Towards Monitoring of Concrete Structures with Embedded Ultrasound Sensors and Coda Waves – First Results of DFG for CoDA

Niklas Epple(✉), Daniel Fontoura Barroso(✉), and Ernst Niederleithinger(✉)
Bundesanstalt für Materialforschung und -prüfung (BAM), Berlin, Germany
niklas.epple@bam.de

Abstract. Due to the importance of reinforced concrete structures for modern society, damage assessment during the entire life-cycle of such structures has become a special interest in non-destructive testing. Using embedded ultrasound sensors in combination with other measurement methods, numerical modeling and self-made data collectors, tailored specifically for monitoring tasks, the German research group DFG FOR CoDA aims to investigate and develop novel methods for damage detection and rapid model updating in reinforced concrete structures. In the first stage of the project, besides the development of custom-built, low-cost data collectors, ultrasonic transducers are embedded in a large, reinforced concrete specimen on a BAM test site near Berlin. In this experiment, the influence of changing environmental conditions (mainly temperature) on the ultrasound signal is investigated using coda-wave interferometry. The results show a correlation between changes in temperature and ultrasonic velocity. Such changes must be taken into consideration in a long-term monitoring setup to distinguish between reversible and permanent changes. By correcting the data using a linear relation between concrete temperature and velocity change to remove the seasonal trends and by low-pass filtering the data to remove daily variations can remove most of the temperature influence on the ultrasound measurements.

Keywords: Ultrasound · Coda wave interferometry · Embedded sensors · Non-destructive testing · Structural health monitoring

1 Introduction

Concrete is one of the most used construction materials on earth. Its durability, compressive strength, and many more favorable attributes make it the perfect material for a wide range of applications. Especially in infrastructure, safety monitoring and damage assessment are crucial during the life-cycle of a concrete structure. Early damage detection helps to increase the lifetime of those structures, delaying expensive reconstruction. Some of the most used tools for
structural health assessment are Ultrasound (US) measurements. In recent years, a new technique called Coda Wave Interferometry (CWI) originally developed in seismology has been adapted in NDT for US data evaluation [1]. Unlike standard techniques based solely on the first arrival, it utilizes the entire waveform, especially the latter part of the recording, the so-called coda. This allows sensing of areas beyond the direct path and detection of small changes in the medium.

One of the major challenges with coda wave monitoring is the distinction between the influence of environmental variations and permanent damages on the measured signal, the localization of these damages, and the integration of these results into digital bridge models and static computations by architects and civil engineers. To solve these problems, the German research foundation has funded a research group uniting experts from Technical University Munich (TUM), Ruhr University Bochum (RUB), Bochum University of Applied Science (HSB) and the German Federal Institute for Materials Research and Testing (BAM). Combining Civil Engineering, Material Science, Nondestructive Testing, and wave propagation expertise, the group aims at characterizing damage indicators found in coda wave measurements, combined with a wide range of state of the art measurement techniques to assess and monitor reinforced concrete structures. In this paper, we will present the first results from BAM within this project. We will describe a large-scale experiment investigating the relationship between temperature and ultrasound velocity changes.

2 Theory of Coda Wave Interferometry

When measuring with ultrasonic waves in scattering media only a part of the energy is transmitted from source to receiver on the direct path. Cavities and material changes induce scattering, which results in significant parts of the signal arriving at the receiver after the first arrival. This scattering process, while looking like unwanted random noise, is actually highly repeatable and the signal does not change if material parameters and sensor coupling remain constant. The multiply scattered part of ultrasonic measurements is called coda. Coda waves have not only propagated on the direct path between source and receiver but sensed a wider area and spent more time in the medium. Therefore they are susceptible to subtle changes in a larger area. While classical first break picking would not show any changes, using Coda Wave Interferometry (CWI) small velocity changes can be detected.

The evaluation of velocity changes with CWI is described extensively in [1–4], and [5]. We refer to these publications for an exact mathematical description and will only describe the basic principles here. The calculation of velocity changes \((\Delta v/v)\) with CWI relies on the maximization of the correlation coefficient (CC) between a perturbed and unperturbed waveform on a time interval T. The unperturbed waveform is compared to either a time-shifted version of the perturbed signal (on a short time window) or a stretched version of large parts or the entire perturbed waveform. If the CC is close to a value of one, the signals are considered to be similar or almost identical. The time shift \((\Delta t/t)\) or stretching...
factor ($\alpha$) resulting in a CC closest to one can then be linked to a velocity change ($dt/t = -dv/v$ or $\alpha = -dv/v$). In this work, we will use this stretching technique (see [2]) for the entire recording. The reference measurement (unperturbed signal) is kept fixed for the entire experiment, so the results can be directly linked to the zero state. A computationally more expensive technique proposed in [6] using shifting references has not been applied for the experiments presented in this paper but might be used in the future for permanent monitoring of structures. The resulting quantities of CWI are the correlation coefficient on the one hand and the relative velocity change (in percent) on the other hand. Most of the evaluation is based on velocity changes.

