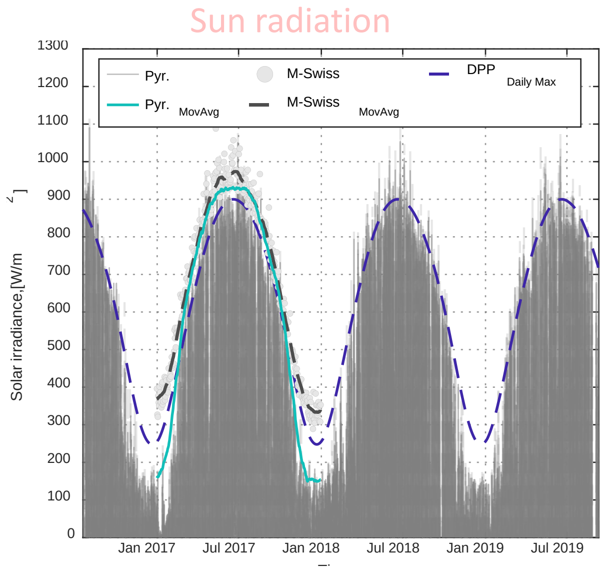






Monitoring the temperature and solar radiation

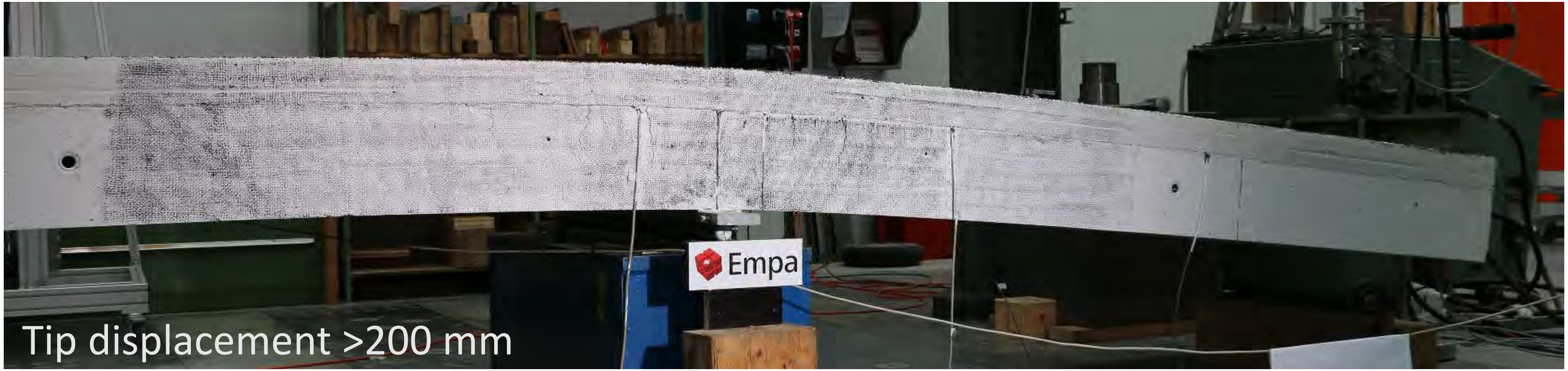




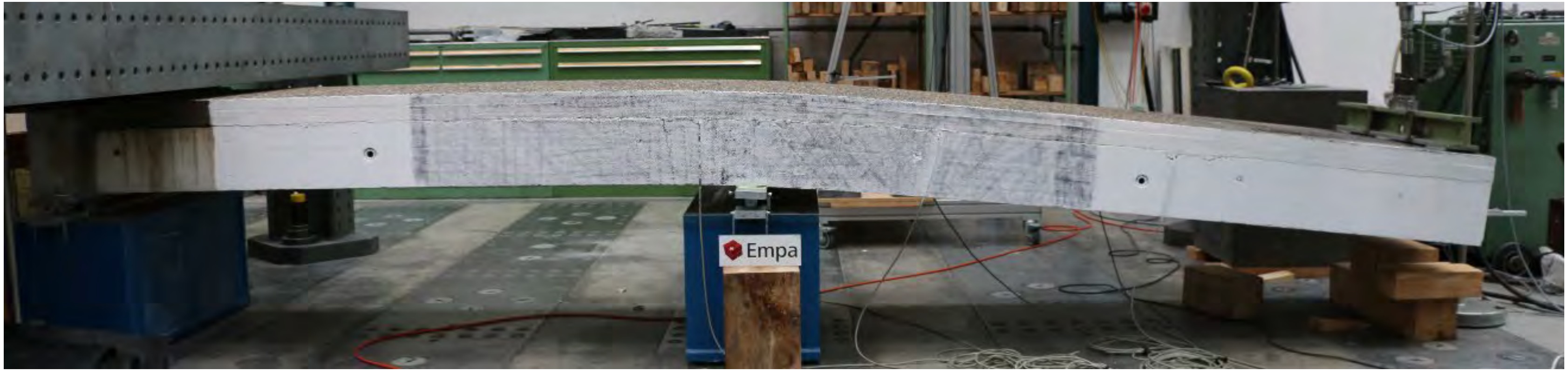
Expoy Slabs 3-4 = 40.9°C
(1 day) >40 °C)
Asphalt 3-4 = 50.5 °C
(39 days) >40 °C)

