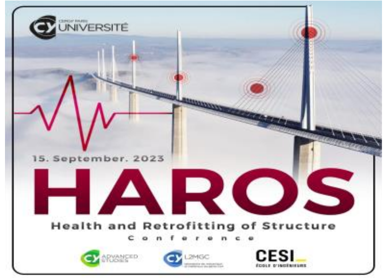
The promises of Surface Acoustic Wave (SAW) integrated sensors, for the SHM of concrete structures

S. Hage-Ali[1], P. Nicolay[2], P. Jeltiri[1,2], F. Al-Mahmoud[1], R. Boissière[1], B. Paulmier[1], T. Makdissy[1] and O. Elmazria[1]
(1) Université de Lorraine, CNRS, Institut Jean Lamour, IJL UMR 7198, F-54000 Nancy, France
(2) Carinthia Institute for Smart Materials (CiSMAT), Carinthia University of Applied Sciences, Villach, Austria

Haros Conference, Cergy, France 15/09/2023



Introduction

***Structural Health Monitoring* (SHM)**, challenge for the future : increasing demand for safer and more resilient buildings.

A possible **innovative solution : Surface Acoustic Wave (SAW) technology**.

Main advantages compared to existing solutions for SHM : fully passive (no embedded electronics/power supply) and wireless.

➔ This work : **1st assessment of wireless commercial SAW sensors implementation for SHM, specifically in concrete.**

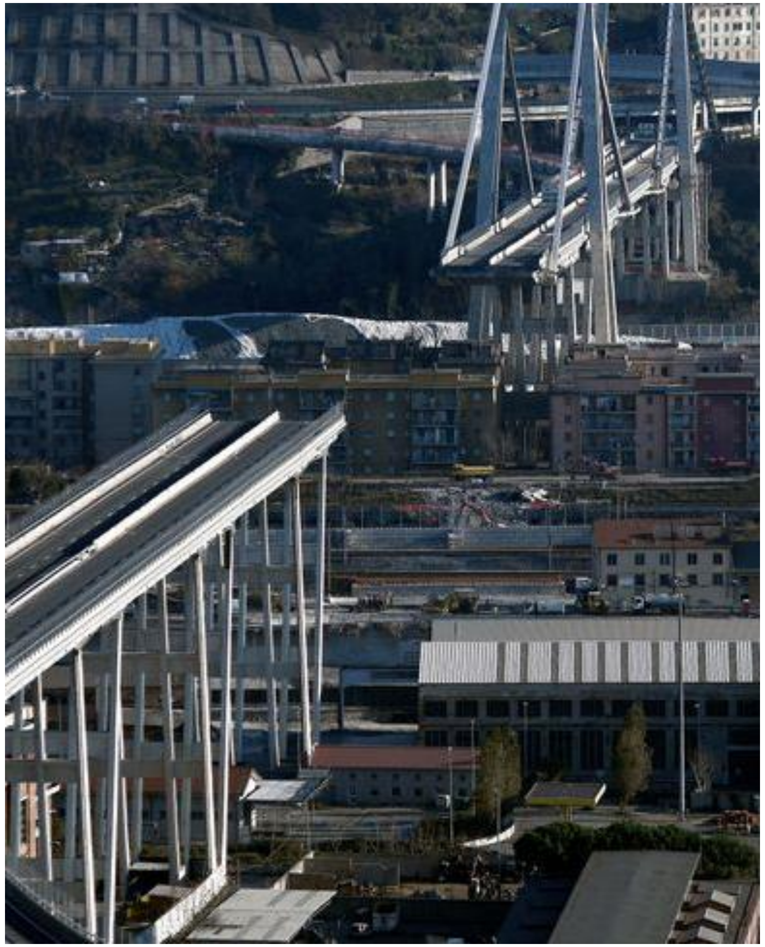


Fig 1 : Collapse of the Morandi bridge in Genoa (2018).

Presentation’s outline

I.Introduction to SAW sensors

II. Instrumenting a RC beam

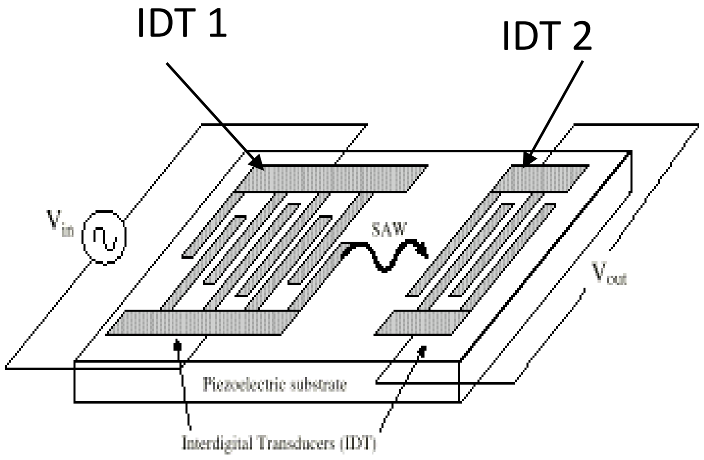
III. Wireless temperature monitoring

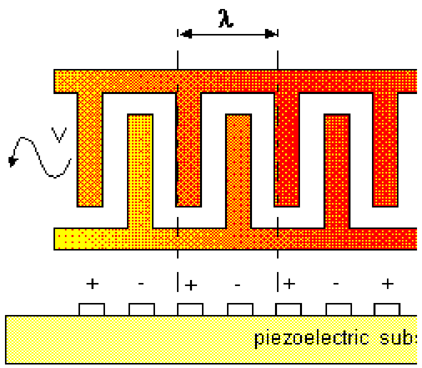
IV. Low strain sensing

V. High strain sensing

The Surface Acoustic Waves (SAW) technology

1. ***Electric RF field applied on the IDT 1 produces a SAW (inverse piezoelectricity effect)***
2. ***The Surface Acoustic Wave travels along substrate surface to the IDT 2***
3. ***The piezoelectric effect produces an electric RF signal from the SAW***