3 Experiments

3.1 US Sensors for Embedding into Concrete

In previous research at BAM, piezoelectric ultrasonic transducers - designed for embedding into concrete - have been developed in cooperation with Acoustic Control Systems, Ltd. (ACS, Moscow, Russia). Unlike externally attached sensors, these transducers have an almost omnidirectional radiation pattern in concrete at a center frequency of 60 kHz. At this frequency, relatively large distances between source and receiver can be covered at a good resolution. Their ability to act as both source and receiver makes them a perfect tool for long term monitoring. A detailed description of the sensors can be found in [7].

3.2 “All Inclusive” Specimen

When monitoring large scale reinforced concrete structures, environmental changes influence the ultrasound signal just as damages do. It is known that temperature [8] and moisture [9] are influencing the wave propagation. When performing a long-term monitoring experiment outside the lab, these factors need to be considered to not accidentally misinterpret a sudden drop in temperature as a damaging event. For the evaluation of the influence of environmental aspects on the specimen, particularly on the coda waves, we have equipped an over ten-year-old specimen at BAM TTS Horstwalde south of Berlin with 19 ultrasound sensors and 5 temperature sensors. All sensors were embedded in boreholes in mid-October 2019. The 19 US sensors are installed at a depth of 40 cm. The temperature sensors (NTC Thermistors) are installed directly below sensors 10, 12, 15, 17 and 19. The sensor layout is depicted in Fig. 2. The temperature sensors are calibrated for a temperature range of $-10^\circ$C to $35^\circ$C and provide precise measurements in this range. Therefore, they are perfectly suited for monitoring subtle temperature changes induced by daily and seasonal temperature variations. After mounting the sensors, the boreholes were refilled with grout. The specimen is covered by a tarp to minimize the influence of moisture on the signal and thus allows the determination solely of the temperature dependencies. Solely for the purpose of temperature monitoring a smaller amount of
sensors would have sufficed, but as the specimen is supposed to be used for damage localization in a future experiment we decided to equip it with a full sensor network right away.

In mid-November 2019 a data acquisition device similar to the one used in [10] was installed for hourly measurements of all 342 Sensor combinations. The measurements are set to run for at least one year without any loading or destruction so that a yearly cycle of environmental variations can be investigated.
We record 10000 samples per measurement at an acquisition speed of 2 MHz. All data is uploaded to an online database accessible for all members of the research group hourly.

4 Results

All ultrasound measurements are preprocessed before CWI velocity change calculations. This includes the removal of any offset, the suppression of crosstalk at the beginning of the signal, bandpass filtering between 10 kHz and 100 kHz for the suppression of low- and high-frequency noise and the removal of the pretrigger samples.

4.1 Large Scale Model “All Inclusive”

The measurements at the All-Inclusive specimen at BAM TTS Horstwalde started on Nov. 15 2019. In this work, we present the measurement results until the end of May 2020. Unfortunately, there were several power blackouts at the measuring station during this period. While this would have been a minor problem with the new data collection device developed within the research group [11] and [12], which restarts automatically and continues the measurements, the Laptop and NI system need to be restarted manually. Unfortunately, either Christmas holidays or the COVID 19 pandemic prevented a quick restart so several days of data are missing (see Fig. 3(a), January 2020). A comparison of the temperature measurements within the specimen with data recorded by a station operated by the German weather service (DWD) in the village of Baruth (≈ 8 km away from the specimen location) showed the necessity of interior temperature measurements. While large outside temperature changes are recognized within

![Fig. 3.](image)

Fig. 3. (Negative CWI Velocity change (blue) and concrete temperature change (orange) from November to the end of May (a) and for April (b), recorded in the center of the specimen.)
the specimen with some delay, small fluctuations do not diffuse inside the concrete. As we want to investigate the influence of temperature on the ultrasound signal, an analysis solely based on environmental temperatures would be certain to produce meaningless results.

