8-2022

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Citation Details

Schumacher, T., & Niederleithinger, E. Combining Passive and Active Ultrasonic Stress Wave Monitoring Techniques: Opportunities for Condition Evaluation of Concrete Structures IN NDT-CE 2022 - The International Symposium on Nondestructive Testing in Civil Engineering Zurich, Switzerland, August 16-18, 2022

NDT-CE 2022 - The International Symposium
on Nondestructive Testing in Civil Engineering
Zurich, Switzerland, August 16-18, 2022

Combining Passive and Active Ultrasonic Stress Wave Monitoring Techniques: Opportunities for Condition Evaluation of Concrete Structures

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Abstract
Concrete structures are invaluable assets to a society and managing them efficiently and effectively can be supported by information gathered through structural health monitoring (SHM). In this paper, a combined approach based on passive, i.e., acoustic emission (AE), and active, i.e., ultrasonic stress wave (USW) monitoring techniques for application to concrete structures is proposed and evaluated. While AE and USW are based on the same underlying physics, i.e., wave motion in solids, they differ fundamentally with respect to the nature of the source. For the former, external stimuli such as mechanical loads or temperature cause the rapid release of energy from initially unknown locations. As a result, AE events are unique and cannot be repeated. For the latter, a known source at a known location is employed at a specified time. This approach is thus controlled and repeatable. It is argued that a combination of these two techniques has the potential to provide a more comprehensive picture of ongoing fracture processes, damage progression, as well as slowly occurring aging and degradation mechanisms. This combined approach does thus promise new opportunities to support condition assessment of concrete structures. After providing an overview and comparison of the two techniques, results, and observations from a full-scale laboratory experiment and an in-service bridge monitoring study are discussed to demonstrate the promise of the proposed combined monitoring approach. Finally, suggestions for further work are presented.

Keywords: Acoustic emission monitoring; Ultrasonic stress wave monitoring; Structural health monitoring; Coda wave interferometry; Condition evaluation; Asset management; Concrete structures.

1 Introduction

Structural health monitoring (SHM) promises to become a valuable support tool for managing civil infrastructure assets such as concrete bridges, by providing owners real-time information regarding performance changes of an asset. Over the last few decades, passive ultrasonic stress wave i.e., acoustic emission (AE), monitoring of concrete structures has found several applications in the field, a practical one being the monitoring of prestressed concrete structures for wire breaks [1, 2]. Additionally, AE can be used during the structural load testing of in-service bridges, providing useful information regarding load-level and cracking [3, 4]. Separately, active ultrasonic stress wave (USW) monitoring has been explored recently to monitor loading of and deterioration processes in real structures [5, 6]. While AE monitoring can capture ongoing internal fracture processes such as cracking, reinforcement-concrete interaction, and reinforcement fracture, USW monitoring, in particular combined with coda wave analysis, can document minute and slowly varying condition changes from, e.g., temperature variation [7], changes in the stress field due to service-level loads [8], and degradation processes [5]. Both methods show potential to provide quantitative measures for changes in structures and materials, e. g., for fatigue [9, 10]. However, this potential is not yet used fully.

Establishing and documenting the condition and condition changes, respectively, of a concrete structure using both passive and active ultrasonic wave monitoring techniques has been proposed and applied but not rigorously evaluated [10-14]. One challenge, in particular for the highly sensitive USW technique, has been to ensure consistent transducer coupling throughout the duration of monitoring [13]. A potential solution is using transducers that can be embedded into the concrete [12, 15, 16].

We hypothesize that integrating (or combining) passive and active ultrasonic stress wave monitoring offers new powerful opportunities for SHM of concrete structures, because the two techniques are complementary in the type of information they provide. Since the same instrumentation can be employed, requiring minimal adjustment of data acquisition configuration and settings, this methodology makes also sense from an economical point of view.