Epoxy Slab 6= 48.9°C
(39 days) >40 °C)

Falilure Tests Slabs



Nr. 3



Nr. 4

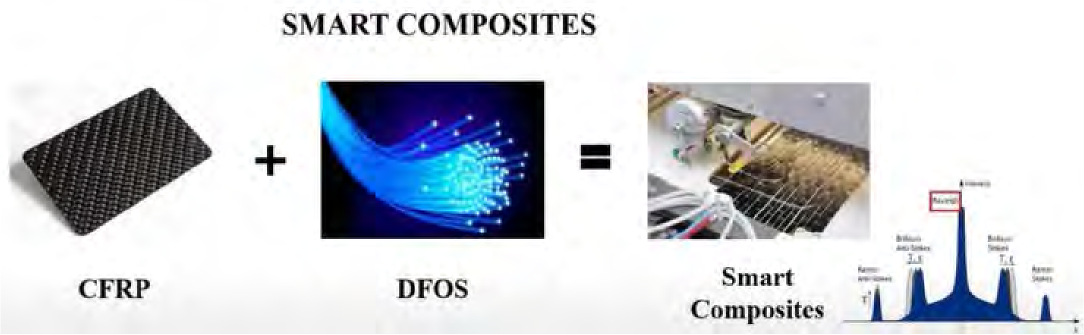
Conclusions

- Data intensive monitoring with wireless sensor networks is feasible
- Embedded data processing and event driven monitoring are key features to achieve long battery life times
- Good accuracy for applications in structural engineering
- Good stability and reliability
- User friendly

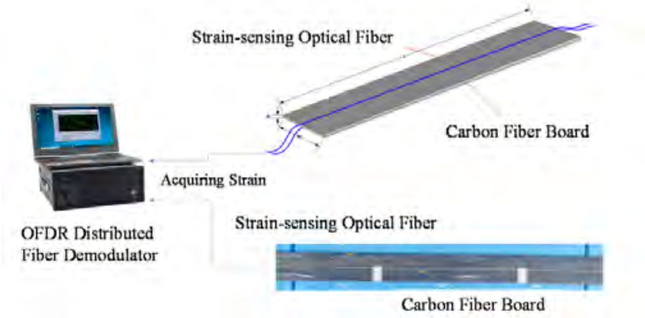
Thermografy - Ultrasonic pulse-echo method

Empa Report

CFRPstrengthening+FiberOptic Measurement



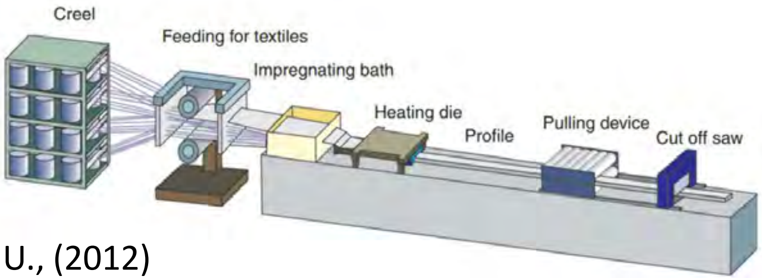
Ferrier (2024) https://www.youtube.com/watch?app=desktop&v=PN_a8uGEVFA



Wang et al 2024

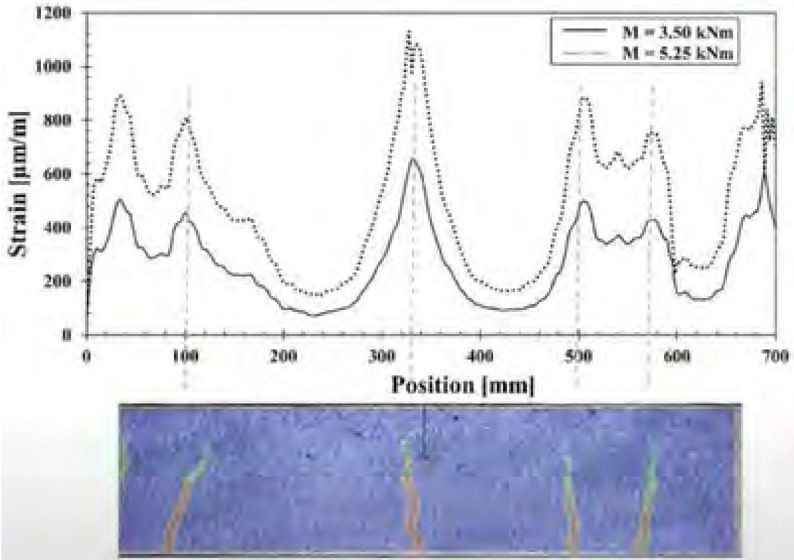
Smart composite materials offer the dual benefits of structural reinforcement and real-time monitoring. They can detect cracks, track their progression, and identify critical factors that contribute to delamination.

