Interdisciplinary Research on the Application of New Ultrasonic Methods for Improved Structural Health Monitoring

Concept, Objectives and First Results of the DFG FOR 2825 Research Unit Applied to the Monitoring of the Gänstor Bridge

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Abstract Monitoring and assessing infrastructure health are prerequisites for efficient maintenance. New technologies and methods enable deeper insights and thus offer improved information for decision makers. The development of such new methods for application requires holistic understanding not only of the method itself, but also of the specific challenges arising when dealing with reinforced concrete structures.

The research group DFG FOR 2825 'Concrete Damage Assessment by Coda Waves (CoDA)', funded by the German Research Foundation investigates the application of a novel ultrasonic based method for the monitoring of reinforced concrete structures [1]. The novelty relies in the use of Coda Wave Interferometry methods, originally developed in the field of geophysics. Therefore, closely linked interdisciplinary research is conducted including laboratory experiments at the specimen (nm - cm) and structural (cm - m) scale, numerical modelling, as well as investigations on real structures. The research is conducted within six subprojects at the Technical University of Munich (TUM), the

German Federal Research Institute for Material Science and Testing (BAM), the Ruhr University Bochum (RUB), and the Bochum University of Applied Science (BU).

Within this contribution, the concept and objectives of the research group are presented. Thereby, it is particularly focused on how complementary competencies and objectives of the individual subprojects create synergies for achieving the overall goals of the project. The Gänstor Bridge, a prestressed concrete bridge passing Danube River is currently monitored by the research unit. The discussion includes selected results from research activities derived in the completed first (2019-2022) and ongoing second (2022-2025) funding period.

1 Motivation and overarching goal

1.1 Challenges in current structural health monitoring

The monitoring of existing reinforced concrete (RC) structures to ensure safe operation is an inherent part of civil engineering activities. Manual inspection, as specified in standards such as DIN 1076 [2], remains the central component of the assessment. However, precise manual inspections are not always possible due to the specifications of the structure and are limited to discontinuous inspections of accessible sections. Ageing infrastructure in increasingly poor condition [3] places pressure on surveillance of central infrastructure assets. This is driving the development of supplementary methods and digitalization of monitoring processes and is successively being incorporated into relevant standards [4, 5].

The research unit FOR 2825 *Concrete Damage Assessment by Coda Waves* (CoDA) [1] funded by the German Research Foundation (DFG) aims to contribute to further development of structural health monitoring into a digital and continuous process. Therefore, a concept for the evaluation of ultrasonic data based on so called Coda Wave Interferometry is investigated. The Gänstor Bridge over the Danube, one of the oldest prestressed concrete bridges built in the 1950s, is publicly known to be damaged [6] and is used as a test structure for the research unit.

1.2 In search of new paths: Learning from geophysics

Ultrasonic transmission measurements are well established for various purposes in civil engineering [7, 8]. The methods thereby mostly rely on the evaluation of the direct wave, which travels along the shortest path between sender and receiver. The rear part of the signal, which contains superimposed information from (multiple) scattered waves, is thereby neglected. In geophysics, which deals with heterogeneous mineral materials very similar to concrete, the term coda is used to refer to this part of a seismic signal [9]. The scattered waves pass through the material extensively, the coda is therefore more sensitive to material changes than the direct wave. It was geophysicists who first introduced a method which not only includes but uses the coda for evaluation of changes in heterogeneous material: *Coda Wave Interferometry* (CWI) [10].

In CWI two ultrasound waves recorded at different times (signal $\tilde{u}$ and reference u) are compared using a correlation coefficient CC. Using the stretching technique [11, 12], the signal is stretched or compressed so that the correlation coefficient between signal and reference (Equation 1) is maximized. The stretching factor ε corresponds to the relative velocity change. If the relative velocity change is unequal to zero, the signal, and consequently the material under investigation, has changed. Negative values indicate deceleration of wave propagation (e.g., due to cracking). The associated correlation coefficient provides information on how well the change in the waveform is explained by pure stretching or compression.

$$CC(\varepsilon) = \frac{\int_{t_1}^{t_2} u(t)\tilde{u}(t(1-\varepsilon))\, dt}{\sqrt{\int_{t_1}^{t_2} u^2(t)\, dt \int_{t_1}^{t_2} \tilde{u}^2(t(1-\varepsilon))\, dt}} \tag{1}$$

A review of first applications of CWI-based methods to concrete was compiled by Planès and Larose [13]. However, links between physical material changes and the changes in the coda part of the ultrasonic signal are still lacking. Furthermore, reliable tests demonstrating the method's ability to monitor real structures have not yet been published.

1.3 Goal of the research unit

The investigations of the research unit CoDA aim at the application of CWI-based methods for the long-term monitoring of RC structures. The overall project objective is to further develop the evaluation methods of CWI for structural health monitoring and to enable the interpretation of the corresponding results in the context of civil engineering.