2 Proposed approach

Figures 1 (a) and (b) illustrate the principles of passive, i.e., acoustic emission (AE) and active, i.e., ultrasonic stress wave (USW) monitoring, respectively. Both techniques are based on the same physics, namely wave motion in solids. While the former captures the stress waves released due to rapid energy releases caused by overloading of the material such as concrete cracking or reinforcing fracture, the latter records stress waves that are produced by a controlled actuator, typically an ultrasonic transducer. Note that we imply that both techniques operate in the ultrasonic range, i.e., above approximately 20 kHz. While stress waves may have frequency content in the audible range, typically high-pass filters are set to reject frequencies below this limit for practical reasons (noise control).

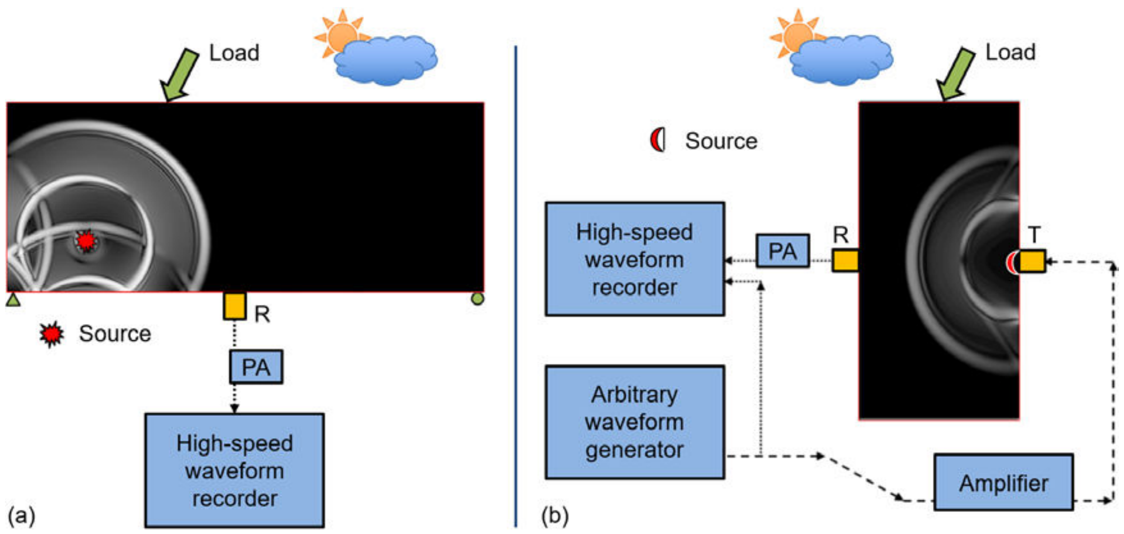

Figure 1: Illustration of principles of (a) passive and (b) active stress wave monitoring techniques. Acronyms: PA = pre-amplifier, R/T = receiving/transmitting transducer. Only one recording transducer (R) shown for simplicity. The sun/cloud symbol signifies exposure to varying environmental factors such as temperature and humidity. The wavefield snapshots were created using Wave2000 [17].

Table 1 provides a comparison of the two techniques. As can be observed, while differences exist with respect to the source and how the recorded waveforms are analyzed, the underlying physics, the instrumentation (both transducers and data acquisition systems), as well as the qualitative parameters that can be extracted from the recorded waveforms, are essentially the same. Looking at the detection abilities, it is evident that the two techniques, if employed simultaneously (or combined), provide complementary information with respect to ongoing fracture processes, damage progression, as well as slowly occurring aging and degradation mechanisms. Because of the high sensitivity required for USW monitoring to capture small condition changes, consistency of both transducer coupling as well as pulse transmission parameters is critical. Embeddable transducers are a practical solution to overcome this requirement [12, 15]. Also, while AE monitoring has been proposed as a tool to monitor small condition changes such as ASR in real structures [18], we hypothesize that USW monitoring can do the same but with higher reliability. The reason for this is that UWS monitoring offers higher control and repeatability of the measurements.