CFRPstrengthening+FiberOptic Measurement

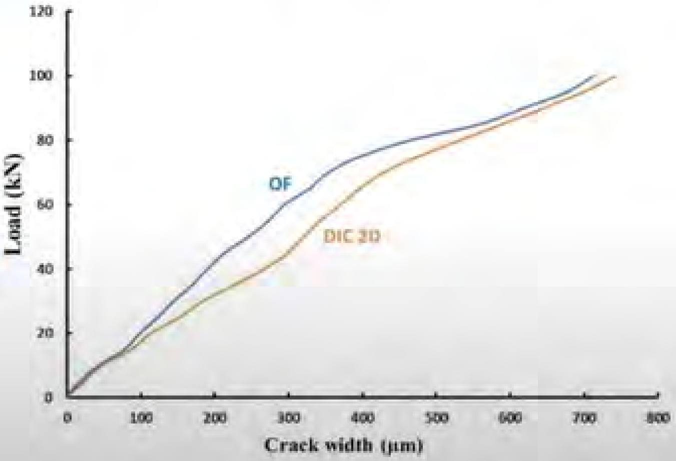


Riedel U., (2012)

CFRPstrengthening+FiberOptic Measurement



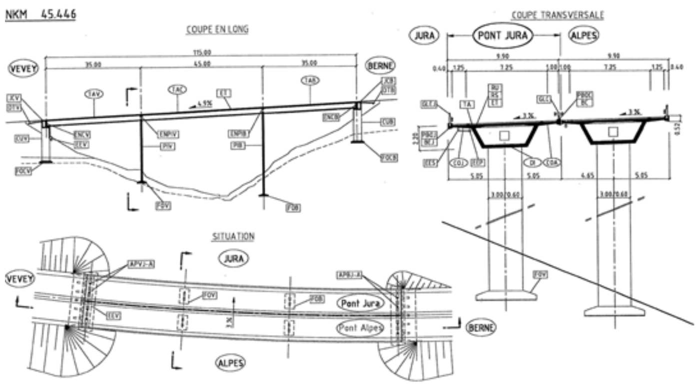
$$w_k = \sum_{i}^{j} \varepsilon \cdot dx$$



Ferrier (2024)

Bridge (Braking) test

- Braking test
- Motorway bridge “Viaduc de Matran” (1968-1970)
- 3 span box girder bridge with floating articulation: Reinforced concrete piers monolithically connected to box girder, abutment with elastomeric supports
- Design braking force: 204 kN



Feltrin G. AGB 2017/002
Validation of the model for computing the dynamic action of the braking force on road bridges, 2021, Forschungsbericht ASTRA.

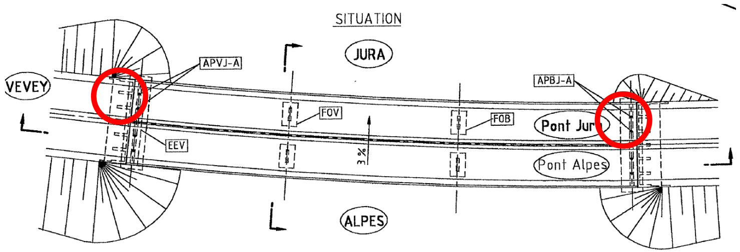
Bridge instrumentation (displacement transducer)

- Each abutment:

2 longitudinal displacements (relative to abutment)

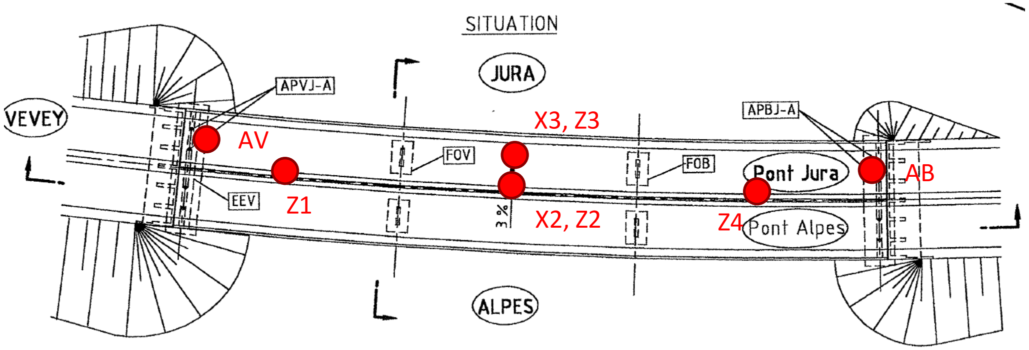
1 lateral displacement (relative to abutment)

