

Coda Wave Interferometry for Monitoring Bridges with Embedded Ultrasonic Transducers – Lessons Learned at the Gänstorbrücke Bridge Ulm, Germany

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Abstract

Ultrasonic Coda Wave interferometry has the potential to detect minute changes in scattering materials like concrete. By permanently installing ultrasonic transducers in concrete, DFG Research unit CoDA aims to develop methods for concrete damage assessment in Germany's aging infrastructure. To test the methods developed in simulations and laboratory experiments on a large scale, we have implemented several ultrasonic transducers at the Gänstorbrücke Ulm, one of Germany's most monitored road bridges. Since fall 2020 we are monitoring parts of the center of the Bridge, as well as an abutment, and compare the results to the commercial monitoring system. All data is recorded with a self-made data collection device, the so-called W-Box, and analyzed with different coda wave-based algorithms to detect signal and volumetric velocity changes. The long-term measurements show that the influence of temperature changes on strains and therefore ultrasound velocity changes calculated with coda waves can be monitored. The capabilities and limitations of the coda wave-based monitoring system are tested in a controlled experiment. Static loading using a truck with varying loads at several positions allows the calibration of the system to improve the detectability of possibly damaging loads and changes induced by this loading. A map of velocity change analyzing data from this load experiment shows that the influence of load on the material and strain distribution can be detected with array measurements.

Keywords: Coda Wave Interferometry, Ultrasound, Embedded Sensors, Bridge Monitoring, Load Experiment

1 Introduction

The capabilities of non-destructive investigation of reinforced concrete structures with ultrasonic coda wave interferometry (CWI) have been demonstrated on many occasions. In 2009, Larose and Hall [1] reported on the dependency of Ultrasonic velocity in concrete and determined relative velocity changes with a resolution of 2×10^{-5} . In the following years, many researchers have further investigated the influence of stress and strain [2]–[5], environmental changes [6]–[8] and damages [3], [9], [10] on the coda signal to evaluate the possibilities of coda wave monitoring of reinforced concrete structures. In 2019, the German Research Foundation (DFG) started funding a research group (FOR CoDA) investigating the detection of damages in reinforced concrete with coda waves to channel expertise from the fields of Geophysics and Engineering Sciences and form a theoretical and experimental, basis for coda monitoring. The transfer of these findings towards the real structure, where effects, are individually controlled in Laboratory experiments is a keystone of research within this group. Therefore, CoDA equipped an in-service road bridge in the German city of Ulm with more than 20 ultrasonic transducers and started continuous monitoring in December of 2020. Additionally, the bridge is equipped with a commercial monitoring system to measure strain and acoustic emission for damage detection. The authors present results from the ongoing monitoring with coda waves, where temperature change was the main influence on coda wave velocity. Additionally, the results of a controlled load experiment are presented to compensate for the absence of changes other than environmental influences.