2 Research program

For application of CWI methods for monitoring of RC structures, material-specific questions, as well as structural considerations need to be answered. Thereby, load-response relationships at the laboratory scale serve as input information for data interpretation from real structures. Laboratory and field experiments are required to explore these relationships, but often limited due to high financial or personnel costs or the lack of appropriate methods. Computational methods can be used to develop suitable models that allow simulations that overcome the shortcomings of real experiments. The research unit CoDA therefore combines experiments and simulations at three different observation scales:

At the *specimen scale* (< 1 m) the response of the CWI parameters (*correlation coefficient and relative velocity change*) to different mechanical and environmental loads are characterized. The basic research carried out at this scale aims to link applied loads and changes in the CWI parameters with alterations in the concrete microstructure. Questions of failure mechanisms and the fundamental characterization of ultrasound propagation in concrete are addressed by means of models and simulations.

The next level of observation is the *structural scale* (1 - 20 m). Here, laboratory experiments are carried out using reinforced and prestressed concrete specimens with dimensions of real structures. Relationships between loads and changes in the CWI parameters are established and issues regarding the detection of reinforcement failure are investigated. Experimental results and models generated at the specimen scale are applied. The transferability of the results is ensured by using the same raw materials to produce specimens at the specimen and structural scale. The analysis also includes damage localization based solely on experimental data or simulations, or on a combination of both.

At the largest scale, *real structures* (> 20 m) are investigated. Two structures located in Germany are monitored by the research unit: the Gänstor Bridge connecting Ulm and Neu-Ulm and the subway station Scheidplatz in Munich. In addition to continuous data collection for long-term monitoring, customized load tests are also carried out. Large scale models are being developed to enable damage localization through simulations.

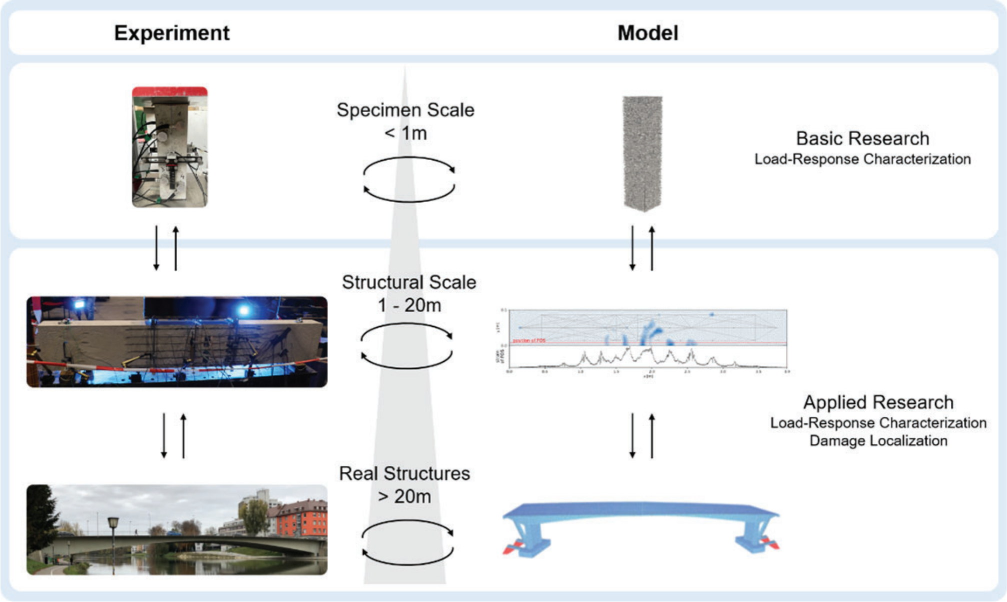

Figure 1: Schematic representation of the interaction between experiments and model-based simulations across the investigated scales.

2.1 Measurement technology

Standardized measurement technology ensures transparency and transferability of analysis techniques and results within the research unit. The ultrasound transducer and the data acquisition equipment were selected based on previous work and continuous developments at the German Federal Research Institute for Material Science and Testing (BAM) (see Section 3.5).

All experimental work is carried out with a custom ultrasonic sensor with a center frequency of 60 kHz (Figure 2) [14]. The sensor can act as a sender and receiver, which is why the term ultrasonic transducer is adopted within the project. The transducer was designed for embedding in concrete so that ideal coupling with the material is achieved.

Ultrasonic signals are currently recorded using either a system assembled from commercial components (sampling rate 2 MHz) or a Raspberry Pi-based system (sampling rate of 1 MHz), both developed at BAM [15]. A customized software for the control of the systems enables the standardized, direct upload of the recorded data into the cloud-based data bank.