3 vertical displacements (relative to abutment)



Bridge instrumentation (accelerometers)

- Longitudinal vibrations of bridge deck (X2 und X3)
- Bending and torsional vibration of bridge deck (Z1, Z2, Z3 und Z4)
- Longitudinal vibrations abutments (AB und AV)

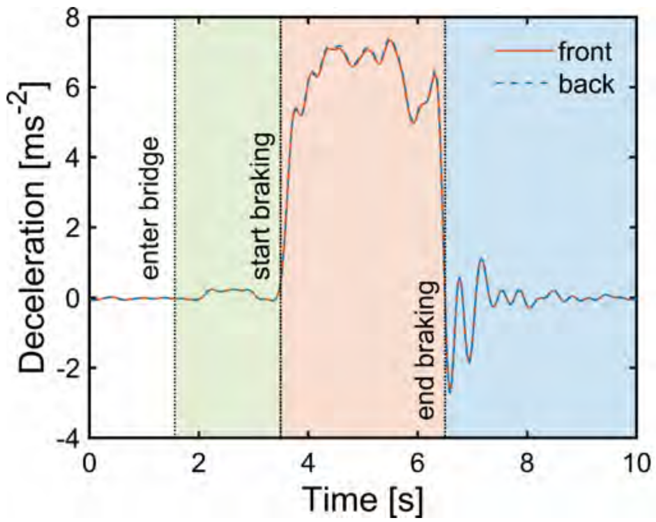


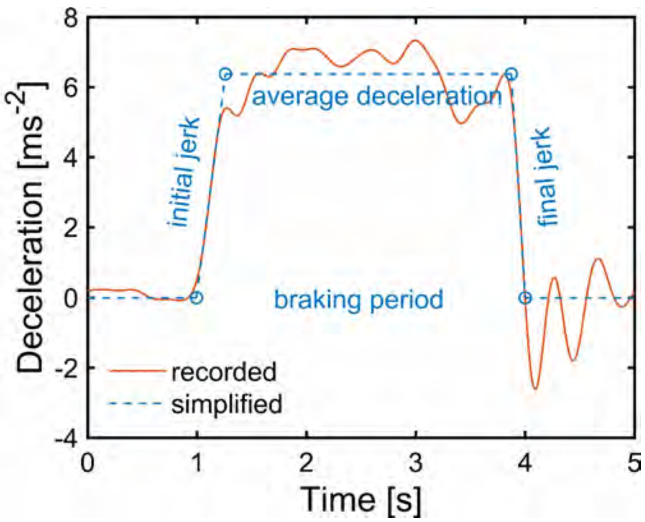
Vehicle instrumentation

- GPS antenna (position and speed)
- 2 capacitive accelerometer (deceleration)
- 2 capacitive accelerometer (vertical vibrations)

Vehicle deceleration

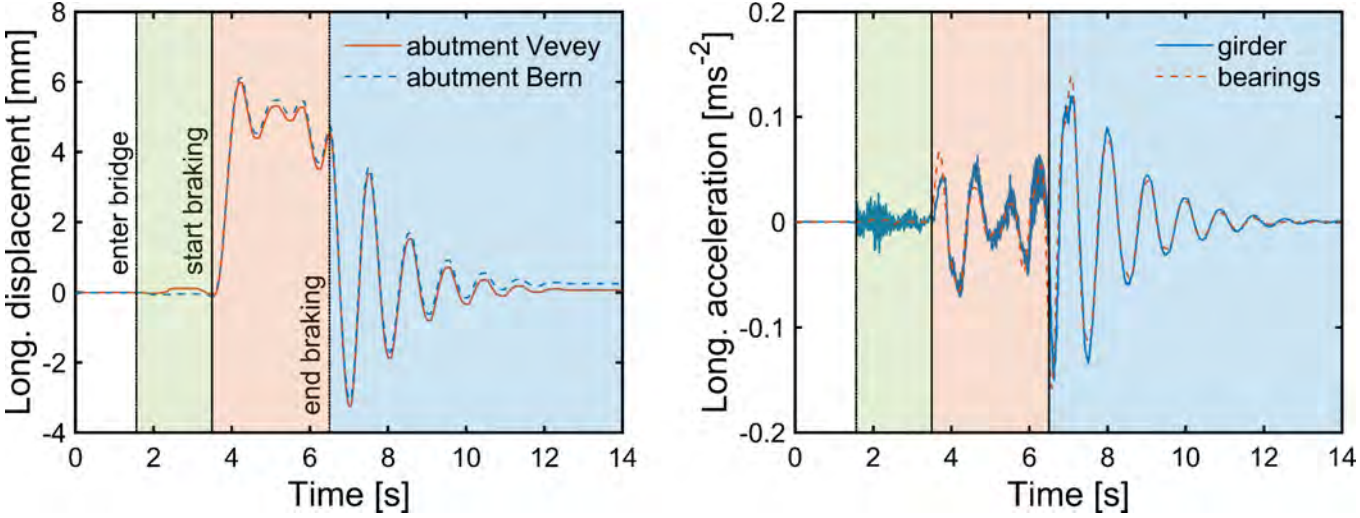
- Rapid increase of deceleration when starting to brake (initial jerk)
- Period of high deceleration
- Rapid decrease of deceleration shortly before vehicle stop (final jerk)
- Longitudinal vehicle oscillation after vehicle stop