Table 1: Comparison between passive and active ultrasonic stress wave monitoring techniques

	Passive - Acoustic emission (AE) monitoring (see, e.g., [3])	**Active - Ultrasonic stress wave (USW) monitoring**
Source cause	Rapid release energy due to internal process	Actuator, typically ultrasonic transducer
Source location and time	Unknown, can be estimated if enough waveforms are available from different transducers [19]	Known, user-controlled
Source type and mechanism	Spontaneous, unique; mechanism depending on fracture process (e.g., expansive vs. shear)	User-controlled, repeatable; mechanism based on type of transducer used (e.g., normal vs. shear wave)
Underlying physics	Wave motion in finite solids	
Frequency content of recorded waveforms	10s to 100s of kHz, highest detectible frequency depending on travel distance of wave	Dependent on pulse used, typically 50 to 150 kHz, depending on transmitter-receiver distances
Data acquisition system	High-speed recorder, capable of discriminating transient waveforms, sampling rates 500 kHz to 10 MHz	
Select qualitative waveform parameters [20]	Amplitude (*A*), Duration (*D*), Energy (*E*), Rise time (*R*), Average frequency (*AF*), Peak frequency (*PF*), Time-of-arrival (*TOA*)	
Select analyses	*b*-Value analysis [21], Historic-severity analysis [22], Source localization [19], Moment tensor inversion (MTI) [23]	*p*-Wave velocity (c_p), *s*-Wave velocity (c_s), Magnitude-squared coherence (MSC) [8], Coda wave interferometry (CWI) [24]
Detection abilities	Micro- and macro-cracking of concrete, rebar-concrete interaction, reinforcement/tendon wire fracture [1, 2]	Temperature variations [7], stress variations due to service-level loads [25], alkali-silica reaction (ASR) (only in laboratory setting) [26], rebar corrosion (only in laboratory setting) [27]
Select reported applications on real structures	Monitoring of prestressing wire breaks [1, 2]	Condition monitoring of a highway bridge [5], Monitoring of damage progression of an ASR-damaged structure [5]

3 Case studies

Select findings from one laboratory experiment and one field study to test the hypothesis stated in Section 1 are presented and discussed subsequently.

3.1 Damage monitoring of full-scale member under reverse-cyclic loading

Select results and observations from a laboratory experiment described in [16] are used to illustrate the kind of information each technique can provide about the degradation processes occurring in a reinforced concrete (RC) member when loaded incrementally to failure. The test specimen is a full-scale column-footing subassembly specimen that has typical detailing of pre-1990s construction. Applying a Cascadia subduction zone loading protocol with variable axial loading, the specimen was loaded to failure [28]. Acoustic emission (AE) and ultrasonic stress wave (USW) monitoring were employed simultaneously and continuously throughout the duration of the experiment. Figures 2 (a), (b), (c), and (d) show an elevation view of the test specimen, the loading protocol, a photo of the AE transducer (surface mounted Panametrics V103), and a photo of the USW transducer (embedded ACS S0807), respectively. Roman letters I through VI in Figure 2 (b) designate the different damage states (DS), as determined by visual inspection. In this article, we focus on DS I and II. DS I was deemed to be within the linear-elastic response of the test specimen, meaning that the load-deformation response was linear, and no cracking was observed visually. During DS II, cracking had initiated but no reinforcement yielding was observed. A more detailed description of all DS, as well as the data acquisition process, are provided in [16].