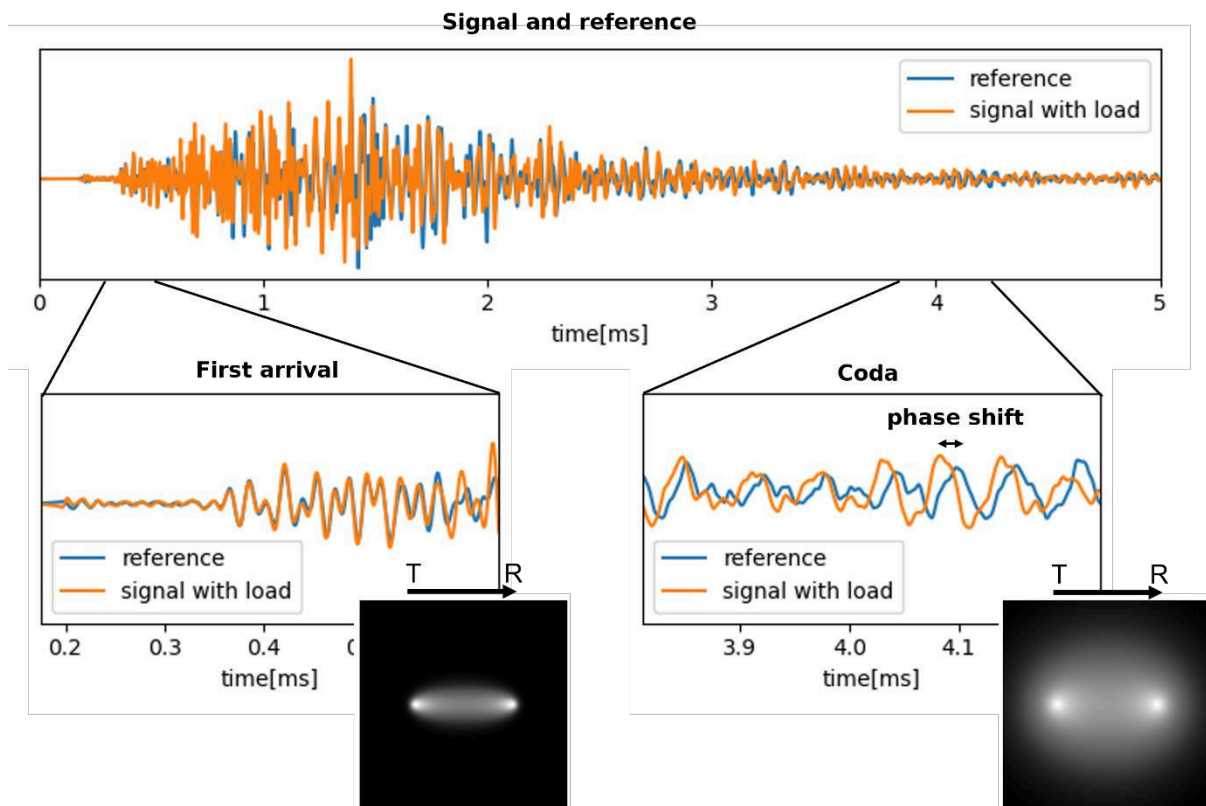


Figure 1: The concept of CWI. When comparing two signals recorded with the same source-receiver combination, small changes in the medium are visible in the coda part of the signal, but not in the first arrival. When analyzing the coda, a large area rather than the direct connection between Transducer (T) and Receiver (R) is investigated. This is indicated by the sensitivity maps at the bottom of the zoomed sections, where bright white means high sensitivity.

2 Coda Wave Interferometry

The ultrasonic coda is defined as the multiply scattered late part of an ultrasonic recording. The concept of coda analysis originated in Seismology. Snieder et. al. [11] showed that using a seismic source and receiver in pitch-catch configuration, small changes in the material can be detected in the coda by comparing the signals with cross-correlation. In Figure 1 this concept is illustrated using two consecutive measurements recorded at the Gänstorbrücke Ulm during a load experiment. Looking at the zoomed section, one can detect a shift between the reference and the signal. This shift is not visible in the first arrival. The sensitivity maps (approximated with diffuse Theory [12]) on the bottom right of the zoomed sections show that the information in the latter part of the recording is collected from a large area/volume, while traditional first arrival analysis only investigates information collected on the direct connection between source and receiver. Therefore, coda monitoring can be used for advanced imaging applications. The signal change in a CWI monitoring setup can be generally quantified with two parameters. The correlation coefficient (CC) describing the similarity ($CC = 1$) and difference ($CC \rightarrow 0$) of two compared signals and the relative velocity change (dv/v). The latter quantity can be calculated in various ways described in [13]. In this work, when comparing two signals u_1 and u_2 on a time interval between t_1 and t_2 we will speak of the following. CC, the raw correlation coefficient,

