Coda Wave Interferometry Used to Localize Compressional Load Effects in a Concrete Specimen

Ernst Niederleithinger, Christoph Sens-Schönfelder, Sven Grothe, Herbert Wiggenhauser

7th European Workshop on Structural Health Monitoring
July 8-11, 2014. La Cité, Nantes, France

CODA WAVE INTERFEROMETRY USED TO LOCALIZE COMPRESSIONAL LOAD EFFECTS IN A CONCRETE SPECIMEN

Ernst Niederleithinger[1], **Christoph Sens-Schönfelder**[2], **Sven Grothe**[1], **Herbert Wiggenhauser**[1]

[1] *BAM – Federal Institute for Materials Research and Testing, Berlin, Germany*
[2] *Helmholtz-Zentrum Potsdam, DeutschesGeoForschungsZentrum GFZ,Germany*

ernst.niederleithinger@bam.de

ABSTRACT

Coda Wave Interferometry (CWI), a method to evaluate subtle changes of elastic wave velocity in a medium, has been proven to be effective to detect small changes or ultrasonic velocity in concrete caused by load, temperature, moisture, damage or other means. While classical CWI is just able to determine velocity changes globally in relatively large areas between and around pairs of transmitters and receivers, several approaches have been proposed to identify the area affected by the changes more precisely. Most of them are based on the calculation of sensitivity kernels for de-correlation of signals measured at a specific state against a reference. Others follow simplified approaches. In a laboratory setup a concrete specimen of $1.5 \times 1.5 \times 0.5\ m^3$ was compressed at a certain point. Maximum loads of 20 to 100 kN have been applied in 5 to 10 kN steps in various cycles. The specimen is equipped with 18 embedded ultrasonic broadband piezo transceivers (60 kHz central frequency). Ten of these receivers have been connected to a multiplexer and ultrasonic transmitting and receiving equipment in a way that allowed almost continuous two way measurements between all sensor pairs. Even simple ways to evaluate the data (e.g. crosscorrelation between signals at different load states) allowed pinpointing the load center at least approximately. A more detailed data evaluation either using CWI or even more one of the more sophisticated localization algorithms gave “sharper” results in terms of localization and a better correlation between load and velocity change/de-correlation. The results are used in upcoming monitoring systems for concrete structures.

KEYWORDS : *Ultrasound, Concrete, Interferometry, Monitoring, Tomography*

INTRODUCTION

Detection of subtle changes in concrete is a major issue in the assessment of various degradation mechnisms (e.g. alcali silica reaction, freeze-thaw damages, reinforcement corrosion) as well as changes in the stress level. Ultrasonic monitoring networks, which will be able to sense variations between sensors even outside the direct path of flight, might close a gap between global, but low sensitivity methods as modal analysis and highly accurate, but local methods as strain sensors. In cooperation with a manufacturer of ultrasonic equipment new embeddable sensors have been designed which can be placed in a structure during or after construction and might remain operational for decades. While it is well known that the ultrasonic velocity is influenced by the stress level in a construction, methods for data evaluation are still mostly applied in laboratory research projects, e.g. [1–3]. The traditional time of flight method has shown to be not sensitive enough for many applications. To evaluate some of these methods we have used a large concrete specimen containing an ultrasonic network that was locally stressed.

1. Theory

Three methods have been used in our study to demonstrate the capabilities of a variety of technologies from very fast real time display of changes to high accuracy localization. All methods explained below require measurements in a reference (e.g. undamaged, unloaded) state.

1.1 Correlation coefficient

To provide a measure for changes in the ultrasonic data over time, which can be implemented in real time monitoring systems, we have chosen to calculate the correlation coefficient of each time series against a reference. Based on a sample of paired data (x_i, y_i), the correlation coefficient is a measure of the linear dependence between two samples, returning a value between -1 and 1 that indicates the degree of correlation:

$$r_{xy} := \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\cdot\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}}$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \qquad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$$

The correlation coefficient enables to distinguish between small and large changes, but doesn't provide any quantitative measure, neither for change or damage assessment nor for localization.

1.2 Coda Wave Interferometry

The theory of coda wave interferometry uses the scattered elastic wave field in a heterogeneous medium to observe the effect of subtle changes in the medium. It was described e. g. by [4]. In connection with passive data it was first used by [5] to obtain a continuous observation in situations without controllable sources like seismology. As suggested by [5] the perturbations in the wave field are measured based on the cross-correlation of the recorded time series versus a reference time series, which is compressed or extended in time by a small factor ν, corresponding to the relative velocity change:

$$CC(\nu) := \frac{\int_0^T h_i(t(1-\nu))\cdot h_0(t)\,\mathrm{d}t}{\sqrt{\int_0^T h_i^2(t(1-\nu))\,\mathrm{d}t\cdot\int_0^T h_0^2(t)\,\mathrm{d}t}}$$

The highest cross-correlation value CC marks the average velocity change in the medium. A similar approach based on shifting parts of the reference in time is used by [4]. The technique is known to have a globally high sensitivity to velocity changes. In case of reversible stress changes, these changes can be referred to changes in the elastic moduli (acoustoelastic effect). As the coda of elastic waves contains about 90 % shear waves, mainly changes of the shear modulus are recorded. CWI as described here lacks localization possibilities and is computationally much more expensive than simply calculation of the correlation index.