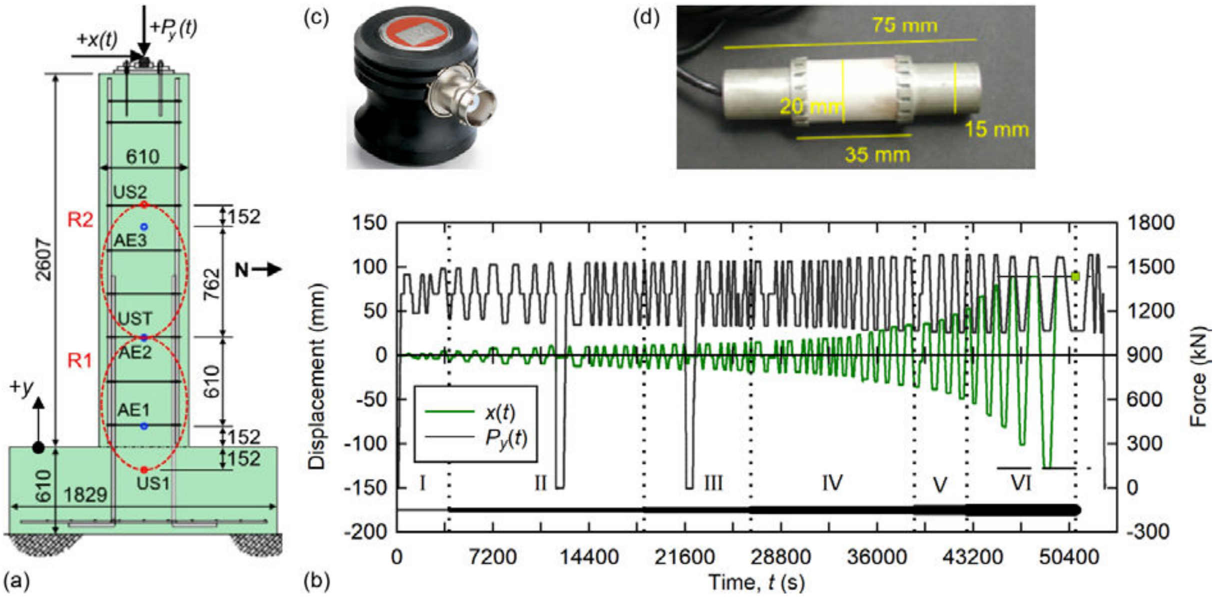

Figure 2: (a) Elevation view of column-footing subassembly specimen, (b) loading protocol, (c) surface-mounted ultrasonic transducers for AE monitoring (labeled AE1, AE2, AE3), and (d) embeddable ultrasonic transducer for USW monitoring (labeled US1, UST, US2). Ultrasonic regions are labeled R1 and R2, where UST is the transmitting transducer. The applied horizontal displacement and vertical loading are labeled, $x(t)$ and $P_y(t)$, respectively. Roman letters I through VI in Figure 2 (b) designate the different damage states (DS). All dimensions in (mm).

Figure 3 shows select measurements recorded at the AE and US transducers for DS I and II. Figure 3 (a) shows the loading protocol [legend see Figure 2 (b)], Figure 3 (b) through (d) show

AE wave form amplitudes and cumulative AE hits recorded at transducers AE3 through AE1, respectively, and Figures 3 (e) and (f) show US waveform amplitudes recorded at transducers US2 and US1, respectively.