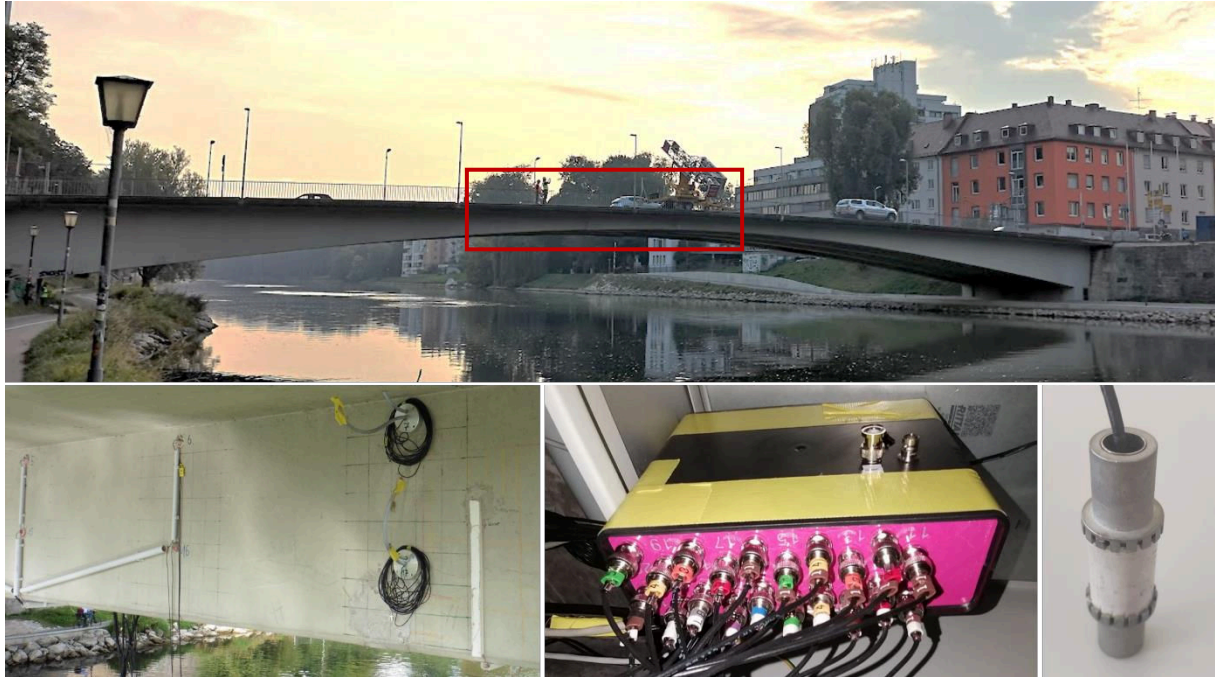


Figure 2: Gänstorbrücke Ulm (top) with the instrumented area (red rectangle), embedded sensors, measurement device, and sensor (bottom from left to right).

and $\alpha = -dv/v$, the relative velocity change determined with the stretching technique (see [13]). A third parameter CC_α , the remaining correlation coefficient after the application of α , the stretching factor, can give a hint about the origin of change, whether it's global (CC returns to one) or local (local changes not explained by relative velocity change remain in the signal). All three quantities can be calculated with the following equation (where α is the α maximizing CC):

$$CC(t_1, t_2, \alpha) = \frac{\int_{t_1}^{t_2} u_1(t(1-\alpha))u_2(t)dt}{\sqrt{\int_{t_1}^{t_2} u_1(t(1-\alpha))dt \int_{t_1}^{t_2} u_2(t)dt}} \quad (1)$$

In monitoring with CWI, the reference measurement can remain fixed if $CC > .7$ (the signals are relatively similar). This method is called the fixed reference technique. For the analysis in this work, we will only use this fixed reference method. For methods with changing references see e.g. [4].

3 Instrumenting the Gänstorbrücke Bridge

The Gänstorbrücke bridge (Figure 2, top) is a road bridge spanning the river Danube and connecting the cities of Ulm and Neu-Ulm since its construction in 1950. The bridge consists of two individual single-span bridges with slab and beam connections. The entire structure is 96 m long and originally consisted of two car lanes and one pedestrian lane in each direction. Since severe damages were detected in the late 2010s, the bridge is monitored with acoustic emission and strain measurements, and crossing traffic is limited to cars lighter than 3.5 tons on two instead of four lanes. In Fall 2020, the bridge was additionally equipped with 20 embedded ultrasonic transducers in the center of the bridge (Figure 2, bottom), as well as



several transducers in the Abutment on the shore of Ulm. The transducers have a center frequency of 60 kHz and have already been characterized [14] and used in several projects [6], [8], [10]. Due to their circular shape, they are best suited for embedding in long thin slabs. The measurement device is a self-developed, raspberry pi-based instrument for permanent ultrasonic monitoring. The system specifications and design can be seen in [15].

In December 2021, the bridge was closed for one night to conduct a loading experiment with two trucks weighing 15 and 32 tons respectively. The trucks were positioned in different positions on the bridge and measurements were taken in the sensor array in the center of the bridge. To reduce the acquisition time, a commercial system similar to the one used in [9] was used during this experiment.