1.3 Coda Wave Tomography

Recently, tomographic methods have been introduced, which allow localization based on changes detected in coda waves. The first approach was published by [6]. Another method was developed in the frame of the MIIC project [7]. This new approach based on energy transfer theory was developed and validated [8]. As it includes the effect of direct waves it leads to better solutions especially in the vicinity of the sensors.

2. EXPERIMENT

A $1.5 \times 1.5 \times 1.5\ m^3$ concrete block ("GK32") has been cast at the BAM labs for various tests of embedded ultrasonic sensors (Figure 1). The lower half contains a certain amount of reinforcement, the upper one is unreinforced. A total of 18 ultrasonic sensors have been embedded, partly during, partly after casting the block. Ten of those have been used for the experiment due to limitation of the available acquisition equipment. A two channel multiplexer connects the sensors to an ultrasonic transmitter (rectangle, 50 kHz) or data recording system, respectively. All 90 sensor combinations can be interrogated within seconds or minutes, depending on the number of repetitions. In the upper half a hole was drilled to insert a thread bolt. Some of the sensors have been just a few cm away from the center of the load, some almost 1 m. Nuts, $10 \times 10cm^2cm$ load distributing plates and a piezo load cell provide a way to introduce localized compressional stress in a controlled, repeatable way. Load steps of 5 or 10 kN were applied in various cycles up a to maximum load between 20 and 100 kN, more than one order of magnitude below the compressive strength of the concrete. The setup is shown schematically in Figure 2.

Figure 1 : Concrete test block GK32

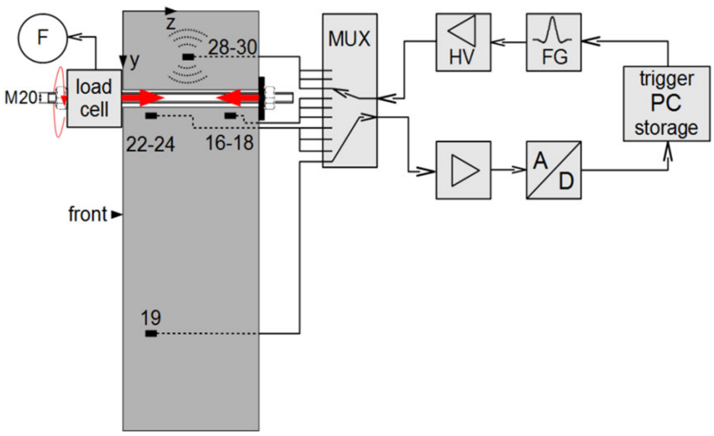

Figure 2 : Experiment setup

3. Results

3.1 Correlation Technique

The correlation coefficients for two sensor pairs for a load cycle from 0 to 20 kN, step 5 kN, are shown in Figures 3 and 4. For a sensor pair close to the borehole, where the stress is induced the correlation coefficient clearly follows is the force applied (Figure 3). The variable stress changes the elastic properties and thus influences the wave propagation (acoustoelastic effect) and the recorded signal. This lead to a decorrelation compared to a reference state (at $time = 0$). The correlation doesn't fully return to it's original state. This is probably not due to a remanent damage but to a continuous temperature change $2C$ in our lab. This can as well be seen in the sensor pair far away from the borehole (Figure 4), showing a slow drop of the correlation coefficient. This sensor pair shows no significant effect related to the load, demonstrating that even this simple technique can be used for an approximate localization.

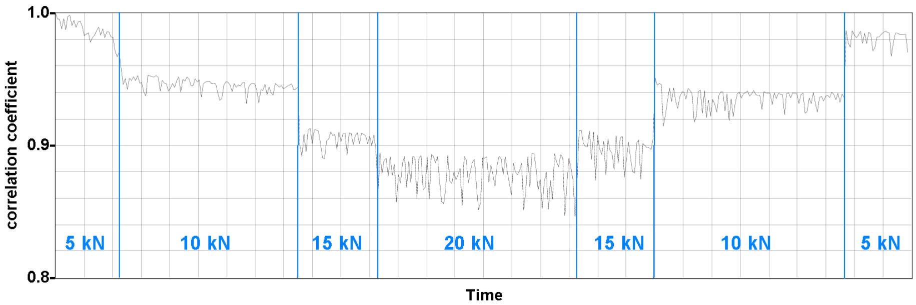

Figure 3 : Correlation coefficient change under load for a sensor pair close to the borehole