To investigate this temperature dependency, we compare the temperature measurements within the specimen with the CWI velocity change calculated with a fixed reference for a period from November 2019 to the end of May 2020 and all 342 source-receiver combinations. An analysis of the measurements for sensor combinations with long distances (> 1 m) shows a decrease of correlation caused by noise. Furthermore, some sensors seem to have coupling problems, causing energy loss when they are used as sources. Embedding sensors in an existing structure most likely increases the number of sensors with bad coupling, as proper bonding of new and old cement paste can not be entirely ensured. Figures 3(a) and 3(b) show the negative velocity change compared to the temperature for US Transducer combination ‘S11-R9’ and temperature sensor ‘T1’. The numbers correspond to the numbers in Fig. 2. The sensors are located in the middle of the specimen to reduce the influence of boundary reflections. The authors chose to display the negative velocity change to transform the indirect proportionality between temperature change and velocity change into a direct proportionality. The changes in velocity and temperature have a similar trend. Especially after the long blackout in the beginning of January, both graphs show a stunning accordance. In the zoomed plot Fig. 3(b) from April’s data the daily variations in a day-night cycle are visible in concrete temperature and velocity change. The apparent discrepancies for the early measurements in November and December were first interpreted as an instrument drift but as it is not continuing in the later measurements we attribute it to the continuous drying of the mortar used for refilling the boreholes. A general decrease in correlation until early January supports this hypothesis.

The similarity of the temperature and velocity curves, especially from January onwards indicates a linear relationship between temperature and Ultrasound velocity change. Figure 4(a) shows the negative velocity change plotted over the temperature change for the data from January to the end of May. The general linear trend is obvious, but linear regression analysis for limited measurement periods in either cold or warm concrete results in a slightly different gradient compared to the regression for the entire data. An analysis of this gradient for all source-receiver combinations with acceptable signals shows a rate of velocity change between 0.03%K$^{-1}$ and 0.05%K$^{-1}$ with some outliers. Generally, a linear trend of decreasing velocity with increasing temperature is visible in the data, but needs to be analyzed over a long time to get a stable estimation of the gradient.

As in an infrastructure monitoring tasks, temperature-induced differences are not of interest, since they are rarely resulting in permanent changes or damages, we want to remove those effects from the recorded data. With the gradient calculated by linear regression analysis, the long term trends can be removed (Fig. 5(a), blue curve). Comparing the original, uncorrected, data to the corrected
Fig. 4. (a) Linear relation between concrete temperature and negative velocity change for the same sensor pair used in Fig. 3. Gradients are calculated for different periods. (b) The gradient of the linear relation for all source-receiver pairs with acceptable signal quality for the warm, cold, and the entire period.

curve, the seasonal differences between winter and spring/summer are mostly eliminated, while the low-frequency daily variations remain in the data. The coda signal used for this analysis senses a larger area, not only the direct path between source and receiver. Therefore, an analysis of the coda will contain information from the near-surface areas just like it contains information from the center. The temperature measurements, however, are taken in the center of the specimen only. Therefore, rapid daily variations affect the ultrasound signal stronger than the core temperature. This can be observed in Fig. 3(b). The temperature peaks and troughs are slightly delayed compared to the US results. This behavior is dependent on the position of sensors and the dimensions of the specimen. Therefore, to generalize monitoring for various geometries and setups, these influences should be removed just like the seasonal variations. As the negative CWI velocity change is a time series, a frequency analysis can help with this problem (Fig. 5(b)). This plot shows the frequency content of the velocity changes from January to May 2020. As a Fourier analysis requires equally spaced data, the data missing due to power outages was linearly interpolated. Besides the low-frequency variations with way less than one cycle per day, one can see peaks at one, two, and three cycles per day (cpd). While the one cpd peak is indicating the daily temperature variations, the higher frequency peaks are more difficult to interpret. They may be related to differences in heating and cooling rate for example, but need to be investigated more thoroughly in the future. As these variations are cyclic, they are not permanent. So for damage detection, we can remove them from the data by low-pass filtering. For filtering we used a fourth-order Butterworth low-pass filter with a cutoff frequency of 10 days. The data needed to be interpolated in the intervals the measurement system was malfunctioning. Therefore, we refrained from using higher cutoff frequencies, as we did not want to imply we have reliable information on cyclic behavior for this
interpolated timespan. The filtered velocity change (black curve in Fig. 5(a)) still has some variations of approximately 0.1%, but the frequent daily variations are removed.

![Figure 5(a): Negative velocity change from January to May as original data (orange), after removal of the linear temperature and velocity relation (blue) and after low pass filtering the corrected signal (black).](image1)

![Figure 5(b): Frequency content of the velocity change from January to May.](image2)

**Fig. 5.** (a) Negative velocity change from January to May as original data (orange), after removal of the linear temperature and velocity relation (blue) and after low pass filtering the corrected signal (black). (b) Frequency content of the velocity change from January to May.

## 5 Discussion and Outlook

The influence of temperature change on long term ultrasound measurements has been demonstrated. In the data we can see a decrease of velocity with an increase in temperature. This is expected, as material densities decrease with increasing temperature, and therefore, the wavespeed decreases. In the first months of measurement in the presented experiments, we assume that solidification of the mortar used for refilling the boreholes influenced the results. Therefore, when installing sensors in existing structures we propose to analyze the results of the first three months with caution, but further analysis of this topic is necessary.