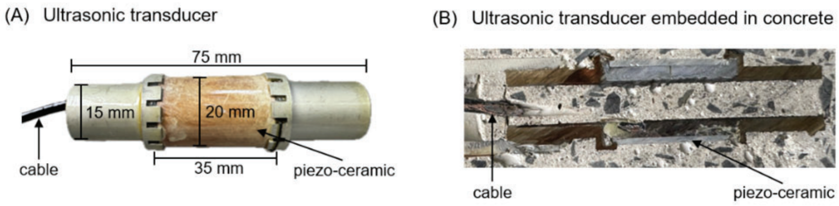

Figure 2: Ultrasonic transducer with a center frequency of 60 kHz (ACSYS S0807). (A) Image of an ultrasonic transducer before embedding. (B) Image of a cross-section showing an ultrasonic transducer embedded in concrete.

2.2 Cloud-based approach for data exchange

Fast and efficient data exchange is essential for the closely linked research program of experiments and simulations. Therefore, a cloud-based system for data storage and documentation has been developed and implemented, consisting of a SQL database (mysql), a webserver and file storage. Sensors are unambiguously identified with their type (e.g., embedded ultrasonic sensor, temperature, humidity, strain, load) and location within the specimen or structure, assigned to a project (freely defined) and the principal investigator for the experiment. In addition to the ultrasonic signals, additional sensors can be defined and their data uploaded utilizing the JSON format or directly accessing the SQL interface of the database. Safe quasi real-time or subsequent upload of experimental data can be implemented by each sub-project for their individual experimental situation. Figure 3 schematically shows the exchange of data collected experimentally or computationally via the cloud-based database.

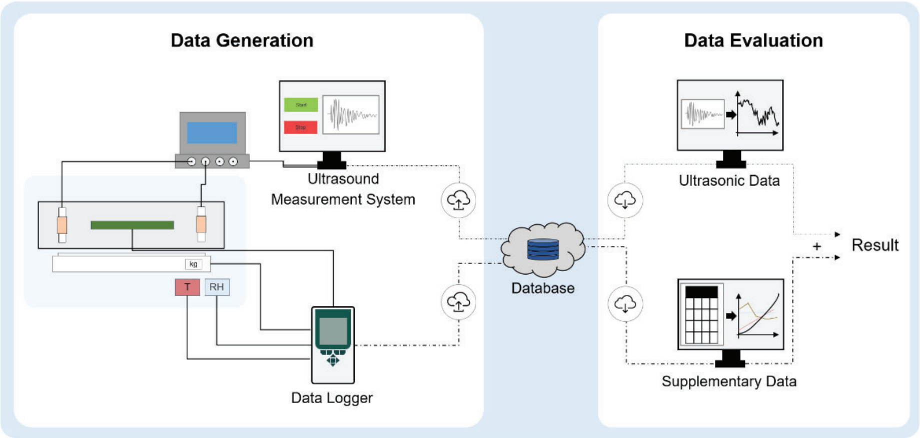

Figure 3: Schematic representation of data generation, storage and exchange within the research unit CoDA. Usage of the common database enables remote access and almost real time evaluation of collected data.

3 Structure of the research group: objectives of the individual sub-projects

Within the research unit CoDA experts in the disciplines of non-destructive testing, signal analysis, construction materials and numerical modelling combine their knowledge and competencies.

Individual aspects of the research program are allocated to six sub-projects at four institutes distributed throughout Germany: One sub-project is located at the German Federal Research Institute for Material Science and Testing in Berlin (BAM) within the division Non-Destructive Testing Methods for Civil-Engineering. Three sub-projects are situated in Bochum, two at the Ruhr-University Bochum (RUB) at the Institute for Structural Mechanics (RUB1) and at the Institute of Concrete Structures (RUB2), and one at the Department of Reservoir Geophysics at the Bochum University of Applied Science (BU). The research unit is further complemented by two sub-projects at the Technical University of Munich (TUM), one at the Chair of Materials Science and Testing (TUM1) and one at the Chair of Structural Analysis (TUM2).

The topics of the sub-projects mainly involve either experiments or modeling and simulations at a single observation scale. Some sub-projects also work at different scales, whereby results from the smaller scale are usually transferred to the larger scale. Close exchange between the individual sub-projects, especially between experimental researchers and modeling experts, is achieved through regular meetings in small groups and at the overall project level.

An overview of the locations and topics of the sub-projects is given in Figure 4. The topics and objectives of the individual sub-projects are described individually in the following sections.