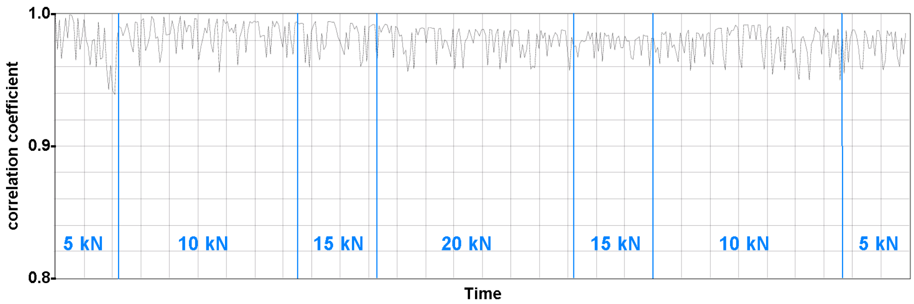

Figure 4 : Correlation coefficient change under load for a sensor pair away from the borehole

The correlation coefficients for all sensor pairs can be compiled in a matrix, which clearly shows which positions are most affected by the stress induced (Figure 5). The sensor closest to the borehole (no. 22) shows the highest decorrelation (lowest correlation coefficient) in general while the combination of two sensors close to the borehole (no. 22/23, row/column) shows the highest anomaly overall. Comparing forward/backward values (changing the role of transmitter/receiver for a sensor pair) gives a hint on reproducibility. In theory, the matrix should be symmetric. Any errors introduced (e.g. noise, temperature changes) leads to different correlation coefficients.

Transmitter \ Receiver	16	17	18	19	22	23	24	28	29	30
16		0,97	0,97	0,98	0,98	0,97	0,95	0,97	0,94	0,97
17	0,97		0,98	0,96	0,95	0,97	0,99	0,98	0,99	0,98
18	0,95	1,00		0,99	0,93	0,99	0,99	0,98	0,96	0,98
19	0,97	0,99	0,98		0,96	0,99	0,96	0,96	0,98	0,98
22	0,99	0,95	0,95	0,95		0,90	0,94	0,94	0,92	0,93
23	0,98	1,00	1,00	0,97	0,88		1,00	0,97	0,99	0,97
24	0,98	1,00	1,00	0,99	0,93	0,98		0,98	0,99	0,99
28	0,94	0,97	0,97	0,96	0,95	0,95	0,95		0,99	0,97
29	0,97	0,97	0,99	0,95	0,93	0,98	0,96	0,99		0,99
30	0,96	0,98	0,98	0,97	0,93	0,98	0,98	0,98	0,99	

Figure 5 : Matrix of correlation coefficients for every transmitter/receiver-combination for 20 *kN* loading

3.2 Coda Wave Interferometry

CWI allows to determine relative velocity changes for each state, which can be related quantitatively to changes in elastic properties. However, as the focus for this study was to localize changes, the results of the evaluation are just represented spatially in Figure 6. The mean value of the velocity change calculated from 10 forward/backward measurements is plotted color coded as a line between the respective sensor pair. As expected the highest velocity changes (about -0.15 %) are to be seen close to the borehole (black line) while sensor pairs located more remotely show almost no change (e.g. those involving sensor 19).

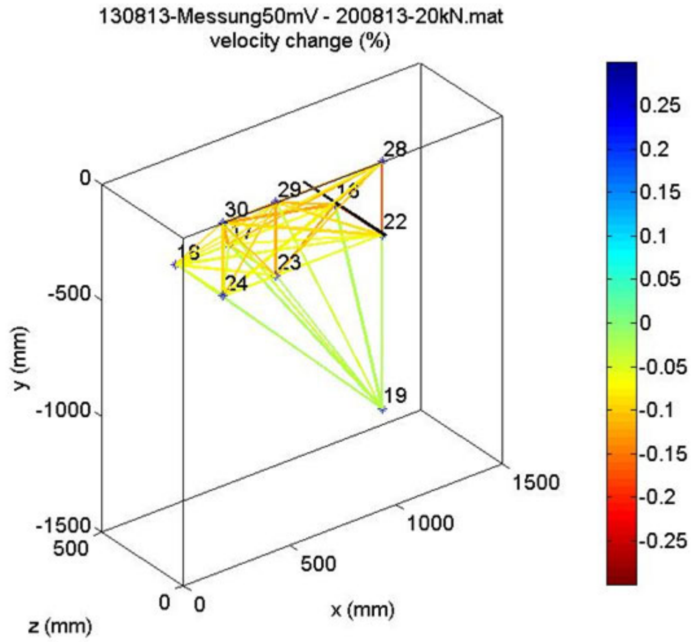

Figure 6 : Result of CWI for 20 *kN* load, displayed as color coded lines between the respective sensors. Load: 20 *kN*. Black line: borehole.