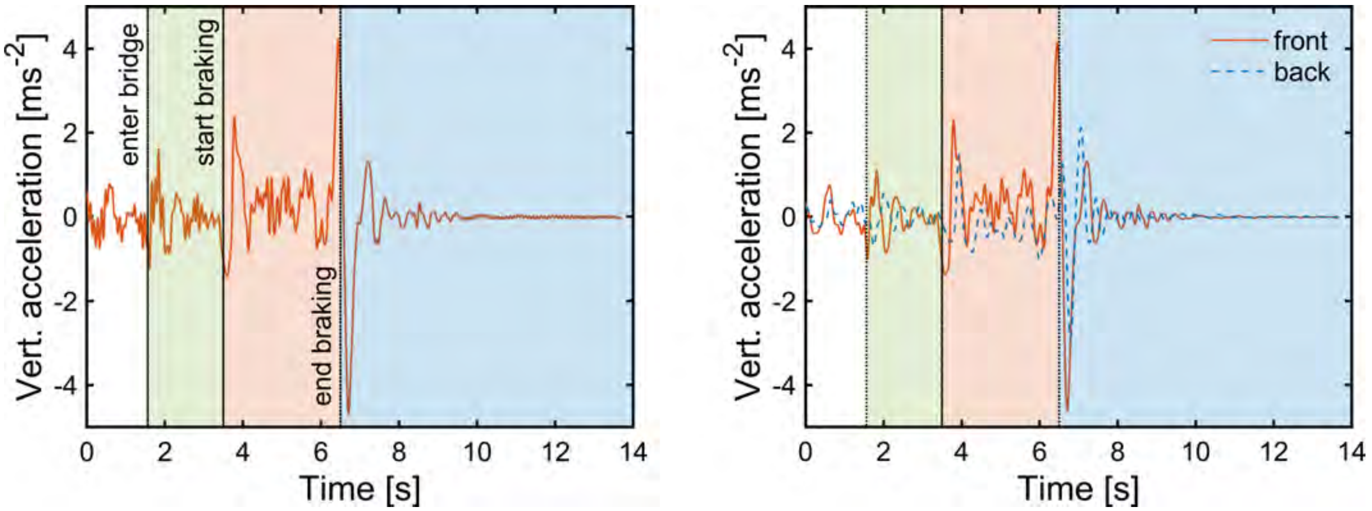
Longitudinal bridge motion

- Longitudinal displacement similar to vehicle deceleration during braking phase
- Strong vibrations after vehicle stop
- Vibration decay due to structural damping
- Acceleration derived from longitudinal displacement agree with recorded acceleration



Vertical acceleration of vehicle

- Strong vertical accelerations at start and end of braking phase
- At end of braking phase much stronger than at start
- Front part of vehicle had higher accelerations than end part



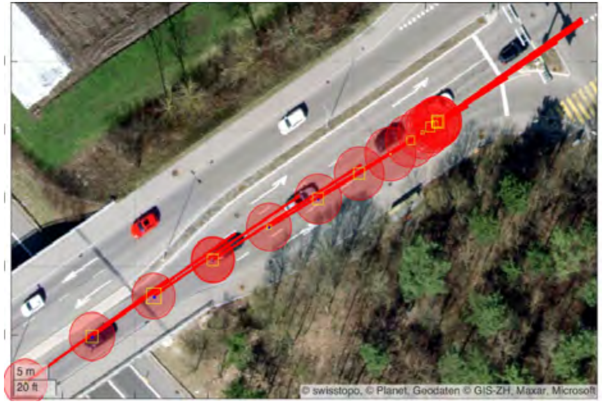
Monitoring of Braking event

- Collection of <u>data on braking events</u>

How often do you brake hard?