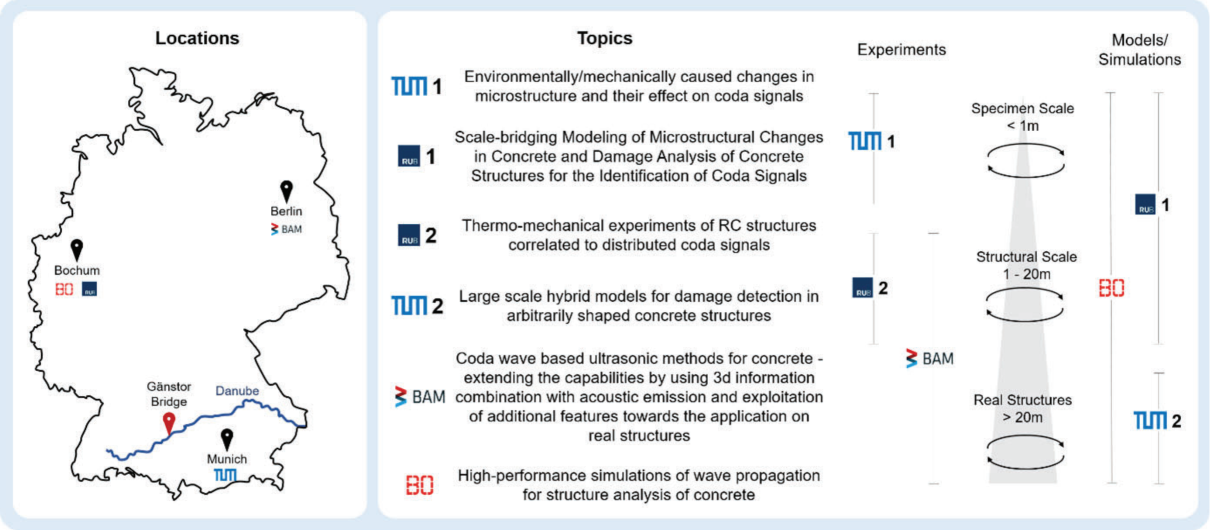

Figure 4: Overview of the six sub-projects forming the research unit CoDA.

3.1 Environmentally/mechanically caused changes in microstructure and their effect on coda signals (TUM1)

The objective of TUM1 is the qualitative and quantitative characterization of load-response relationships between mechanical and environmental loads as well as concrete specific phenomena and the parameters obtained through CWI analysis. Three objectives are addressed in the investigations:

Using closely controllable one-dimensional experiments calibration curves and concrete-specific parameters are obtained to enable calibration and signal compensation of structural scale experiments and real structures. Calibration curves for mechanical loads such as uniaxial compressive and tensile strength are determined. Further, the effect of temperature and moisture changes is quantified to compensate for fluctuating environmental conditions.

The second focus of this project is the investigation of long-term processes influencing the durability of concrete structures. Typical concrete phenomena, e.g., carbonation and frost attack, are analyzed by means of experiments using standardized testing procedures and CWI-based monitoring. These investigations are intended to add a time-dependent, material-specific component for the application of CWI-based methods for long-term monitoring.

Furthermore, the activities of this project cover characterization of microstructural changes in concrete. The loads applied in the experiments induce alterations in the material microstructure, e.g., microcracking or porosity alteration, that lead to changes of the material properties. The experiments performed elucidate the relationship between load, microstructure and CWI parameters. In addition, the results are used as input for material modeling and simulations conducted by other sub-projects.

3.2 Scale-Bridging Modeling of Microstructural Changes in Concrete and Damage analysis of Concrete Structures for damage Identification based on Coda Signals (RUB1)

The research sub-project RUB1 is focused on the early detection of damage in concrete structures using advanced computational modeling. To this end, a virtual mechanical-thermo-ultrasonic laboratory is developed.

In a first step, a classifier is created to identify various stages of microstructural damage, such as reversible deformation, microcracking, and microcrack coalescence, using synthetic ultrasonic signals. Subsequently, the methodology is expanded from the specimen scale to the structural scale, with careful consideration of environmental factors like temperature fluctuations and moisture changes. The feasibility of applying damage classifiers, originally developed at the material scale, to larger structural contexts is being actively explored. This includes a thorough examination of various factors, such as the impact of structural geometry, the ability to distinguish between environmental and load-induced damage, and the effect of transducer-receiver placement on detection accuracy. Additionally, given that concrete with a high microcrack density is generally more sensitive to temperature changes, the potential to quantify damage levels based on the sensitivity of ultrasonic signal variations to temperature fluctuations is also under investigation.

3.3 Thermo-mechanical experiments of RC structures correlated to distributed coda signals (RUB2)

The RUB2 sub-project is situated at the structural scale within the research unit CoDA. The project aims at fieldwise processing and correlation of thermomechanical variables, including stresses, strains, crack patterns and widths, as well as temperatures, in conjunction with ultrasonic results obtained by Coda Wave Interferometry. To this end, large-scale tests on reinforced and prestressed concrete structures are carried out.

The development of an ultrasound-based method for the early detection of tendon breaks in prestressed concrete bridges represents a key objective of the sub-project. It is documented that corrosion-related damage to tendons has also occurred on the Gänstor Bridge [6]. The progressive deterioration of tendons up to the subsequent tendon break is emulated in tests on loaded and unloaded prestressed concrete beams under laboratory conditions, accompanied by measurements with embedded ultrasonic transducers. First results on tendon break detection were published recently [16]. The sub-project also addresses the issue of cracking in concrete structures. Cracks are an inherent and necessary consequence of the load-bearing behaviour of reinforced concrete, but excessive crack widths can compromise durability and structural safety. Consequently, the ultrasound-based determination of crack widths in concrete structures is being investigated. Strain measurements with fibre-optic sensors and strain gauges, as well as digital image correlation, are used as reference measurement techniques in the sub-project's experiments.