$$f_0 = \frac{v}{\lambda}$$

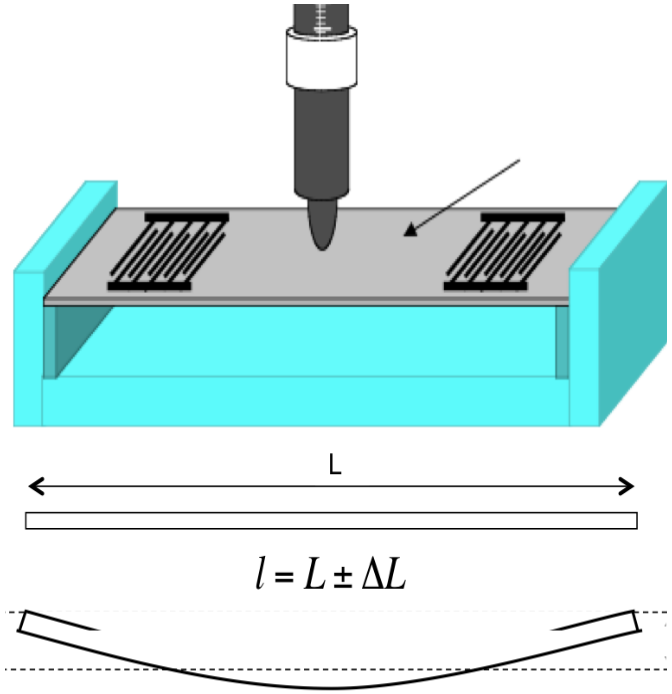
<u>Photolithography limit =0.3 µm l= 1.2 µm</u>
Quartz: V = 3km/s, f_0=2.5 GHz

SAW temperature and strain sensing

Higher temperatures → Thermal expansion : $\Delta\lambda$ / Velocity change : Δv → Frequency/delay shift Δf ⟶ $\mathrm{TCF} = \frac{1}{f_0}\frac{\Delta f}{\Delta T}$

Temperature Coefficient of Frequency

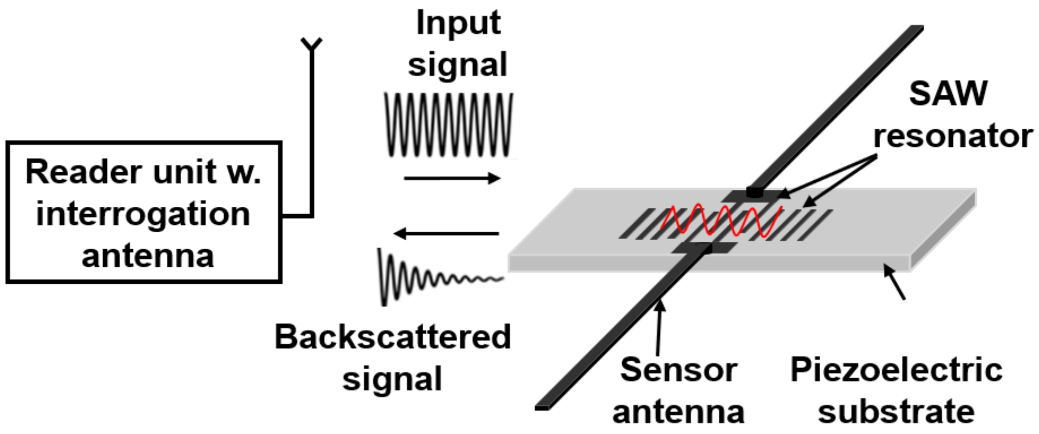
Strain

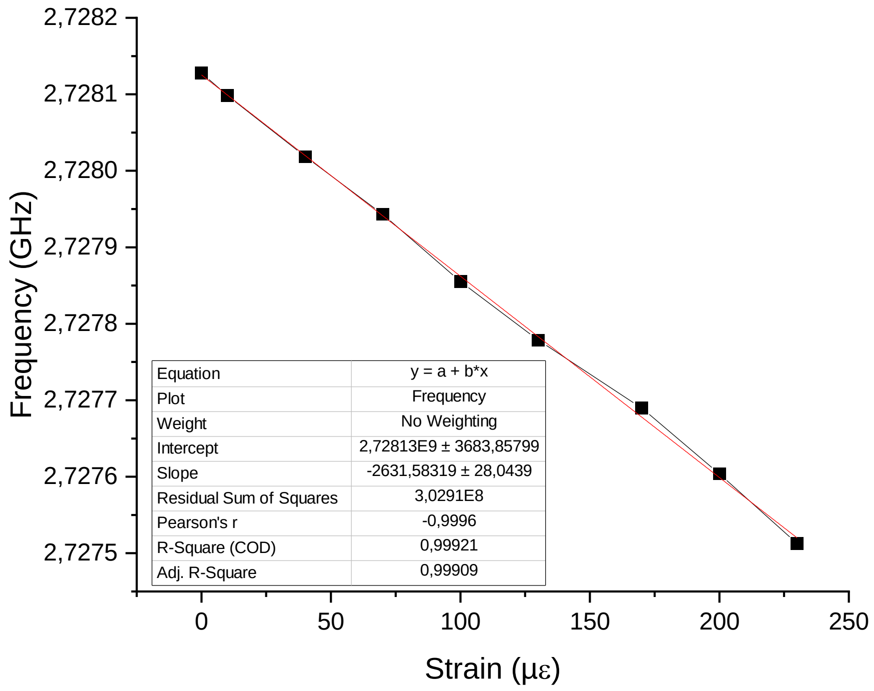


$\Delta\lambda/\Delta v$ ➡ Δf

SAW wireless 1-port resonator configuration

Resonator





- **Remote query**
- **Batteryless / fully passive**
- **Attractive for SHM**

II-Instrumenting a RC beam

- Reinforced concrete beam : 1.2 m long, with a 155 mm x 200 mm cross-section.

- Instrumented rebars on the lower part.