Where do you brake hard?

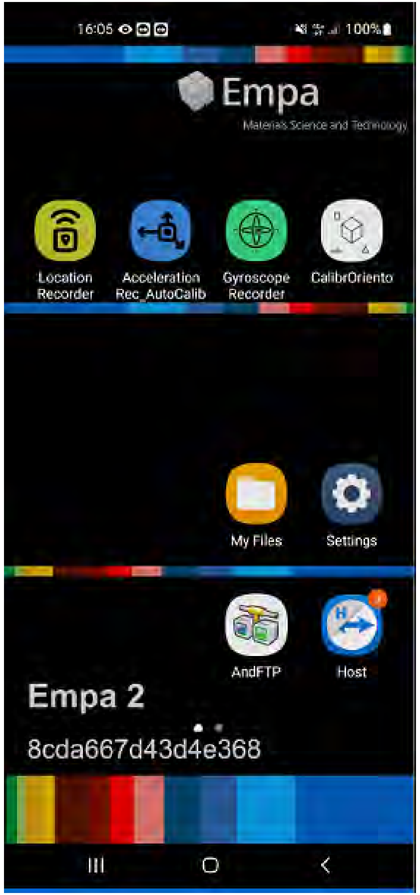
How much deceleration is applied?



Feltrin G.,Breveglieri M. BGT_20_02D_01 Monitoring of braking events of heavy vehicles for determining braking forces on road bridges, 2024

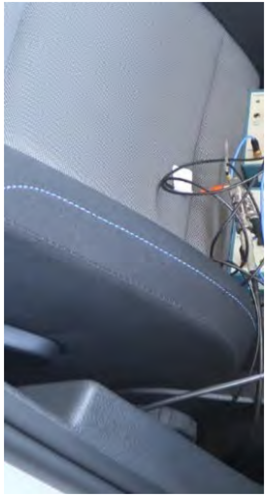
Monitoring of braking events

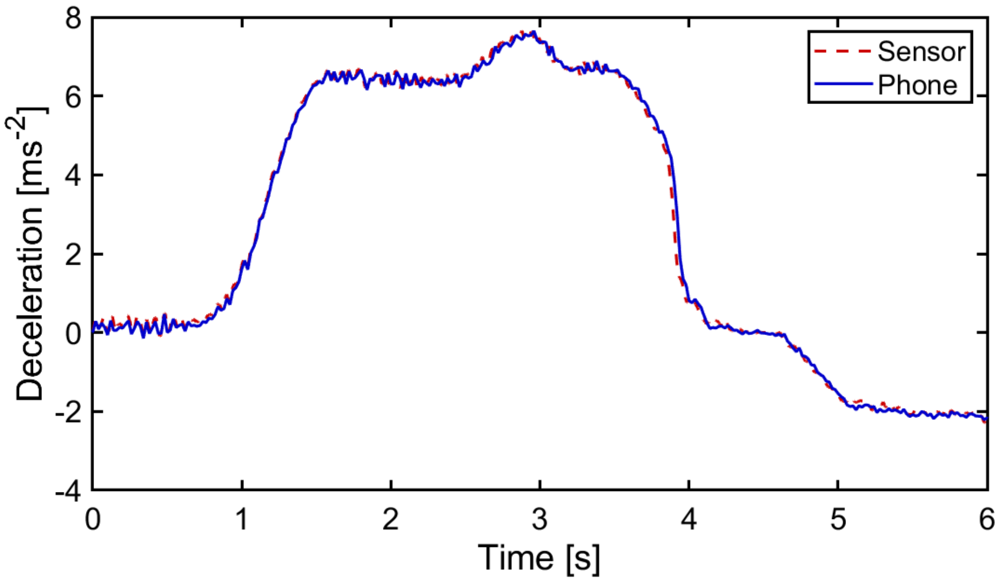
- Smartphone as a sensor
- Cheap monitoring and communication device
- Apps recording
  - Vehicle position (GPS)
  - Vehicle deceleration (Accelerometer)
  - Vehicle angular velocity (Gyroscope)
- Automatic data upload to server
- Remote maintenance (TeamViewer)