3.4 Large scale hybrid models for damage detection in arbitrarily shaped concrete structures (TUM 2)

As a contribution to permanent, robust, non-destructive monitoring, TUM2 develops methods to detect damages with coda wave interferometry and an inverse problem. The approach is to have a model that can describe the highly complex behavior of the scattered ultrasound in concrete. The developed model can then be utilized for an inverse problem that identifies a change of input parameters from the measurements. Due to a preprocessing of the signals, the identified parameters are assumed to be new scatterers that come from cracks.

Such a framework that relates measurement from reality to numerical simulations is commonly referred to as digital twin (DT). TUM2 is working on a framework to extend the DT to different measurement technologies that are all included in one digital model. This comprehensive approach, which bridges the gap between model and reality and combines various measurement technologies, is crucial for accurately assessing the current condition of structures and deriving reliable forecasts for the future. For permanent structural health monitoring one possible application is determining thresholds for the various measurement systems from calculations on the structural model and individual test loads.

3.5 Coda wave based ultrasonic methods for concrete - extending the capabilities by using 3D information combination with acoustic emission and exploitation of additional features towards the application on real structures (BAM)

To start with, BAM provides necessary tools to the other groups of the project. The ultrasonic transducers exclusively developed for BAM have been made available as well as a newly developed low-cost data acquisition unit, storing data directly in the joint cloud database (section 2.3). BAM also provided code for data evaluation. Furthermore, BAM is focused on reducing the effect of environmental influences and improving the imaging of damages based on sensitivity kernel calculated by simulations. In addition, BAM is working on extracting higher order, more sensitive and specific features, making use on the natural temperature changes which have a different effect on sound and cracked concrete. Moreover, BAM is now combining active ultrasonic monitoring with passive acoustic emission measurements, performed using the same transducers and a single acquisition device.

To demonstrate the findings of the research unit, BAM has instrumented and is monitoring two real structures. First, in September 2020, several transducers have been installed at the Gänstor Bridge (see section 4) over the river Danube between Ulm and Neu-Ulm. Some were installed at a tension element at the northern end of the bridge (funded by DFG FG 2825 CoDA phase 1) and some in the center of one of the main girders (funded by BASt/German Federal Road Research Institute). The monitoring will continue until the demolition of the bridge, scheduled for end of 2024. Second, the metro station "Scheidplatz" was instrumented in 2022 by BAM in cooperation with TUM1, TUM2 and RUB2. By monitoring the concrete structure continuously with high time resolution, BAM was able to observe the recovery rate and behavior of the structure following the load induced by the passage of a tram above the metro station. To explore it in depth, a load test (within the allowable service load limits) will be performed in fall 2024.

3.6 High-performance simulations of wave propagation for structure analysis of concrete (BU)

Concrete is a strongly heterogeneous and densely packed composite material. Due to the high density of scattering constituents and inclusions, ultrasonic wave propagation in this material consists of a complex mixture of multiple scattering, mode conversion and diffusive energy transport. For a better understanding of the effect of aggregates, porosity, and of crack distribution on elastic wave propagation in concrete and to optimize inverse techniques it is useful to simulate the wave propagation and scattering process explicitly in the time domain. For this purpose, BU uses the Rotated Staggered Grid (RSG) finite-difference technique [17] for solving the wave equations for elastic, anisotropic, and/or viscoelastic media.

4 First results applied for monitoring of the Gänstor Bridge

4.1 Description of the structure and measurement setup

The Gänstor Bridge is one of only three bridges connecting the cities of Ulm and Neu-Ulm in Germany, traversing the river Danube. The 96 m bridge was constructed in 1950 as one of the first prestressed concrete bridges, after World War II, in 1950. Since damage has been detected in the form of corrosion and subsequent wire breaks, the bridge is currently monitored with acoustic emission and strain sensors until its dismantled and rebuilt.

In 2020, the bridge was equipped with 30 ultrasonic transducers, 10 of them at a tension element on the northern edge of the bridge. 20 transducers are located in the center of the westernmost girder of the bridge to perform active ultrasonic measurements in a part of the structure where tension is highest and cracks can be observed. Within Figure 5, the array of 20 transducers is illustrated schematically. Monitoring is performed since December 2021. Automated data upload to the database as illustrated in Figure 3 enables remote management and ongoing evaluation of the collected data. Since installation, data is collected continuously with only short interruptions due to power failures or communication breakdowns.