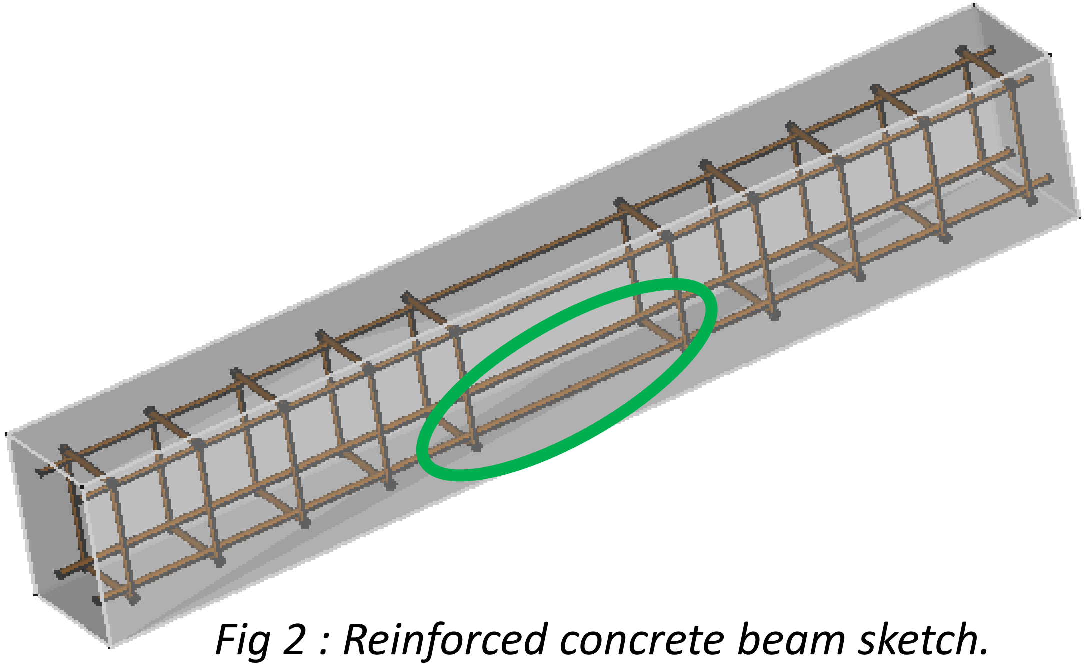


Fig 2 : Reinforced concrete beam sketch.

Fig 3 : Metallic reinforcements assembled (upside-down view).

II-Instrumenting a RC beam

- Reinforced concrete beam : 1.2 m long, with a 155 mm x 200 mm cross-section.
- Instrumented rebars on the lower part.

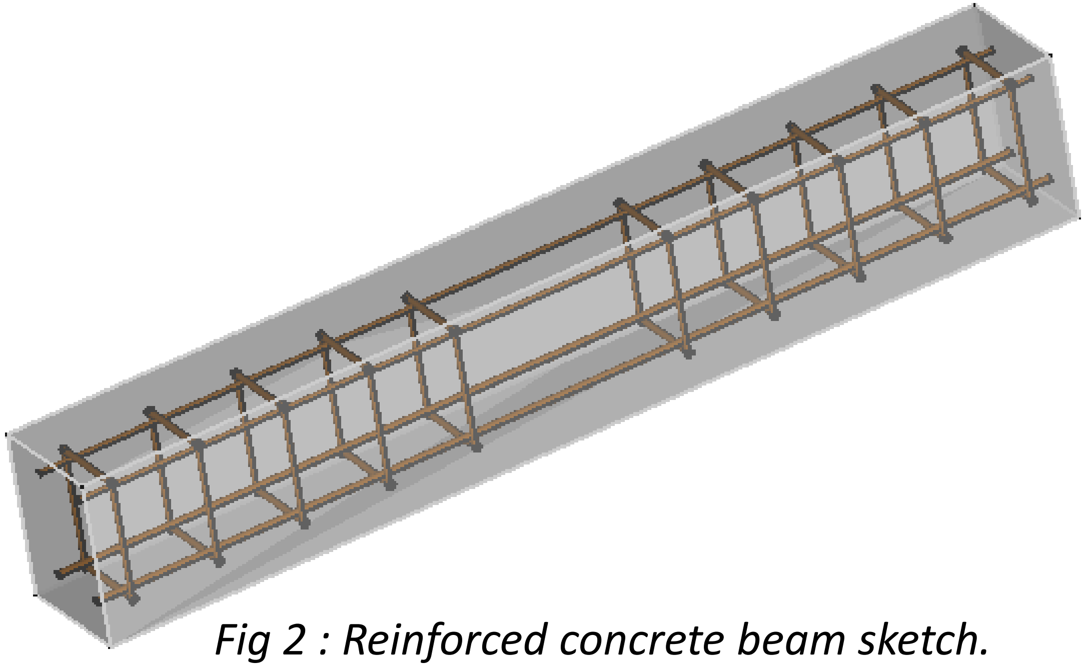


Fig 2 : Reinforced concrete beam sketch.

Fig 4 : Final concrete beam.

II-Instrumenting a RC beam

- SAW sensors from SAW Components Dresden.
- On both rebars : 868 MHz 1 port SAW resonators as strain sensors, 1 wireless and 1 wired.
- Strain sensors : bare chips glued to the rebars, with a cyanoacrylate adhesive.
- A 2.45 GHz wireless SAW temperature sensor.
- On both rebars, piezoresistive strain gauges as reference sensors.