4 Results

With the monitoring system up and running for more than one year, the experiment has been continuously delivering data. While the experiment was mainly designed to test CWI itself, it has also shown the benefits and disadvantages of the self-made measurement system. While it was able to perform the monitoring task, its slow measurement speed made measuring many sensor combinations difficult when constant environmental conditions should have been guaranteed recording array data. Furthermore, the device had to be repaired several times, which resulted in loss of data and different power delivery (signal amplitude). As the amplitude is not crucial for CWI analysis in general, this is no major drawback but limits further signal analysis. When the reliability of the system can be further improved (and repairs accelerated and standardized), it is a perfect monitoring system for embedded ultrasonic sensors due to its low-cost point and low-threshold design.

4.1 Long Term Monitoring

The monitoring system has been running since December 2020. Figure 3 shows the relative velocity change calculated with fixed reference CWI over 1.5 years, as well as a zoomed section from June 2021 with strain and temperature data from the center of the bridge. As no damages were recorded by acoustic emission, the main long-term influence on the bridge was the temperature. Temperature is influencing the ultrasonic velocity by approximately $-0.03 \text{ \%}/^{\circ}\text{K}$ to $-0.05 \text{ \%}/^{\circ}\text{K}$ [8]. This lines up with a velocity variation of 1% and mean temperatures ranging from 0°C in winter to 25°C (and more in recent years) in summer. The long-term trend shows that the relative velocity change is similar (close to zero) in Dec. 2020 and Dec. 2021 when temperatures are comparable. In the summer months, when temperatures were highest in Ulm ultrasonic velocity decreases by up to 1%. Taking a closer look into the correlation of temperature and CWI velocity change, while adding strain measurements from the center of the bridge shows that temperature changes influence the material due to thermal expansion and affect stress and strain and therefore the ultrasonic velocity as described by acoustoelastic theory. In the zoomed part in Figure 3, three subsections are marked where the average temperature is either increasing (Subs. A, Subs. C) or decreasing (Subs. B). One can observe that, while general temperature change influence on velocity is linear, heating and cooling does have a different influence on the velocity change, as velocity increase is slower in cooldown phase B than in warmup phase A and C.

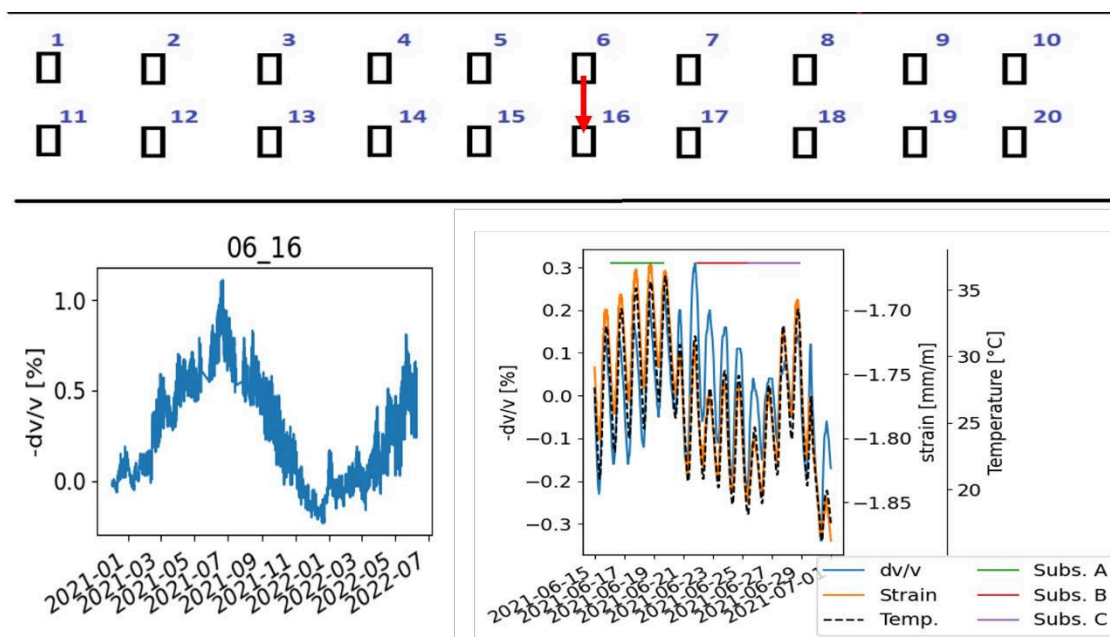


Figure 3: Negative relative velocity change with fixed reference from Dec. 2020 to June. 2022 for sensor pair 06-16 (bottom left). The negative relative velocity change, strain, and temperature are following the same trend in daily cycles.