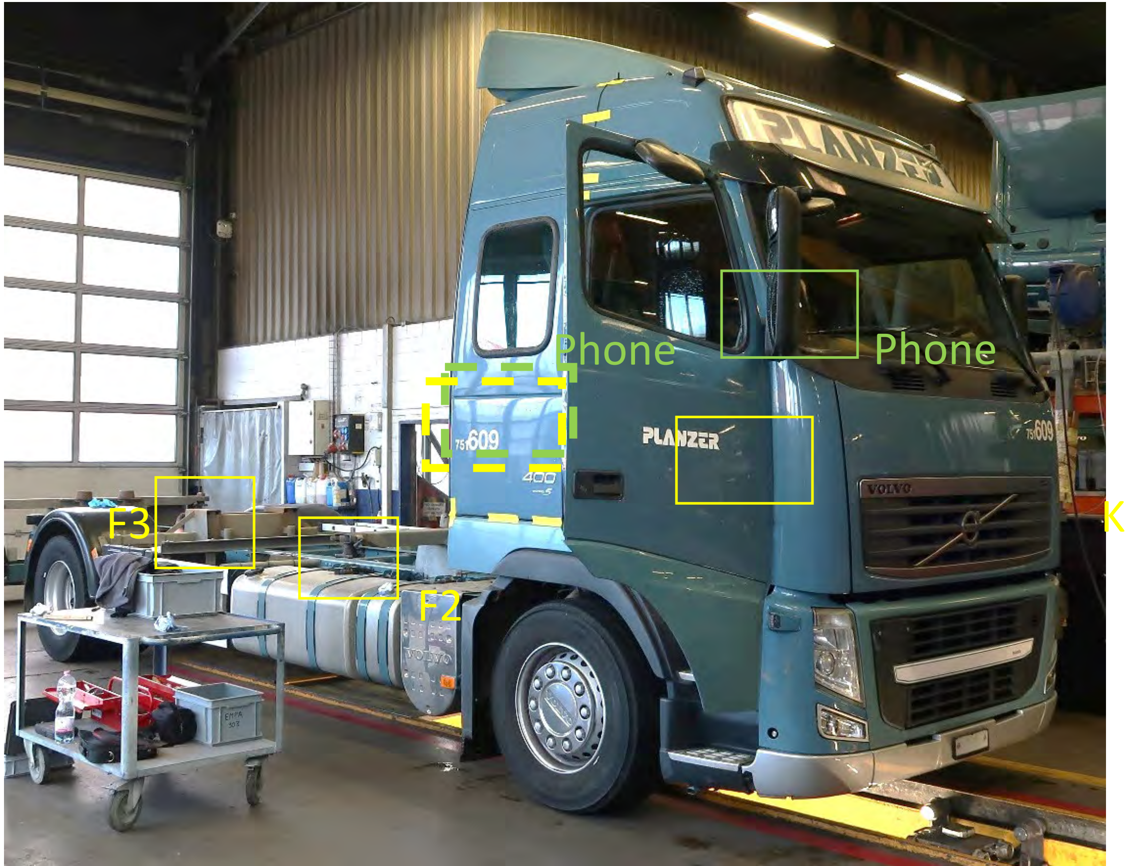
Deceleration record with smartphone

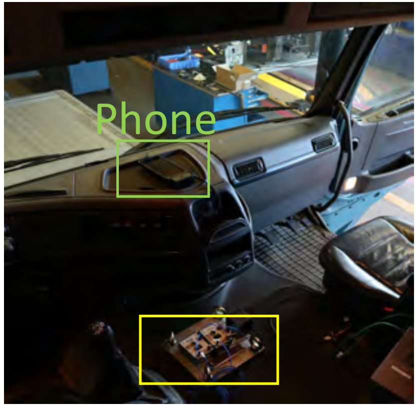
- Comparison with high accuracy sensor and data acquisition device

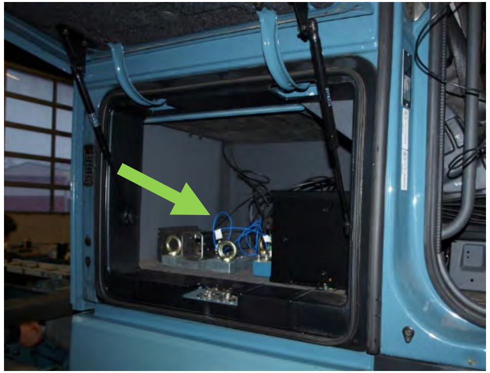




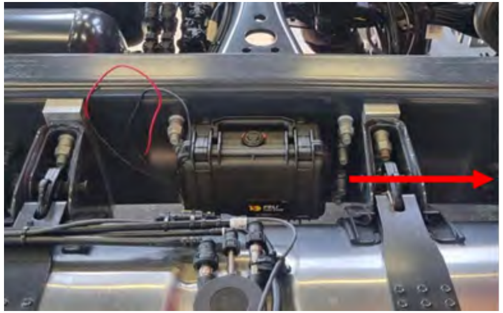
Accuracy data braking events with smartphone test