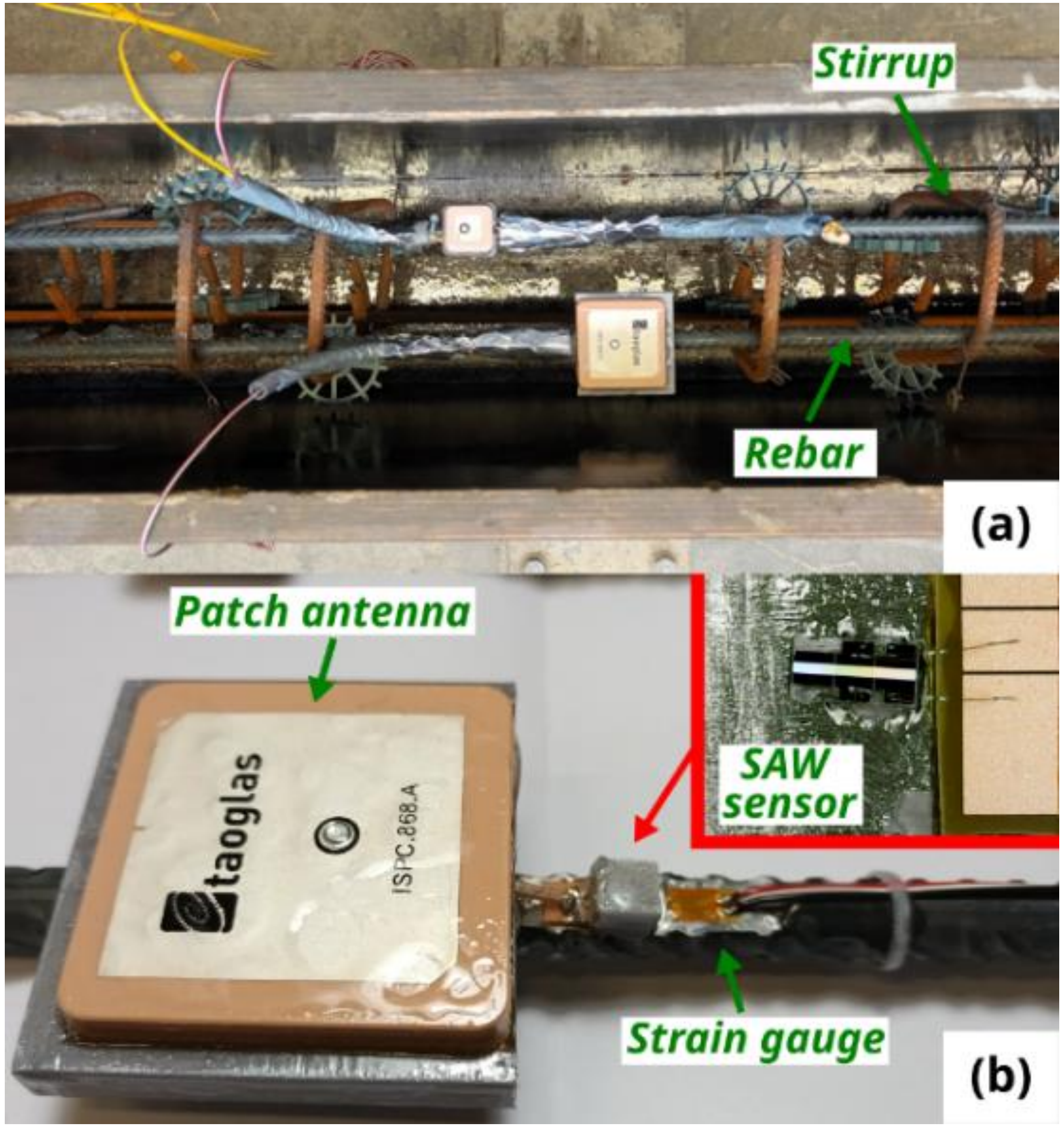


Fig 5 : (a) Instrumented beam before concrete casting (upside down view).
(b) Instrumented rebar 1. Inset: SAW device glued on metal flat.

II-Instrumenting a RC beam

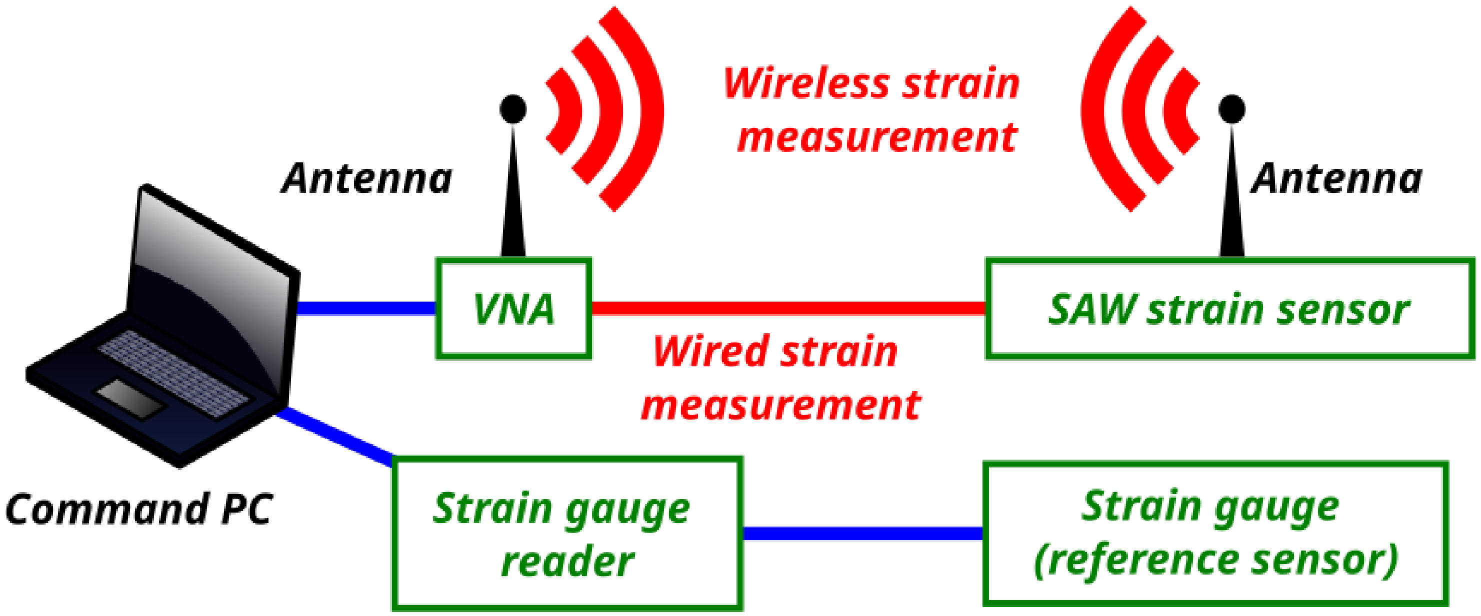


Fig 6 : Schematic diagram of the strain measurement setup.

- At 868 MHz, reading of the SAW resonators with a VNA : acquisition of S11 then post-processing to track the frequency of the minimum.
- At 2.45 GHz, commercial reader from SCD.
- Commercial reader for the strain gauges (reference sensors).

III-Wireless temperature monitoring

- During 21 days after casting.
- Reader antenna 2.5 cm from the beam.
- Coherent with expected behavior of concrete during hardening (exothermic reaction in early stage, then thermalization of the structure).
- Maximum reading distance around 1 m.