4.2 Load Test

As during the long-term monitoring period no significant signal and therefore no significant material changes were detected, we decided to test the system with a controlled load experiment in the early morning hours of Dec. 8th, 2021. This way, a major influence on the bridge and strong changes in stress and strain and crack opening are enforced and can be monitored with the embedded sensors. Two trucks with weights of 15T and 32T were positioned in 5 different positions on the bridge (Figure 4), and “no-load” measurements were performed repeatedly during the experiment.

Figure 4 shows the results of CWI analysis with sensor combinations 8-9. This combination is directly below Load position three. Both CC and dv/v show that a load on position 3 has the strongest influence on the measurements. When the trucks are in positions 2 and 4, there is still detectable influence, especially by analysing the relative velocity change. The change of sign in the second position is striking, indicating an increase in speed in the middle of the bridge. At the end of the experiment, after some drive-over tests which showed that fast measurements are influenced by strong loads passing the bridge, we performed a long-time loading test at position three using the 32T truck. This test showed that the relative velocity change is a delayed effect in the load scenario. While the correlation coefficient itself stabilizes quickly after less than 5 minutes, relative velocity change does not approach a constant value for 10-15 minutes. This shows, that in the case of analyzing a crack with CWI, measurements should not be taken right after the event was detected by acoustic emission, but rather after some time has passed and the system has stabilized. When comparing the CWI results to the strain measurement (bottom right Figure 4) one can see that these measurements were also detecting the trucks at position three

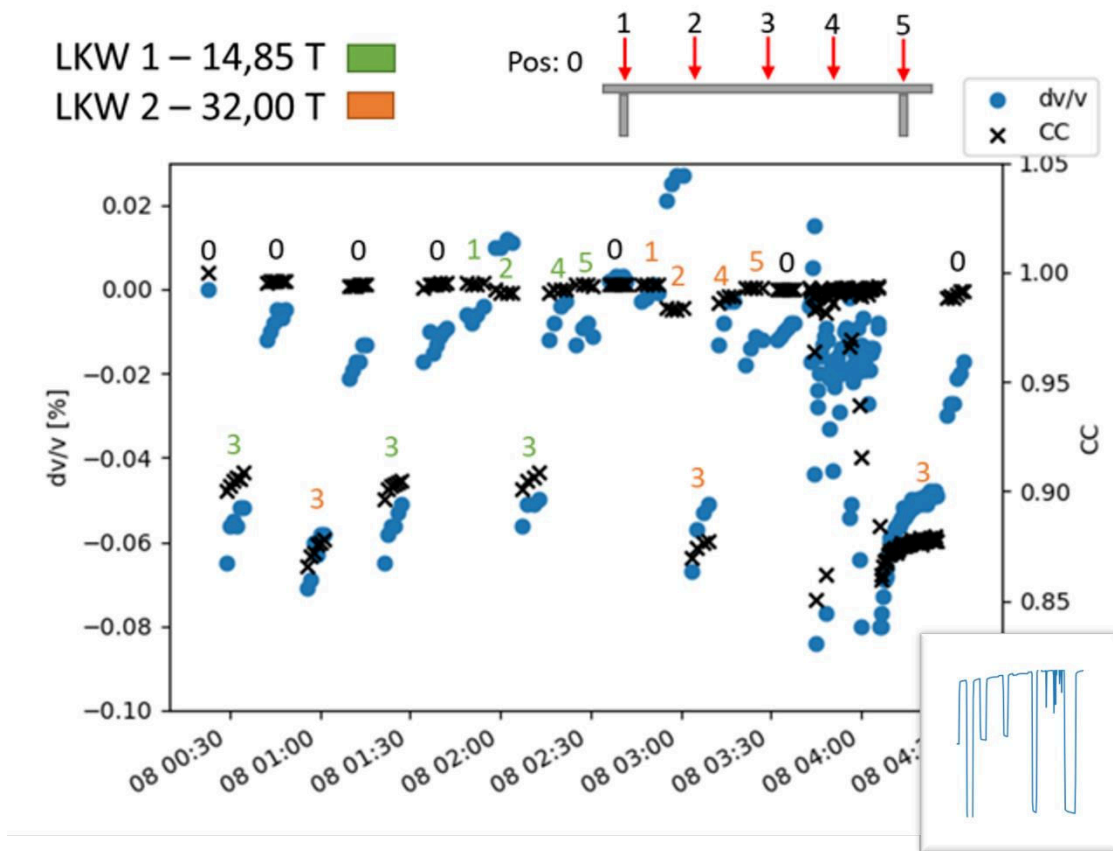


Figure 4: Analysing a single horizontal source-receiver combination (CC and dv/v) for the duration of the load test shows the influence of the two different loads (orange and green) at the different positions. The used source-receiver combination is right below position three in the center of the bridge. Strain measurements from the time of the experiment show the influence of the trucks as well.

right above the strain sensor, as well as the truck driving across the bridge. Due to errors in the time stamps, it was not possible to distinguish the recordings during truck positions 1, 2, 4, and 5.