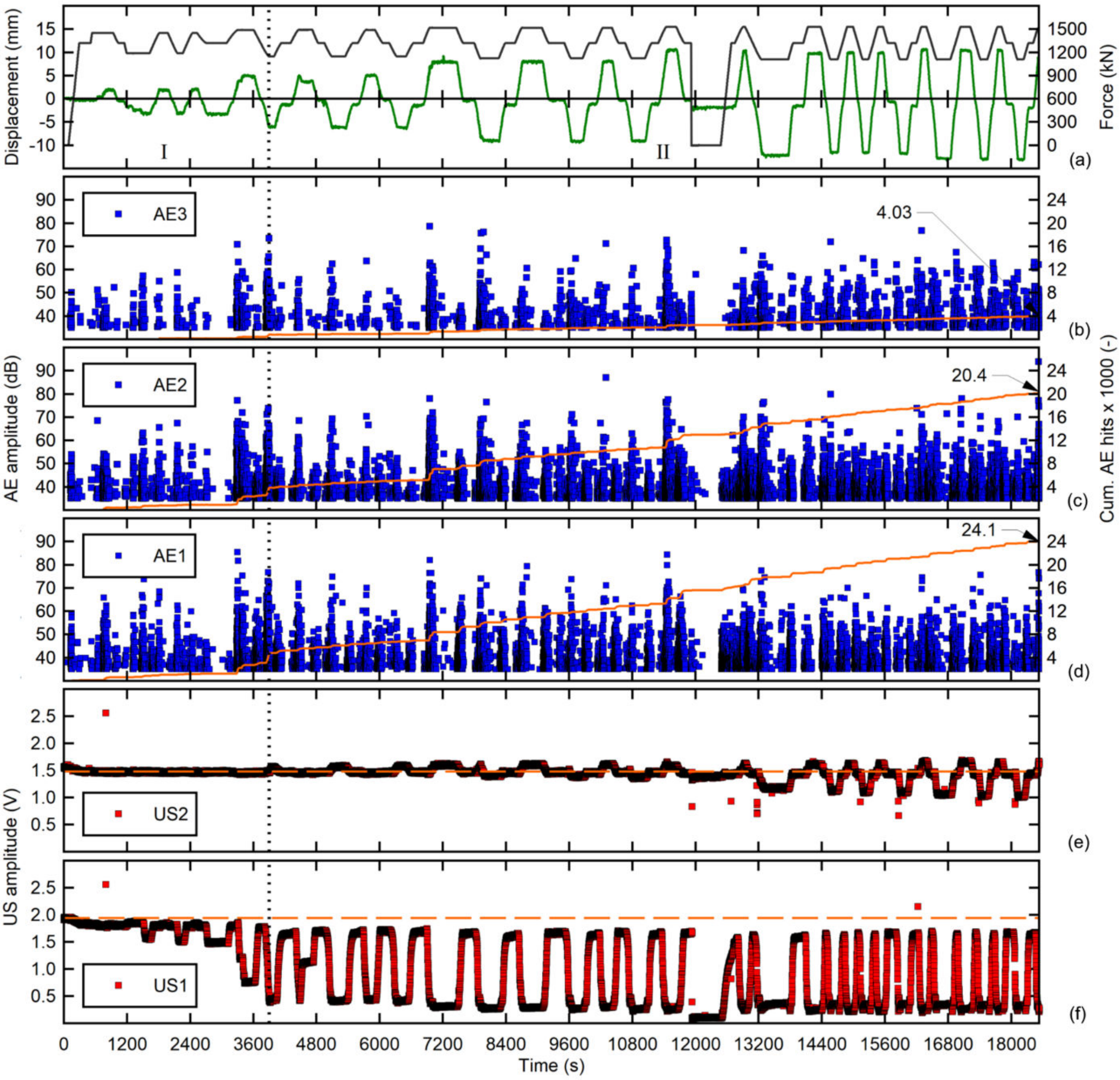

Figure 2: Select AE and USW measurements for DS I and II: (a) Loading protocol, (b) through (d) AE waveform amplitudes and cumulative AE hits recorded at transducers AE3 through AE1, respectively, and (e) and (f) US waveform amplitudes recorded at transducers US2 and US1, respectively. Locations of all transducers are provided in Figure 1 (a). The black dotted vertical line indicates the transition between DS I and DS II.

The following observations can be made for the recorded AE data:

- AE are recorded any time the test specimen is loaded either axially and/or horizontally. The first notable increase in the AE waveform count (or hit) rate (orange curves) can be observed at the loading cycle occurring at approximately 3280 s. Note that this is one cycle prior to the cycle that was found to show initial cracking by means of visual inspection, which is at approximately 3900 s (= black dotted vertical line).

- The cumulative number of AE hits decreases with distance, *y*. This is expected as it is consistent with the bending moment demand, which is largest at the bottom of the slab, i.e., $y = 0$. The level of degradation in form of cracking also decreases with distance, *y*.
- While some differences exist between the number and distribution of AE amplitudes per loading cycle, no reliable consistent trend can be observed that would like AE data to the level of degradation in the test specimen.