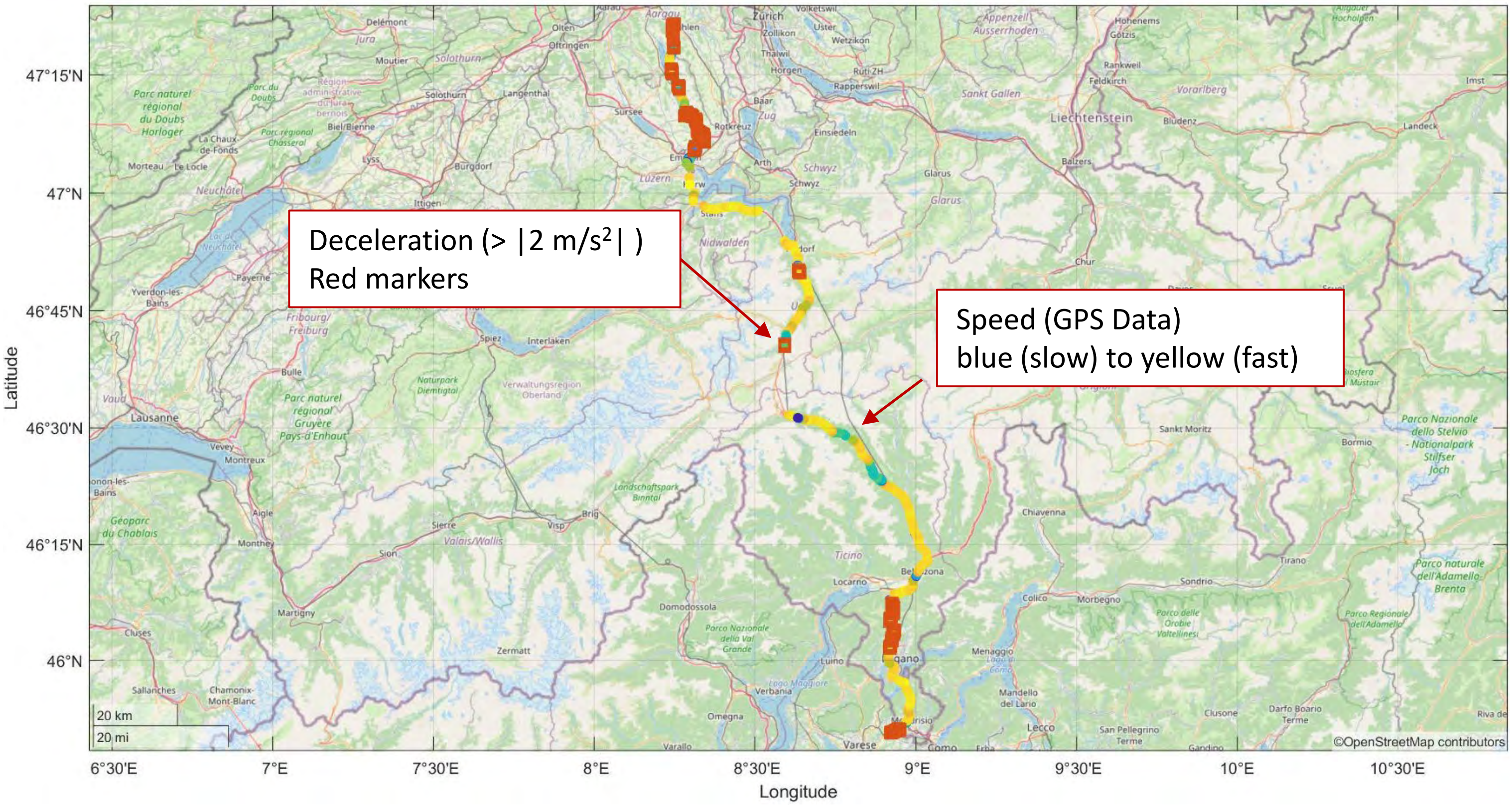
Mounting of smart phone on trucks



Test Phase
in cooperation with Planzer AG

A fleet of 22 trucks will be driving across Switzerland for a period of 6 to 9 months. Various types of truck are being employed on the main routes.

Record of a day



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Projects

- Sustainable bridges
- Integrated smart and safe built (I-SSB)
- Low power wireless sensor networks for monitoring civil infrastructure
- Hydronet
- TULcoEMPA
- Validierung des Modells zur Berechnung der dynamischen Einwirkung der Bremskraft auf - Strassenbrücken
- Monitoring von Bremsereignissen schwerer Fahrzeuge zur Bestimmung der Bremskräfte auf Strassenbrücken

Acknowledgments

- European Commission
- Staatssekretariat für Bildung und Forschung
- Astra
- Swiss electric research
- Polish – Swiss research program
- Innoswiss