3.3 Coda Wave Tomography

Newly developed algorithms allow to invert for the probability, that the decorrelation of coda waves relates to a material or stress change in a certain region of the medium. The results for the technology described in [8] are shown in Figure 7. Note, that this data evaluation scheme allows, up to a certain extent, the assessment of parts of the body which are not in the region covered by direct rays. Using a predetermined threshold value one can map the area most affect by change (3D surface in Figure 7). In our case this resembles roughly a rugby ball shaped body around the borehole. Deviations reflect not just inaccuracies in the measurements and the inversion procedure, but also inhomogeneities in the medium and the load distribution.

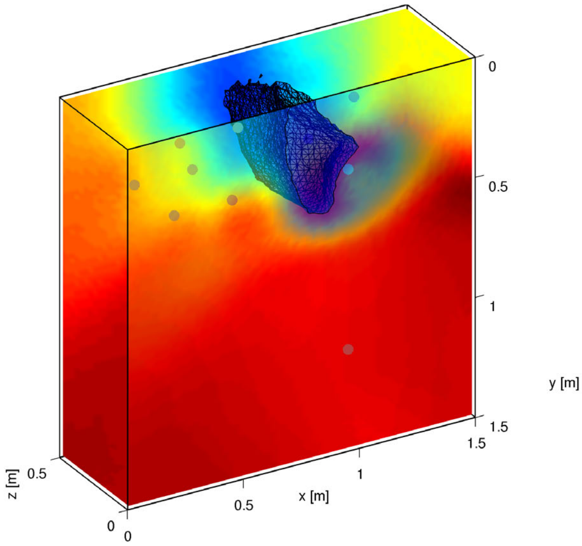

Figure 7 : Result of coda wave tomography for 20 *kN* load, change probability plotted color code in a semi-transparent way (red: low, blue: high). A certain level of change probability is plotted in addition as a 3D surface.

Conclusion

We have demonstrated three ways to evaluate ultrasonic transmission measurements acquired at a concrete specimen subjected to local stress. All methods were able to detect stress changes which are low compared to the compressive strength of the concrete. While calculation of correlation coefficients, which is fast and can be implemented into real time systems, just allows to qualitatively assess the amount of change and a rough localization, CWI can provide a quantitative measure of the change in stress level. Coda wave tomography allows to locate changes or damages much more precisely even outside the area covered by the lines of direct flight between sensors. Quantitative validation of all methods has yet to be done. Referencing the results to the transmitter-receiver pair least affected by load change, as proposed in [3] will lead to further improvement. A combination of the real time correlation method and coda wave tomography might provide the background for practical application of ultrasonic monitoring systems.

References

[1] E. Larose and S. Hall. Monitoring stress related velocity variation in concrete with a 2.10^-5 relative resolution using diffuse ultrasound. *J. Acoust. Soc. Am.*, 125:1853–57, 2009.

[2] S. Stähler, C. Sens-Schönfelder, and E. Niederleithinger. Monitoring stress changes in a concrete bridge with coda wave interferometry. *J. Acoust. Soc. Am.*, 129 (4):1945, 2012.

[3] Y. Zhang, O. Abraham, F. Grondin, A. Loukiliand, V. Tournat, A. Le Duff, B. Lascoup, and O. Durand. Study of stress-induced velocity variation in concrete under direct tensile force and monitoring of the damage level by using thermally-compensated coda wave interferometry. *Ultrasonics*, 52 (8):1038–45,

2012.

[4] R. Snieder. The theory of coda wave interferometry. *Pure and Applied Geophysics*, 163(2-3):455–473, 2006.

[5] C. Sens-Schönfelder and U. Wegler. Passive image interferometry and seasonal variations of seismic velocities at merapi volcano, indonesia. *Geophys. Res. Lett., vol 33, p. L21302, 2006*, 33:L21302, 2006.

[6] E. Larose, T. Planes, V.Rossetto, and L. Margerin. Locating a small change in a multiple scattering environment. *Applied Physics Letters 96*, 20:2014101:20120, 2010.

[7] C. Sens-Schönfelder, E. Niederleithinger, M. Gassenmeier, K. Thiemann, and F. Köllner. Monitoring and imaging based on interferometric concepts. In *Same Volume*, 2014.

[8] T. Planes, E. Larose, L. Margerin, L. Rossetto, and C. Sens-Schönfelder. Decorrelation and phaseshift of coda waves induced by local changes: multiple scattering approach and numerical validation. *Waves in Random and Complex Media, 2014*, 2014.