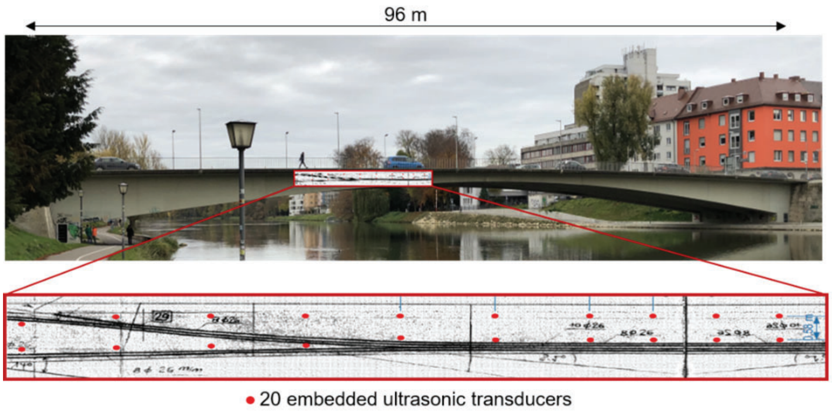

Figure 5: Photo of the 96 m long Gänstor Bridge connecting Ulm and Neu-Ulm. The location of the 20 ultrasonic transducers, embedded in the central part, is schematically indicated in reference to original design drawings showing the location of the tendon ducts. Illustration following [18].

4.2 Learnings from continuous monitoring and customized load tests

4.3 Continuous Monitoring

Initial CWI evaluations of long-term ultrasonic data from the monitoring of the Gänstor Bridge initially published by Epple et al. [18] show the strong dependence of the CWI parameters on fluctuations in ambient temperature. Within Figure 6 (B) the relative velocity change is illustrated over time together with the ambient temperature and results from strain measurements for the period of one month. It is visible that the relative velocity change is correlated with the temperature change. A modified representation of the same data with relative velocity change as a function of temperature in Figure 6 (C) indicates a linear relationship between the values.

The observations are in good agreement with the findings of Diewald et al. [19] who characterized the relationship between relative velocity change and temperature at the specimen scale. Their results reveal a linear relationship between temperature and relative velocity change as shown in Figure 6 (A). The ultrasonic velocity is found to decrease with increasing temperature as it is indicated by the negative sign of the percentual change, both in the results at the specimen scale and at the structural scale. The relationship is found with similar magnitudes with around 0.04 %/°C for the specimen scale experiment and around 0.025 %/°C for the real structure.

These results emphasize that calibration of measurements from real structures can be achieved using additional laboratory experiments. An important aspect here is the composition of the material, which plays a decisive role in the specific value of the dependency. A first step to include the the information about the material micro- and mesostructure into consideration was made by Holla et al. [20] and Vu et al. [21, 22] who developed and adopted a multi-scale material model for the material mix used at the specimen scale. The model has then been used to study the sensitivity of the CWI-based monitoring method with regard to material damage by using ultrasonic wave propagation simulations [23].

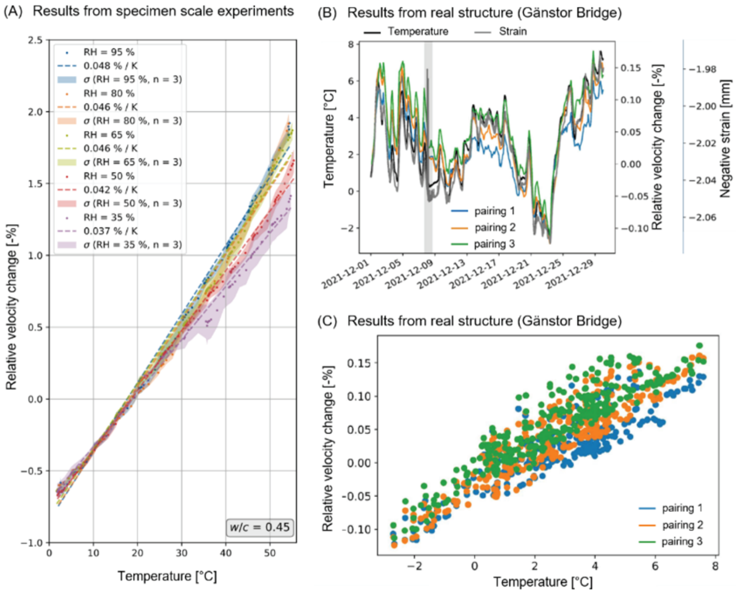

Figure 6: Relationship between relative velocity change and temperature obtained by CWI-analysis of ultrasonic signals (A) from specimen scale laboratory experiments [19] and (B, C) from a real structure (Gänstor Bridge) [18]. Images taken from prior publications. Laboratory and field experiments reveal the strong dependency of relative velocity change on ambient temperature with a similar magnitude.

4.4 Load Tests

A customized load test was performed in December 2021 with two trucks of 15 and 32 tons. The trucks were placed in five different positions over the bridge. Ultrasonic signals were collected prior, during and between changes in the loading. Further descriptions of the testing procedure and subsequent signal analysis are given by Epple et al. [18]. Load induced relative velocity changes up to around 0.4 % were detected. The detected relative velocity changes did pre-dominantly occur with negative values, especially in the area where the load is applied (sensors directly below truck position), indicating velocity decrease. Negative relative velocity change, i.e. velocity decrease, is associated with damage or tensile stresses, which was also shown in specimen scale experiments performed by Diewald et al. [24] on pure concrete specimens. For loading of real structures made of reinforced concrete, tensile stresses seem to dominate the observed relative velocity change, even though compressive stresses are occurring simultaneously. This was also found within the studies of Clauß et al. [25, 26], who performed four-point bending tests on structural scale reinforced concrete specimen.