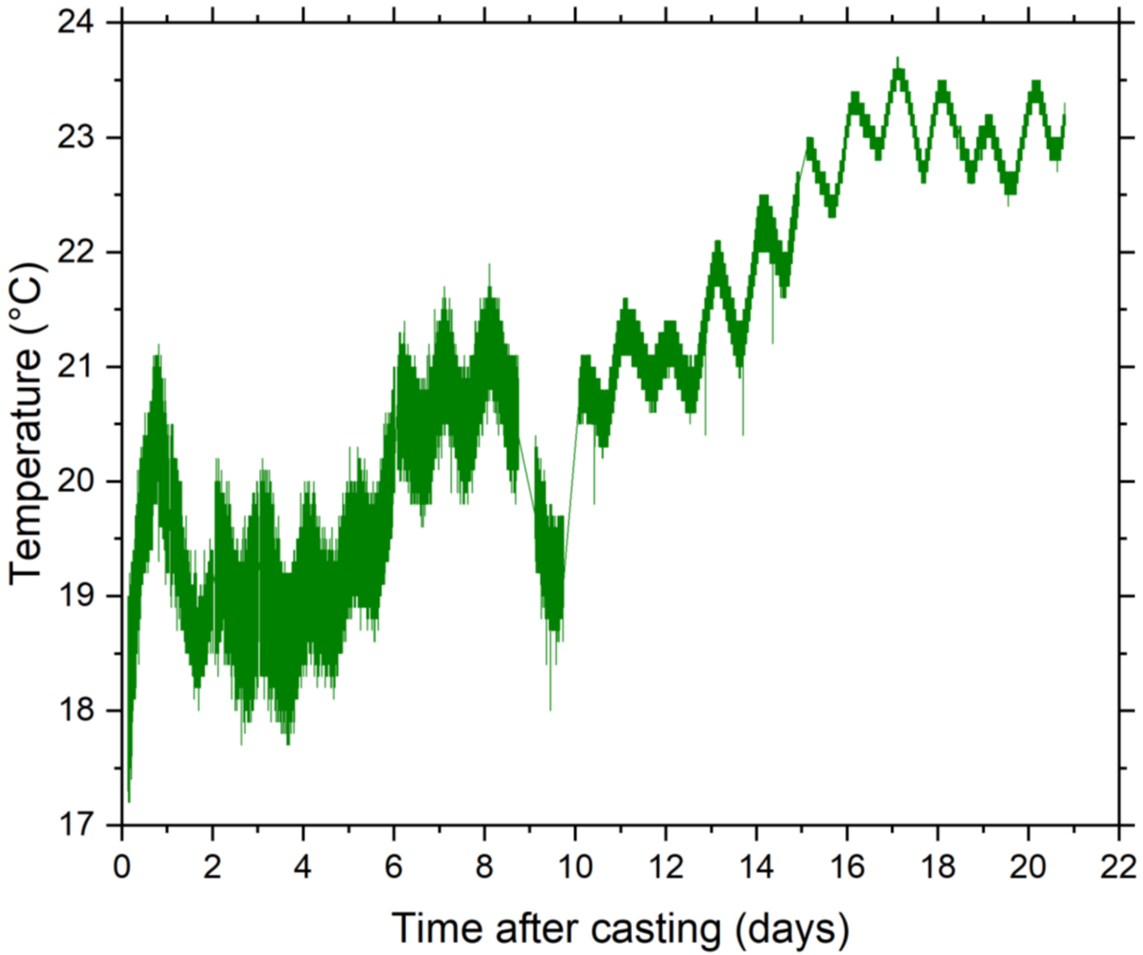


Fig 7 : Wireless temperature measurement with the commercial SAW sensor at 2.45 GHz (rebar 2).

IV-Low strain sensing

- **Low strain cycle** with manually placed metal weights (up to 200 kg).
- **Wired measurement (rebar 2).**
- Good correlation of the two sensors.
- SAW sensor sensitivity around 0.6 ppm/με.

