System Identification with Coda Waves at the Gänstorbrücke in Ulm

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Abstract The Gänstorbridge in Ulm is crossing the Danube with a maximum span of 82,40 m. Among others is the bridge instrumented with 20 ultrasound transducers for structural health monitoring. These special types of ultrasound waves allow for the monitoring of concrete structures with diffuse ultrasound (coda waves). The advantages of the method include large-scale coverage of the geometry by the ultrasound and at the same time immense sensitivity to a wide range of measurable variables. These characteristics of the technology, together with the widespread use of concrete and the aim of preserving aging infrastructure for as long as possible, underline the great potential of coda waves.

Instrumented is a 12 m long field in the middle of the bridge. During a closure at night, loading experiments were performed with heavy trucks that were evaluated with a focus on damage detection. To do this, an inverse problem is solved whose solution allows for the localization of damages. The focus of the article is on the presentation of the method, challenges in practical application, and the results of the load tests.

1 Introduction

The Gänstorbrücke is crossing the Danube in Ulm. It has a vital role as one of two bridges over the Danube in the city. Due to its age of 74 years, it has several problems, such as tendon corrosion, and will thus be replaced in the following years. In order to ensure structural safety until its deconstruction, the bridge is partially closed and heavily monitored with various structural health monitoring technologies. Müller et al. [1] give an excellent overview of the bridge's history, status, and monitoring. Next to the established monitoring techniques described in [1], ultrasound sensors are subsequently installed to allow monitoring with coda wave interferometry (CWI). CWI is a type of ultrasound monitoring originating from geophysics and can also be applied to concrete structures. The technology has great potential due to its enormous sensitivity to influences from temperature, moisture, and stress changes, and it also allows for the detection of damage occurring. This contribution focuses on the latter. Chapter 2 gives a short overview of the damage detection with CWI, Chapter 3 introduces the experiment performed at the Gänstorbrücke, and Chapter 4 discusses the results.

2 Methodology

Coda waves result from ultrasound that travels heterogeneous media and is scattered multiple times traveling from a source to a receiver. Thus, concrete, with its heterogeneous mix of cement, aggregates, pores, and reinforcement, is an ideal material for the technology. The scattering extends the sensing area and increases the sensitivity to small changes in the medium. A good review of the basics of CWI in concrete can be found in Planès et al. [2]. The CWI is a relative measurement technology that always needs a reference measurement, which means the technology can only detect additional damage compared to the reference. The central element in CWI is a cross-correlation (CC) evaluation of the measurement φ with its reference measurement φ_{ref}:

$$CC(t) = \frac{\int_{t-T2}^{t+T2} \varphi_{ref}(t)\varphi(t)dt}{\sqrt{\int_{t-T2}^{t+T2} \varphi_{ref}^2(t)dt \int_{t-T2}^{t+T2} \varphi^2(t)dt}} \tag{1}$$

With no change appearing, the diffuse signals can be reproduced, leading to a CC near or equal to 1. A change in the medium, e.g., by cracks that affect the scattering behavior, lowers the CC. The change of the signal's waveform strongly depends on the crack's position relative to the source and receiver location and evaluation time within the signal. These characteristic effects on the signal can be described with sensitivities of the measurement that represent the effect of an input parameter change (here crack) on a measured response (here CC). Pacheco et al. [3] use a model of random paths to compute the sensitivities of coda waves. The sensitivities, stored in the sensitivity kernel K, depend on source s and receiver r and evaluation location x as well as evaluation time t within the signal:

$$K(s,r,x,t) = \frac{\int_0^t I(s,x,u)I(x,r,t-u)du}{I(s,r,t)} \tag{2}$$

In Eq. (2), I represents the signal intensity. To obtain this intensity, the scattered ultrasound wave needs to be modeled. As an accurate model of a high-frequency wave in concrete that consists of cement, aggregates, and pores is computationally highly complex and expensive, a simplification is applied. Among others, Ryzhik et al. [4] have shown that the spread of the wave's energy in a random media as concrete can be approximated with a diffusive spread in a homogeneous medium. Therefore, a diffusion problem in a homogeneous material is solved to obtain the signal intensities of Eq. (2). This simplification allows for application in large structures such as the Gänstorbrücke. This study uses the finite element method (FEM) to solve the diffusion problem which gives additional geometrical flexibility as the problem can be solved in unstructured meshes. With the coda wave sensitivities, an inverse problem can be formulated whose solution is the damage location. Grabke et al. [5] give further insights into the FEM-based computation and