First results for damage detection and localization were achieved by the development of a substitute model which is based on a finite element simulation and formulation of an inverse problem, that is subsequently solved. This approach was implemented first for the structural scale four-point bending test mentioned [27] and was then transferred to the real structure. Using ultrasonic signals from the Gänstor Bridge collected for the unloaded and loaded state during load testing, spatially resolved information on decorrelation of the signals can be obtained. Decorrelation, i.e. values of the correlation coefficient below 1, indicate non-linear changes in the microstructure. High decorrelation between signals obtained in the unloaded and loaded states indicate strong material changes such as crack opening. Figure 7 shows the position of the 32 t truck within the loaded state together with results from spatially resolved CWI-based analysis. A damage zone is suggested to be present in the middle of the bridge. The results will be validated by more experiments and actual cutting of tendons before demolition of the bridge at the end of this year.

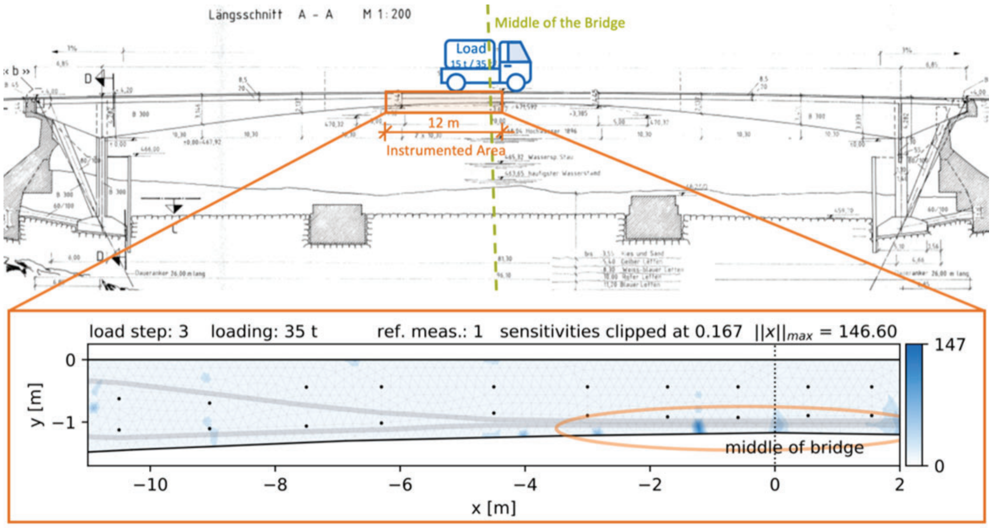

Figure 7: Damage localization with CWI.for a loading of 35 t in the middle of the bridge

5 Conclusions and Outlook

The results achieved by the research unit in the completed first (2019-2022) and ongoing second (2022-2025) funding period confirm the initial hypothesis that CWI-based methods are well suited for continuous structural health monitoring of RC structures. Large volumes were reliably monitored with little maintenance effort thanks to the selected setup and methodology. The transferability of findings at the laboratory scale to real structures was further demonstrated. The research unit CoDA will continue to work on the development, evaluation and combination of experiments, models and simulations at different scales.

One highlight is the planned demolition of the Gänstor Bridge. In this context, the transfer of laboratory results from the structural scale to the real structure will be central. The initiation of a controlled tendon break is intended. Additionally, activities relating to calibration and long-term monitoring are continued.

6 Acknowledgements

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7 References

[1] DFG FOR 2825 Homepage, https://www.mae.ed.tum.de/en/coda/home/, last accessed 2024/08/31.

[2] DIN: DIN 1076:1999-11 Ingenieurbauwerke im Zuge von Straßen und Wegen - Überwachung und Prüfung. (1999).

[3] Federal Highway Research Institute (BASt): Brückenstatistik (Stand 01.03.2024), https://www.bast.de/DE/Statistik/Bruecken/Brueckenstatistik.pdf;jsessionid=34732BB1C53146696ED4D1FACF885519.live113 last accessed 2024/08/16

[4] Marzahn, G. et al.: Bauwerksprüfung nach DIN 1076. Bautechnik 100(11), 699–706, (2023). https://doi.org/10.1002/bate.202300090

[5] DIN: E DIN 1076:2024-02 Ingenieurbauwerke im Zuge von Straßen und Wegen – Überwachung und Prüfung. (2024).