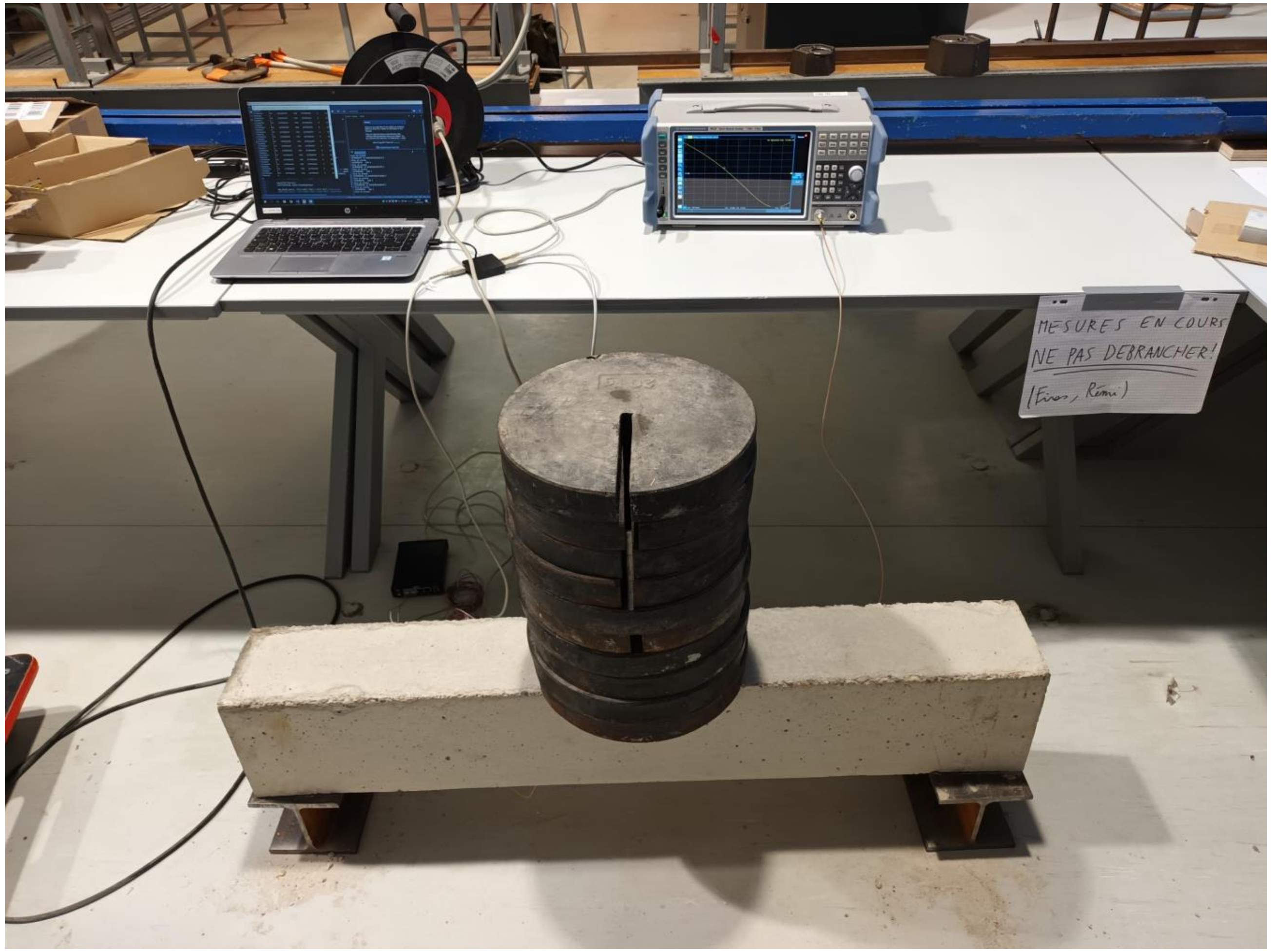


Fig 8 : Strain measurement setup for small loads (metal weights visible on the beam).

IV-Low strain sensing

- ➢ **Low strain cycle** with manually placed metal weights (up to 200 kg).
- ➢ **Wired measurement (rebar 2).**
- ➢ Good correlation of the two sensors.
- ➢ SAW sensor sensitivity around 0.6 ppm/με.

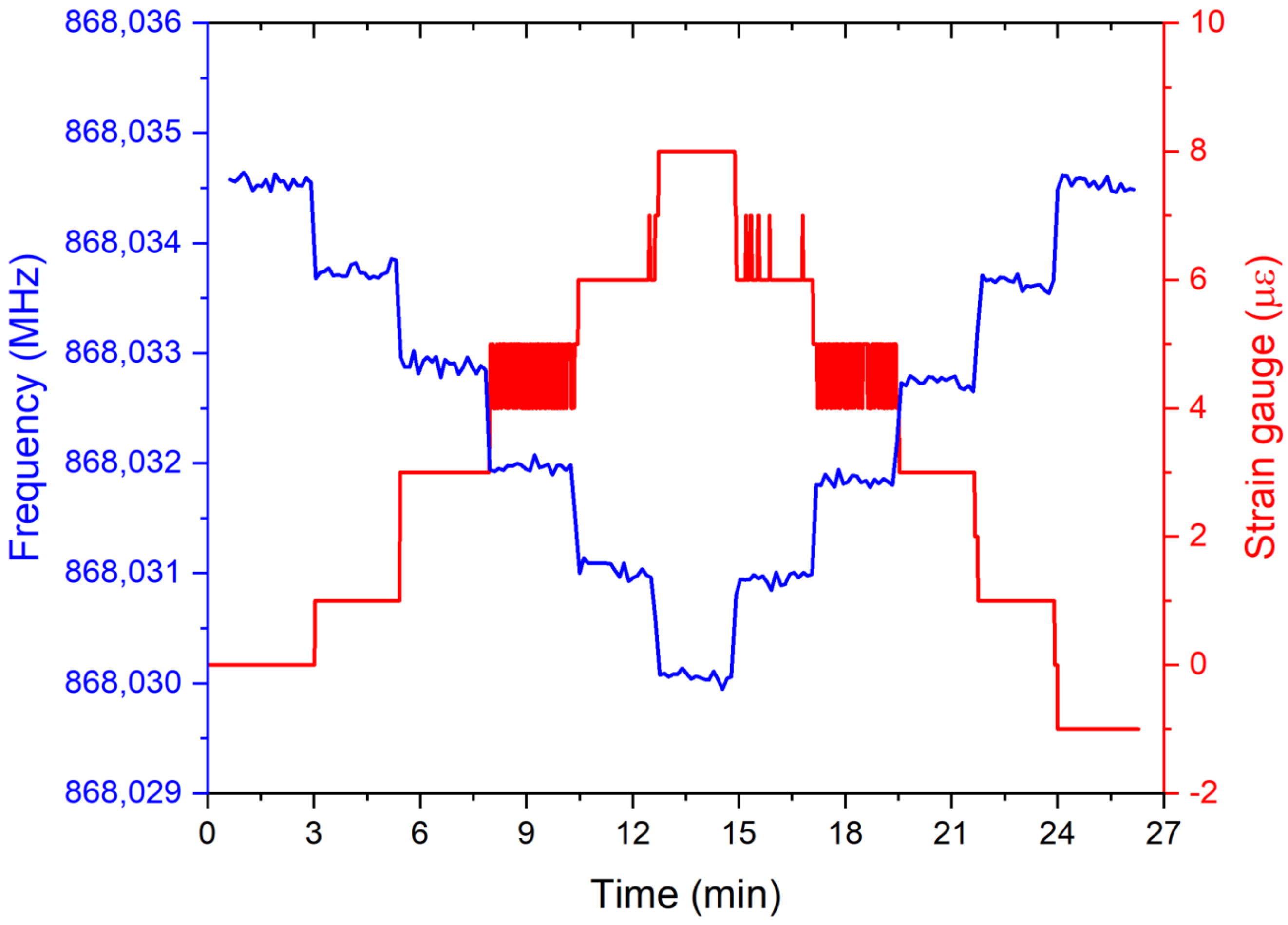


Fig 9 : Wired strain measurement during low strain cycle (rebar 2).

V-High strain sensing

- Use of an hydraulic bending machine to reach higher loads.
- Several automated high strain cycles conducted.
- Wireless and wired measurements presented.