For the recorded USW data, the following can be stated:

- Recorded US waveform amplitudes are highly sensitive to variations in both horizontal as well as axial load applied to the test specimen. Note the significant drop in amplitude when the axial load was accidentally removed while no horizontal displacement was applied (at approximately 12,000 s).
- US amplitudes are distinctly different between region R1 and R2. While the US amplitudes recorded at transducer US2 are constant through DS I, they become a function of the loading during the very early cycles, i.e., at approximately 1400 s. This is again explainable by the distribution of the bending moment demand in the test specimen. Coincidental with the first notable increase in the AE hit rate at approximately 3280 s, US amplitudes show a larger drop. This provides further evidence that actual initial cracking in the test specimen might have been missed by visual inspection.
- A shift in the US amplitude baseline occurs in the US amplitudes recorded at transducer US1. This can be explained by the increasing degradation taking place in the test specimen associated with increasing levels of cracking.

In summary, AE monitoring provides useful information about fracture and cracking processes in real-time. USW monitoring provides information between fracture events but can capture degradation progression with high sensitivity. The consistent decrease in the US amplitude baseline provides information regarding the level of degradation.

3.2 Monitoring of damage, and load and temperature variations on in-service bridge

The Gänstorbrücke is one of Germany's best monitored road bridges [29]. After a thorough assessment, revealing that some prestress tendon wires have lost up to 50% of their cross-section due to corrosion, two lanes of the four-lane bridge were closed and the maximum vehicle weight reduced to 3.5 t. The bridge is already equipped with strain gauges, LVDTs, temperature sensors and an AE system. The latter has given evidence of (very few) wire breaks in the past years.

The German DFG Research unit CoDA aims to develop USW monitoring methods for concrete damage assessment of Germany's aging infrastructure. To test the methods developed in simulations and laboratory experiments on a large scale, we have embedded about 30 ultrasonic transducers (same as described in Section 3.1) at the Gänstorbrücke in Ulm. The results are continuously evaluated using coda wave interferometry (CWI), an extremely sensitive method able to reveal even small changes in velocity and waveform [30].

Figure 3: Photo of Gänstorbrücke, built 1950, prestressed concrete, over the river Danube from Ulm to Neu-Ulm. Some tendon wires suffer from 50% cross section loss due to corrosion [2].

One of the main aims of this project was to check whether wire breaks, indicated by AE events, and the resulting prestress losses, can be picked up by USW monitoring to give a qualitative or even semi-quantitative judgement on the amount of damage. The influence of variations in the level of prestressing on ultrasonic velocity has been shown in, e. g., [31] and ([32], same volume). Unfortunately, or perhaps "fortunately" from an owner's perspective, at this time we are still waiting for new wire break events to occur. The only observed changes in the ultrasonic signals has been associated with temperature variations.