damage localization based on Planès et al. [6].
The sensitivity kernel of Eq. (2) is a model that simulates the effects of new scatterers in the propagation medium. It allows us to relate coda wave sensitivities to correlation measurements in an inverse problem. With the assumption of small damage, the relation of a change in the medium x and the corresponding measurement values is assumed to be linear [6]:

$$Ax = y \tag{3}$$

A is a matrix containing the sensitivity kernel for one pair at a specific time in each row. The vector y contains the signal's measured decorrelation (DC) with pair and time matching the sensitivity kernel in the corresponding row. The DC is closely related to the CC; in fact,

$$DC = 1 - CC \tag{4}$$

The size of matrix A is $m \times n$, with n referring to the number of nodes in the mesh and m referring to the total number of measurements. Typically, the number of nodes in the mesh is larger than the number of measurements, and thus the problem is underdetermined. To solve the inverse problem, a generalized Tikhonov regularization is applied, which is derived from a least-squares formulation of the problem in Eq. (3):

$$x_{k+1} = x_k + (A^T C_Y^{-1} A + C_X^{-1})^{-1} A^T C_Y^{-1} (y - Ax_k) \tag{5}$$

C_X^{-1} represents the inverse covariance matrix of the solution. This study uses a scalar of the identity matrix $C_X = \alpha$ I to damp the solution step Δx in each iteration k and increase numerical stability. C_Y^{-1} is the inverse covariance matrix of the measurements. With the assumption that all measurements are uncorrelated, $C_Y = I$ is used. As an additional regularization, the maximum sensitivity values are limited to a fraction of 1/6 of its maximum. Looking at the spatial distribution of the sensitivities, they form an extremely sharp peak at the position of transducers. This leads to numerical problems and a localization that often only detects transducer locations as damaged positions. Parameter studies have shown a very positive effect of clipping these peaks at a fraction of its maximum. This fraction is obtained from empirical observations. The solution x represents the localized crack positions. Obtained values are difficult to interpret directly but for consecutive load increases “damage values” of the same experiment can be compared.

3 Experimental Setup

Within research projects funded by the DFG and BASt, it was possible to instrument the Gänstorbrücke to test the practical applicability of CWI. An overview of the DFG research group and its work on

CWI is given in a contribution to this conference by Jaegle et al. At the Gänstorbrücke, an approximately 12 m long area in the middle of the bridge with a total span of 82,40 m was instrumented with ultrasound transducers. Fig. 1 and Fig. 2 give an overview of the bridge and the instrumented area. Instrumentation and load experiments were performed by colleagues from the Bundesanstalt für Materialforschung und -prüfung (BAM).

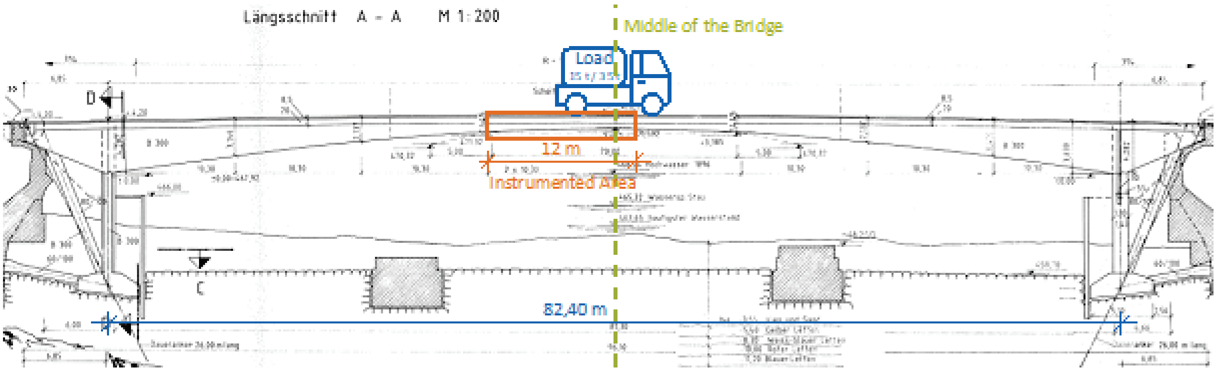

Figure 1: Overview of the instrumented bridge (adapted from [1])

The ultrasound transducers are subsequently mounted with core drillings filled with the transducers and grouted with concrete. The sensors have a central frequency of 60 kHz. Niederleithinger [7] gives an overview of the sensors used and the installation procedure. The subsequent installation ensures a good coupling of the sensors with the concrete and is the most durable installation for such a practical experiment where long-term monitoring is desired. After instrumentation, test measurements were performed by colleagues from BAM. The bridge was closed for this purpose and only loaded with a 15 t and a 35 t heavy truck in the middle of the bridge. Tab. 1 gives an overview of the loading process.