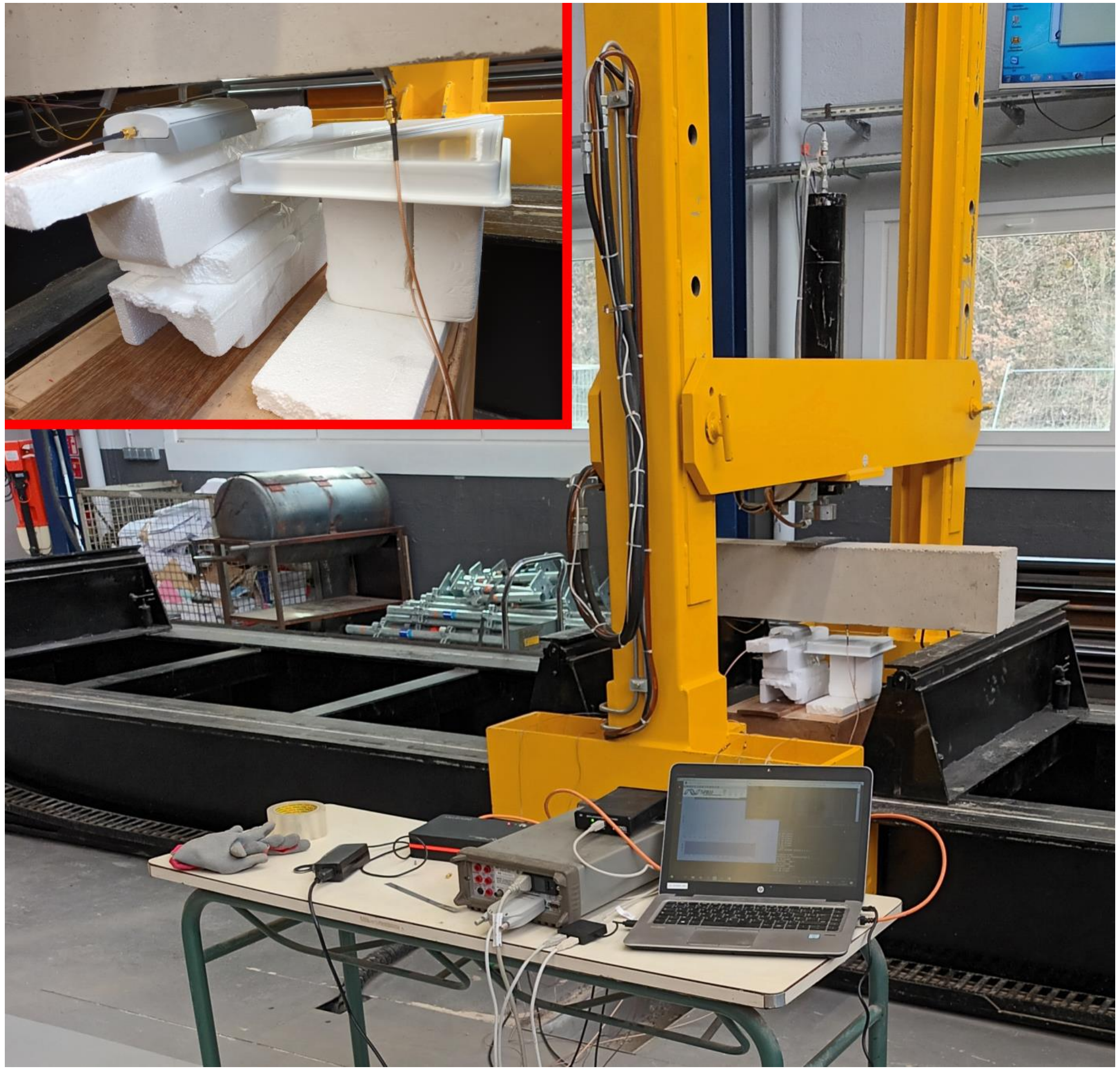


Fig 10 : Measurement setup for high strain cycles. Inset : interrogation antennas under the beam.

V-High strain sensing

- **Wireless measurement,** 7 cm under the beam.
- Noisy signal of the SAW sensor, but matching the strain gauge trend.

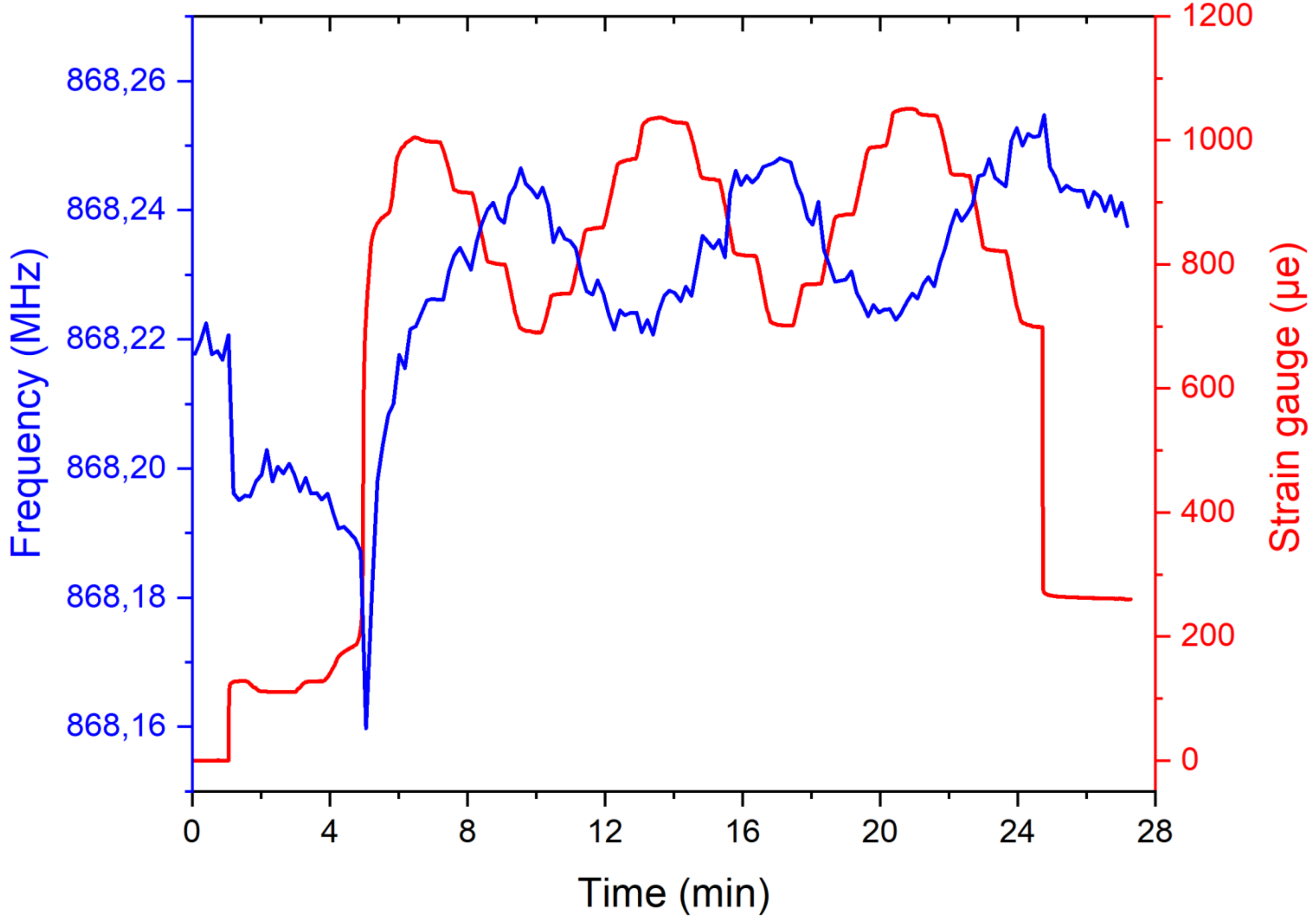


Fig 11 : Wireless strain measurement (rebar 1) during an automated high strain cycle.