Figure 5 shows an areal analysis of the load experiment with the 32T truck standing at position 3. The areal map is calculated using an interpolation approach as described in [4] and shows the different influences of the weight on the array. While right below the truck, bending extension and crack opening cause velocity decrease, this transforms into velocity increase on the left side. This is following the layout of the tension ducts (Figure 5 top), which are splitting up in this part of the bridge resulting in different force distribution.

5 Conclusion

Transferring knowledge and methods developed in controlled lab environments to the real structure is the ultimate test of these methods. With this work being called ‘lessons learned’ we can take the results collected at the Gänstorbrücke back to the lab and continue studying coda

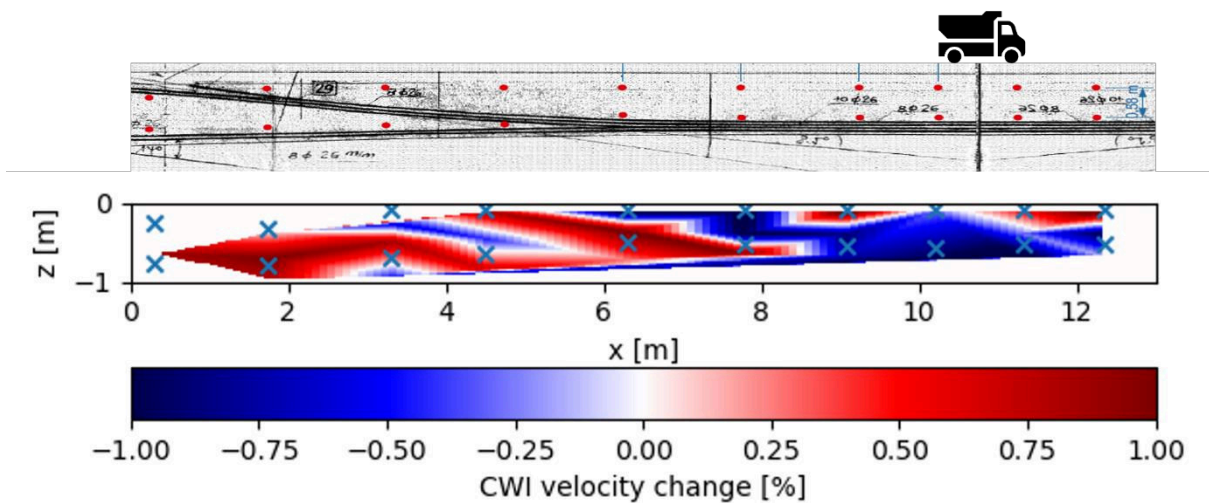


Figure 5: An areal analysis, using neighboring combinations and an interpolation approach gives a map of velocity change in the sensor network. While below the truck, velocity decreases, possibly due to crack opening, in the area to the left, the effect of the splitting tension ducts on stress distribution is visible

waves in concrete while keeping the data for applications of algorithms to be developed in the future. The key findings (or lessons) we take out of more than one year of bridge monitoring with coda waves are:

- CWI monitoring with a fixed reference can be done for more than one year if no irreversible damages are happening to the structure
- The main influence is temperature, which can mask small damages
- The difference in temperature response in cooling and heating phases can be further investigated to extract information about the structure from thermal expansion
- The system is sensitive to different loads and also reacts to influences outside the monitored area
- The relative velocity change is not stabilizing instantaneously when the load is changed
- Simple interpolation-based mapping techniques can give a good first areal impression before the application of advanced imaging methods

Besides the scientific conclusions from the experiment, we have shown that we can equip an in-service bridge with embedded sensors and simple measurement devices in addition to a commercial system without disturbing acoustic emission sensing. This shows that the CWI monitoring system can be used complementary to state-of-the-art commercial systems if we can extract useful additional information from the measurements.

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