The DC of the received signals is evaluated in 5 consecutive windows with a length of 400 μs. All measurements are compared to the first measurement used as a fixed reference, ensuring a reliable and consistent comparison. On the numerical side, a model with an average node distance of 0.15 m that leads to 1746 nodes is used. The T-shaped three-dimensional cross-section is simplified to a two-dimensional model using the vertical cutting plane in the middle. To describe the scattering of the 60 kHz in concrete with the diffusion simulation, a diffusivity of 400 m2/s is chosen. The same diffusivity for the homogenization is used in Grabke et al. [8] and is also in accordance with Fröjd [9], who uses 440 m2/s for a 50 kHz signal.

Before application of the damage detection, a thorough inspection of received signals is necessary to check for malfunctioning of selected transducers. This meticulous selection ensures a good reproducibility of signals. It is done by putting a CC threshold of 0.9 on an evaluation at load step 3, where no change to load step 1 is expected and a high reproducibility of coda signals is expected. The threshold leads to a filtering of 29 pairs out of 110 that are not able to reproduce the signals at the desired accuracy. With a set of 81 measurement pairs, the measurements under load are investigated to see if there are indications for cracks in the structure that open up under load.

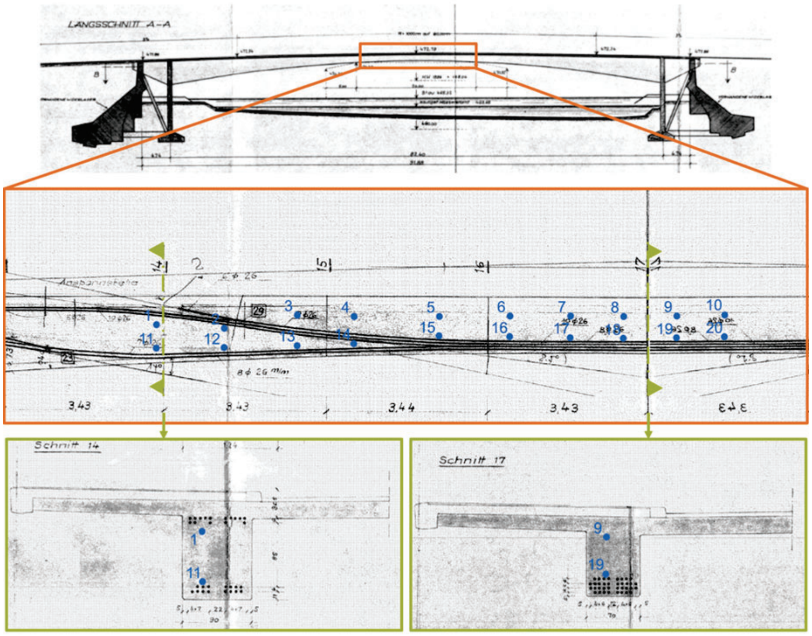

Figure 2: Overview of sensor placement (blue dots) and cross- section.

Table 1: Overview of the loading process.

Load step	Loading	Position
1 (reference)	no load	-
2	15 t	middle oft he bridge
3	no load	-
4	35 t	middle oft he bridge
5	no load	-
6	15 t	middle oft he bridge
7	no load	-

4 Results

The problem with the existing structure is a lack of information on the current state and reference measurements for the CWI results. This means there can be multiple cracks in the medium, and if nothing about them changes, they are not detectable with CWI. To cause the greatest possible change in the monitored area, the bridge is loaded in the middle, which also causes the maximum deflections. A complete set of measurements is recorded during each loading with a heavy truck. Each of these datasets is used in the inverse problem for damage detection. The results are shown in Fig. 3. Note that the order of the visualization is adapted such that the load increases from top to bottom, which is different from the loading procedure in the experiment (cf. Tab. 1). On the top there is an evaluation at load step 3, where no load is applied, to have a reference for the evaluations under loading. The blue color shows the located damage positions. Also, under no loading, the solution to the inverse problem shows a few potential damage locations. This is not related to cracks but the different accuracy at which the signals are reproducible. As soon as there are non-zero measurements, the inverse problem will detect certain positions in its least-squares fitting. One can see a big difference when comparing the magnitude of these detections with the ones under loading. This suggests that the detections under loading come from some change in the medium that only appears under load. The two results in the middle are both evaluations under loading of 15t in the middle of the bridge. In terms of located positions and their magnitude, they are very similar. Also under a loading of 35 t, the location of possible cracks matches the results from 15 t. Only the localization around x = 1m from load steps 2 and 6 cannot be seen under 35 t loading. The only difference at load step 4 is the larger magnitude, which follows the increased loading. The shown results can thus be regarded as very conclusive. However, despite the bridge condition, which requires close monitoring, we could not find crack documentation of the structure to validate the results.