[6] Müller, A. et al.: Die Gänstorbrücke in Ulm – Untersuchung, Probebelastung und Brückenmonitoring. Beton- Und Stahlbetonbau 115(3), 164–178 (2020). https://doi.org/10.1002/best.201900071

[7] Komlos, K. et al.: Ultrasonic pulse velocity test of concrete properties as specified in various standards. Cement and Concrete Composites 18(5), 357–364, (1996). https://doi.org/10.1016/0958-9465(96)00026-1

[8] Kashif Ur Rehman, S. et al.: Nondestructive test methods for concrete bridges: A review. Construction and Building Materials 107, 58–86, (2016). https://doi.org/10.1016/j.conbuildmat.2015.12.011

[9] Aki, K.: Theory of Earthquake Prediction with Special Reference to Monitoring of the Quality Factor of Lithosphere by the Coda Method. In: Kisslinger,C., Rikitake,T. (eds) Practical Approaches to Earthquake Prediction and Warning, pp. 219–230. Springer, Dordrecht (1985). https://doi.org/10.1007/978-94-017-2738-9_2

[10] Snieder, R.: The Theory of Coda Wave Interferometry. Pure and Applied Geophysics 163(2–3), 455–473, (2006). https://doi.org/10.1007/s00024-005-0026-6

[11] Sens-Schönfelder, C., & Wegler, U.: Passive image interferometry and seasonal variations of seismic velocities at Merapi Volcano, Indonesia. Geophysical Research Letters 33(21), L21302, (2006). https://doi.org/10.1029/2006GL027797

[12] Niederleithinger, E. et al.: Processing Ultrasonic Data by Coda Wave Interferometry to Monitor Load Tests of Concrete Beams. Sensors 18(6), 1971, (2018). https://doi.org/10.3390/s18061971

[13] Planès, T., & Larose, E.: A review of ultrasonic Coda Wave Interferometry in concrete. Cement and Concrete Research 53, 248–255, (2013). https://doi.org/10.1016/j.cemconres.2013.07.009

[14] Niederleithinger, E. et al.: Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring. Sensors 15(5), 9756–9772, (2015). https://doi.org/10.3390/s150509756

[15] Fontoura Barroso, D. et al.: A Portable Low-Cost Ultrasound Measurement Device for Concrete Monitoring. Inventions 6(2), 36, (2021). https://doi.org/10.3390/inventions6020036

[16] Sträter, N. et al.: A new technique to detect altered stresses in tendons early. In: Biondini, F. & Frangopol, D. M. (eds.) Life-Cycle of Structures and Infrastructure Systems - Proceedings of the 8th International Symposium on Life-Cycle Civil Engineering, IALCCE 2023, pp. 1813–1820. CRC Press (2023).https://doi.org/10.1201/9781003323020-222

[17] Saenger, E. H. et al.: Modeling the propagation of elastic waves using a modified finite-difference grid. Wave Motion 31(1), 77–92, (2000). https://doi.org/10.1016/S0165-2125(99)00023-2

[18] Epple, N. et al.: Ultrasonic monitoring of large-scale structures - input to engineering assessment. In: Biondini, F. & Frangopol, D. M. (eds.) Life-Cycle of Structures and Infrastructure Systems - Proceedings of the 8th International Symposium on Life-Cycle Civil Engineering, IALCCE 2023, pp. 1805–1812. CRC Press (2023). https://doi.org/10.1201/9781003323020-221

[19] Diewald, F. et al.: Impact of temperature and relative humidity variations on coda waves in concrete. Scientific Reports,14(1), 18861, (2024). https://doi.org/10.1038/s41598-024-69564-4

[20] Holla, V. et al.: Computational Generation of Virtual Concrete Mesostructures. Materials 14(14), 3782, (2021). https://doi.org/10.3390/ma14143782

[21] Vu, G. et al.: Numerical Simulation-Based Damage Identification in Concrete. Modelling 2(3), 355–369, (2021). https://doi.org/10.3390/modelling2030019

[22] Vu, G. et al.: Reduced Order Multiscale Simulation of Diffuse Damage in Concrete. Materials 14(14), 3830, (2021). https://doi.org/10.3390/ma14143830

[23] Finger, C. et al.: Sensitivity of Ultrasonic Coda Wave Interferometry to Material Damage—Observations from a Virtual Concrete Lab. Materials 14(14), 4033, (2021). https://doi.org/10.3390/ma14144033

[24] Diewald, F. et al.: Impact of External Mechanical Loads on Coda Waves in Concrete. Materials 15(16), 5482, (2022). https://doi.org/10.3390/ma15165482

[25] Clauß, F. et al.: Comparison of experimentally determined two-dimensional strain fields and mapped ultrasonic data processed by coda wave interferometry. Sensors (Switzerland) 20(14), 1–16, (2020). https://doi.org/10.3390/s20144023

[26] Clauß, F. et al.: Correlation of Load-Bearing Behavior of Reinforced Concrete Members and Velocity Changes of Coda Waves. Materials 15(3), (2022). https://doi.org/10.3390/ma15030738

[27] Grabke, S. et al.: Damage Detection at a Reinforced Concrete Specimen with Coda Wave Interferometry. Materials 14(17), 5013, (2021). https://doi.org/10.3390/ma14175013