V-High strain sensing

- **Wired measurement.**
- Again, good matching of the trends of both sensors.
- Drift of the SAW signal at constant load, increasing at higher loads.
- Likely due to relaxation in the glue layer under the chip.

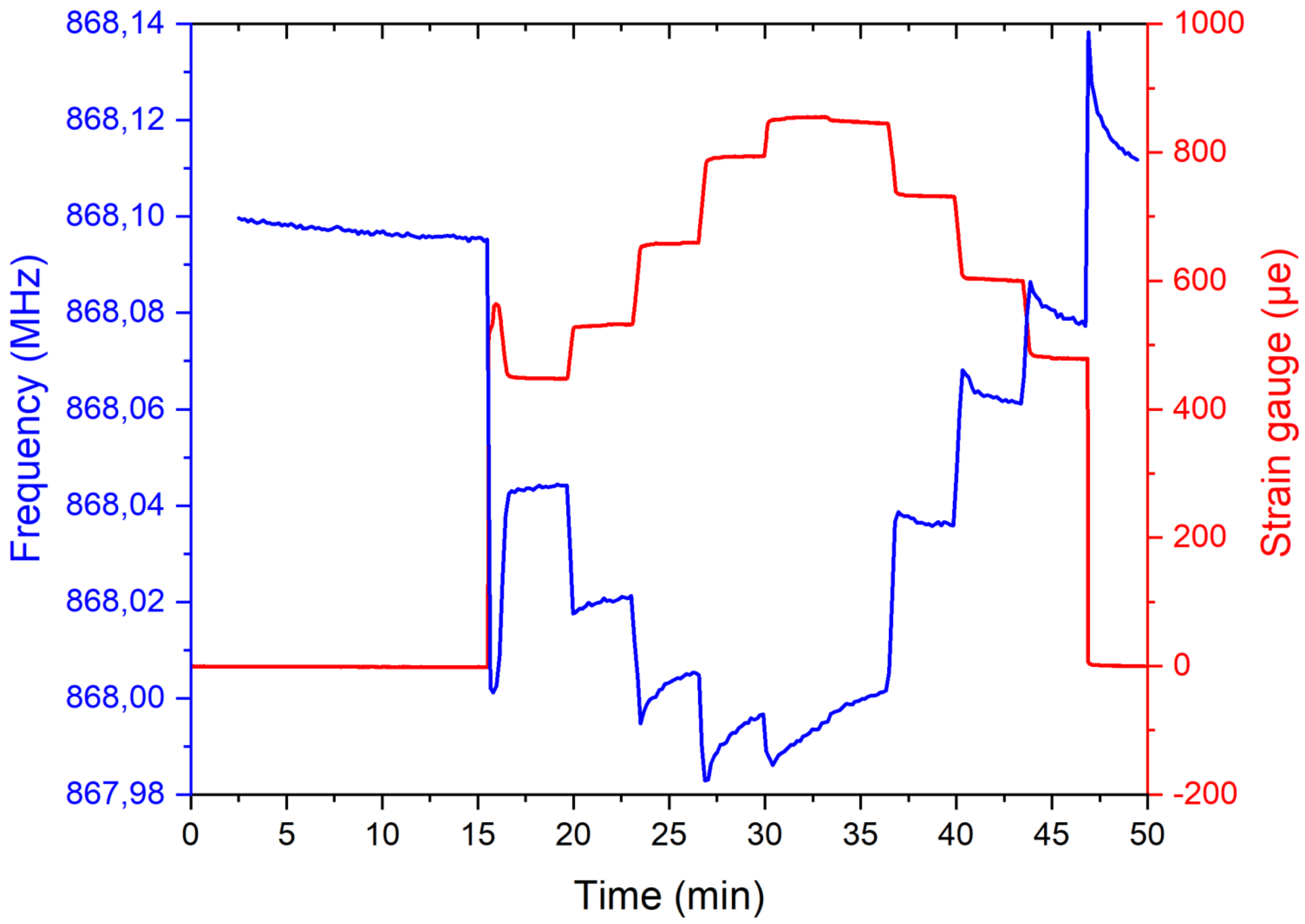


Fig 12 : Wired strain measurement (rebar 2) during an automated high strain cycle.

Conclusion

- ❖ Commercial SAW resonators (as bare chips) can be directly glued on rebars and serve as strain sensors inside concrete, in a wireless or wired configuration. Wireless temperature monitoring was successful. Results in [1]

- ❖ Wireless readings can be improved using other types of antennas, better antenna tuning, commercial readers instead of VNA…

- ❖ SAW signal drifts as applied strain increases, due to relaxation/creep inside the adhesive layer. Possible solutions : better adhesive, glue-less bonding with NanoFoil [2] or direct integration of SAW sensors on metallic pieces [3].

sami.hage-ali@univ-lorraine.fr ; P.Nicolay@fh-kaernten.at ; pierre.jelriti@univ-lorraine.fr

[1] P. Jeltiri et al. "Wireless strain and temperature monitoring in reinforced concrete using Surface Acoustic Wave (SAW) sensors", IEEE Sensors Letters 2023 https://doi.org/10.1109/LSENS.2023.3315219
[2] P. Nicolay et al. "Glue-Less and Robust Assembly Method for SAW Strain Sensors," IUS 2108, doi: 10.1109/ULTSYM.2018.8580224.
[3] P. Mengue et al., "Direct integration of SAW resonators on industrial metal for structural health monitoring applications," Smart Mater. Struct., Oct. 2021, doi: 10.1088/1361-665X/ac2ef4.