After successfully detecting multiple damage locations, the question of what is being detected remains. As these positions are difficult to access and crack documentation is unavailable, only assumptions can be made. It is intriguing that only under load are the 3-4 orange circled crack positions detected, and nothing can be seen at the measurements in between without loading. One possible explanation could be cracks that open up under loading and thus change the material microstructure. Without loading, these cracks close again due to the pretensioning. Another possibility is an effect of the stress change on the signals that usually causes stretching or compression of the signals which is filtered out. However, if the stretching effect is highly non-linear, a significant waveform distortion remains that creates decorrelation of the signal. This question can only be answered conclusively by a local inspection of the detected positions.

5 Conclusion

The results from Fig. 3 indicate several damages and underline the great potential of CWI. The preprocessing of the signal data showed some sensors or selected sensor pairs malfunctioning. With the sensors embedded into the concrete at hardly accessible positions, a fixture of such a hardware problem is impossible. The remaining sensor network, however, was sufficient, and the localization worked. The experiment was performed during night closure of the bridge. This allowed us to perform load experiments with precise knowledge of applied forces. When the bridge is in regular operation, the loading changes within seconds. Currently, the measurement of a complete set of sensor pairs, as in this case 110, takes a few minutes. Therefore, applying the presented method under traffic load is not yet possible. However, it would be conceivable to carry out a controlled inspection, as in this experiment, as part of the main bridge inspection that takes place every six years for bridges in Germany, especially if the bridge is in a particularly critical condition. One could also attach temporary external ultrasonic transducers to the structure for such an application scenario. With the embedded sensors in the Gänstorbrücke, long-term monitoring will now be performed to see the effects of other environmental influences on the coda signal, such as temperature and moisture.

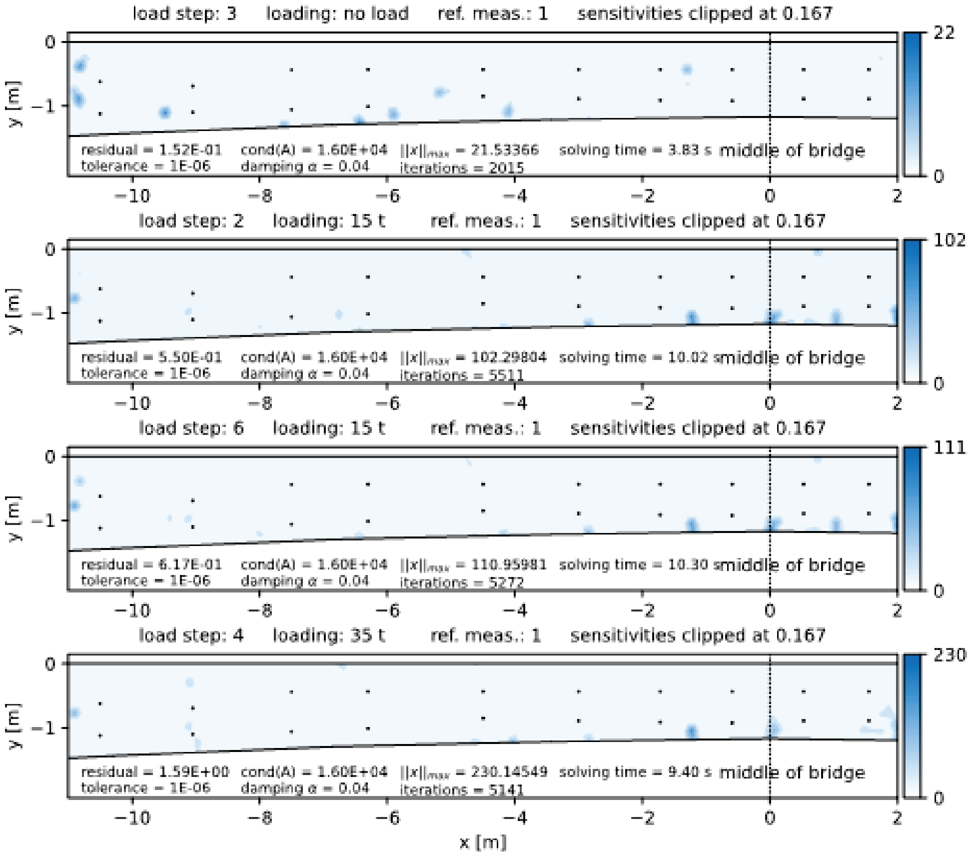

Figure 3: Damage localization at the Gänstorbrücke for increasing loading.

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