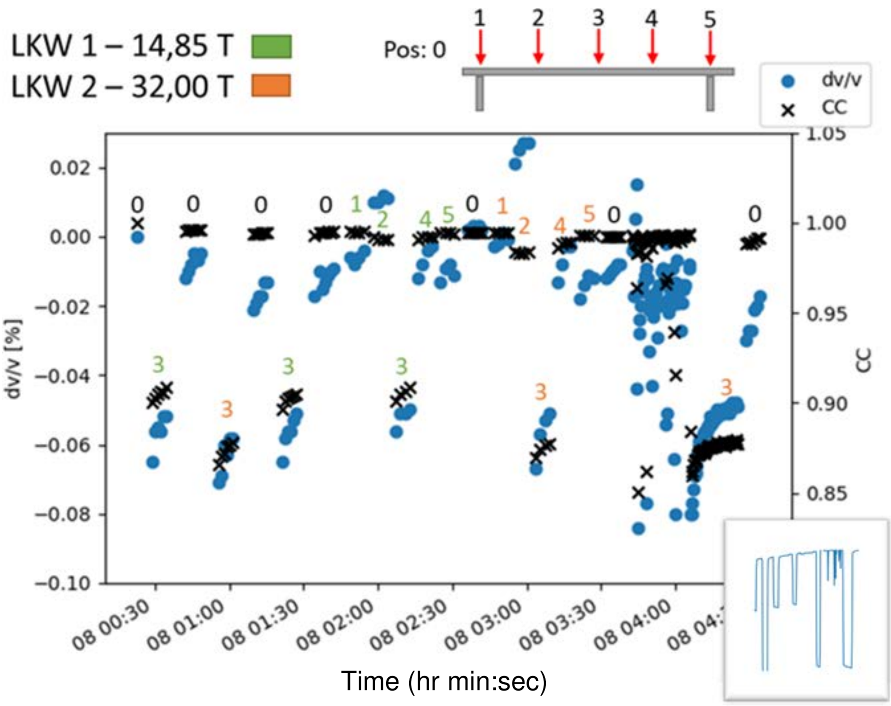

Figure 4: Velocity and waveform correlation change for mid-span transducer pair during a static load test with two different trucks at various positions. Note, effect is highest when trucks are above the transducer pair (Position 3) and truck load is higher (orange). In addition, creep effects are visible. Box in bottom right: qualitative result of strain gauge measurements mid span [2].

The capabilities and limitations of the coda wave-based monitoring system were tested in a static load experiment, using a 32 and a 15-t truck. The results for a mid-span transducer pair are shown in Fig. 4, revealing a clear correlation of velocity and waveform correlation change to truck weight and position. Details and more results of this experiment, including a way to image the coda wave results and produce maps indicating stress change patterns, are reported by Epple et al. (same volume, [6]).

The monitoring will continue along the next years, potentially until the bridge is replaced (currently expected in 2024), allowing got additional experiments (e.g., cutting of tendon wires) between closure and demolishment. The potential of the combination of AE and USW monitoring is already clear, i.e., the former and latter would give a real time alert of wire break events and a measure for the level of damage, respectively.

4 Conclusions and further work

Based on performed work, we demonstrate the potential of combined passive (AE) and active ultrasonic stress wave (USW) monitoring. The two techniques are complementary in that they provide information regarding ongoing fracture processes as well as degradation progression, respectively.

Further work that should be pursued:

- Establish a holistic framework (simulation, data acquisition, processing, evaluation, interpretation) with the goal to integrate the two monitoring techniques most effectively.
- Develop algorithms that can associate recorded US waveform changes with their causes such as stress variation, temperature variation, cracking, degradation processes, and changes in transducer coupling.
- Develop and evaluate inexpensive open-source instrumentation and analysis techniques, see, e.g., [33].
- Working towards guidelines and standardization of these two techniques to foster practical implementation while assuring quality of installation and data evaluation. For AE monitoring, some general guidelines exist, e.g., [34, 35], while specific guidelines are in the making (e. g., from DGZfP).
- Evaluate the use of new technologies such as fiber-optic distributed acoustic sensing (DAS) to perform combined AE and USW monitoring.

Acknowledgements

The Oregon Department of Transportation (ODOT) provided funding for the laboratory experiment discussed in Section 3.1, through sponsorship of their research project SPR 802 [28]. The help of graduate students AKM Golam Murtuz and Ali Hafiz, as well as undergraduate students Patrick McCoy, Ilya Palnikov, and Evgeny Hadji, with manufacturing, installation, and instrumentation of the test specimen is greatly appreciated. Furthermore, the authors appreciate the contribution of several colleagues from the Bundesanstalt für Materialforschung und -prüfung (BAM), the project partners in DFG FOR 2825 CoDa, the German Road Research Institute (BASt), and the cities of Ulm and Neu-Ulm for making the Gänstorbrücke project described in Section 3.2 possible.

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