We calculated a rate of velocity change between 0.03%K$^{-1}$ and 0.05%K$^{-1}$. This is in good agreement with Niederleithinger and Wunderlich [8] who calculated a rate of change of 0.05%K$^{-1}$ in a temperature range between 0°C and 50°C in laboratory experiments. Earlier investigations - all with external sensors - have given values of 0.16%K$^{-1}$ [1] and 0.33%K$^{-1}$ [13]. Especially the last result was calculated for measurements with higher temperatures where material changes cannot be excluded.

Using the linear relation between velocity change and temperature change can remove the seasonal variations, while short therm fluctuations remain. Ultrasound measurements using coda waves are affected by changes not only on the direct path between source and receiver. Temperature changes - when measured in the core of the specimen - are less sensitive to daily variations compared to the CWI results, as the temperature change requires time to diffuse into the core
of the specimen. This is supported by the data presented in this experiment. For monitoring and damage detection in infrastructure, we want to remove those high-frequency daily variations from the data just like the low-frequency seasonal variations. This is achieved by a frequency analysis followed by lowpass filtering of the data. The resulting smoothed curve still indicates some long term variations, but the velocity change is on a corridor below 0.1% change. With this smoothed curve, reduced from most environmental effects, the detectability of permanent damaging events should be increased. With the dense sensor network in the presented specimen, this hypothesis will be tested in a future experiment after a full annual cycle has been recorded with the present setup. Furthermore, the remaining small changes will be investigated in the future work of the research group to eliminate as many uncertainties as possible on the way towards ultrasound monitoring of reinforced concrete structures.

Acknowledgements. We would like to thank the German Research Foundation (DFG) for funding project FOR 2825. Furthermore, we would like to thank all project partners from TU Munich, Rhur University Bochum, and Bochum University of Applied Sciences.

References

1. Planès, T., Larose, E.: A review of ultrasonic coda wave interferometry in concrete. Cement Concrete Res. 53, 248–255 (2013)
2. Lobkis, O.I., Weaver, R.L.: Coda-wave interferometry in finite solids: recovery of p-to-s conversion rates in an elastodynamic billiard. Phys. Rev. Lett. 90(25), 4 (2003)
3. Poupinet, G., Ellsworth, W.L., Frechet, J.: Monitoring velocity variations in the crust using earthquake doublets: an application to the calaveras fault, California. J. Geophys. Res.: Solid Earth 89(B7), 5719–5731 (1984)
4. Roberts, P.: Development of the active doublet method for monitoring small changes in crustal properties. Seismol. Res. Lett 62(1), 36–37 (1991)
5. Snieder, R., Grêt, A., Douma, H., Scales, J.: Coda wave interferometry for estimating nonlinear behavior in seismic velocity. Science 295(5563), 2253–2255 (2002)
6. Niederleithinger, E., Wang, X., Herbrand, M., Müller, M.: Processing ultrasonic data by coda wave interferometry to monitor load tests of concrete beams. Sensors (Basel, Switzerland) 18(6) (2018)
7. Niederleithinger, E., Wolf, J., Mielentz, F., Wiggenhauser, H., Pirskawetz, S.: Embedded ultrasonic transducers for active and passive concrete monitoring. Sensors (Switzerland) 15(5), 9756–9772 (2015)
8. Niederleithinger, E., Wunderlich, C.: Influence of small temperature variations on the ultrasonic velocity in concrete. In: AIP Conference Proceedings, vol. 1511, pp. 390–397 (2013)
9. Ohdaira, E., Masuzawa, N.: Water content and its effect on ultrasound propagation in concrete - the possibility of NDE. Ultrasonics 38(1), 546–552 (2000)
10. Wang, X., Chakraborty, J., Bassil, A., Niederleithinger, E.: Detection of multiple cracks in four-point bending tests using the coda wave interferometry method. Sensors (Switzerland) 20(7), 1986 (2020)
11. Barroso Fontoura, D., Epple, N., Niederleithinger, E.: Portable Low-Cost Ultrasound Measurement Device for Concrete Monitoring. Manuscript in preparation (2020)

12. Knopp, F., Mielentz, F., Bernstein, T.: Ultraschall-messsystem für die langzeitüberwachung von betonkonstruktionen. In: DGZfP Jahrestagung 2019. Friedrichshafen, Germany (2019). https://www.ndt.net/article/dgzfp2019/papers/P11.pdf

13. Niederleithinger, E.: Seismic methods applied to ultrasonic testing in civil engineering. Habilitationsschrift, Rheinisch-Westfälische Technische Hochschule Aachen, Aachen (2017)