46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-1234

A REVIEW ON ULTRASONIC MONITORING OF CONCRETE: CODA WAVE INTERFEROMETRY AND BEYOND

Ernst Niederleithinger
BAM
Berlin, Germany

Odile Abraham
IFSTTAR
Nantes, France

Eric Larose
ISTERRE
Grenoble, France

ABSTRACT

The propagation of ultrasonic waves in concrete is affected by its micro- and macro-structure, geometry and properties as well as external influences as stress, temperature or moisture. In addition, age and degradation have a strong influence. Therefore, Ultrasound has been used to monitor concrete samples and structures since decades. However, early applications using conventional techniques as time-of flight or changes in amplitudes have been limited to detect changes in a late stage close to serviceability or ultimate load states.

Around 2000, several new, more sensitive techniques adopted from geophysics or other field of material sciences have been introduced to research in ultrasonic monitoring of concrete. The most discussed methodologies are coda wave interferometry, a technique which allows to detect very subtle changes from repeated ultrasonic measurements. Nonlinear acoustic techniques help to identify e. g. cracks even in an inhomogeneous background. Both techniques can be combined.

This paper reviews methods and results achieved so far on the laboratory scale and with full scale models the directions for future research and application is given as well.

Keywords: concrete, ultrasound, monitoring, coda wave interferometry, nonlinear, review

NOMENCLATURE

CC	correlation coefficient
φ(t)	ultrasonic amplitude (waveform)
ε	stretching factor
t	time
V	ultrasonic velocity

1 INTRODUCTION

Ultrasound (US) transmission measurements for concrete are a standard procedure since decades. P-Wave time of flight (TOF) data are applied in a standardized manner to assess concrete strength using ultrasonic velocity as a proxy [1][2]. US is as well used to monitor changes in concrete in controlled experiments by following changes in velocity and/or amplitudes [3]. However, the sensibility and sensitivity of conventional approaches is limited.

Since around 2000 several researchers have started to extend the capabilities of ultrasonic monitoring either by using more sensible data evaluation techniques as coda wave interferometry or evaluating more sensitive features as those from nonlinear acoustics. The potential of these approaches and progress of the early years has been compiled in several publications [4][5].

Meanwhile, these methods and their applications have been significantly extended and applied on larger structures

2 CODA WAVE INTERFEROMETRY

Coda wave interferometry (CWI) was first introduced in seismology to detect subtle changes in the seismic coda after two similar earthquakes, called seismic doublets [6], and further developed in a more general framework [7]. The stretching technique is preferentially used to evaluate relative velocity changes dV/V between two states of the material. To that end, the final waveform is interpolated at times $t(1-\varepsilon)$ and the correlation coefficient with the initial waveform is evaluated:

$$CC(\varepsilon) = \frac{\int_{t_1}^{t_2} \varphi'[t(1-\varepsilon)]\varphi(t)dt}{\int_{t_1}^{t_2} \varphi'^2[t(1-\varepsilon)]dt \int_{t_1}^{t_2} \varphi^2(t)dt} \qquad (1)$$

where t_1 and t_2 mark the time window in the coda where the relative velocity change is measured. This calculation is reproduced for various stretching factors ε until the correlation coefficient CC reaches its maximum. The corresponding stretching factor ε_{max}, is then the actual relative velocity change in the medium: $\varepsilon_{max} = dv/v$.

CWI interferometry was shown to be able to detect changes of rigidity efficiently and quantitatively due to different solicitations: thermal changes [7], stress changes through acousto-elasticity [8], humidity [9] and small damages [10].

3 NONLINEAR CWI

A recent method, called nonlinear coda wave interferometry (NCWI), has been proposed to detect damage that are invisible to classical techniques (such as early damage, closed crack and/or to monitor subtle damage changes such as crack healing in concrete [11]. NCWI combines the high sensitivity of CWI with non-classical nonlinear ultrasonic methods that are very sensitive to micro-cracks and micro-contacts. The principle is to activate with a low frequency pump wave (FIGURE 1) non-classical nonlinearities such as clapping and tapping, hysteresis, nonlinear dissipation and slow dynamic effects. Modifications between the state with no pump and a state with a given pump level are efficiently monitored by CWI. Relations between the velocity variations, and the decorrelation, as a function of pump amplitude provide information about the damage severity. The pump wave modifies the concrete state which makes it possible to use classical CWI tools to monitor its influence. As the reference signal is included in the technique, NCWI can thus be used as an NDE technique and/or as a monitoring method. It is expected that a combination of NCWI with CWI imaging algorithm will allow the mapping of existing micro-cracks.

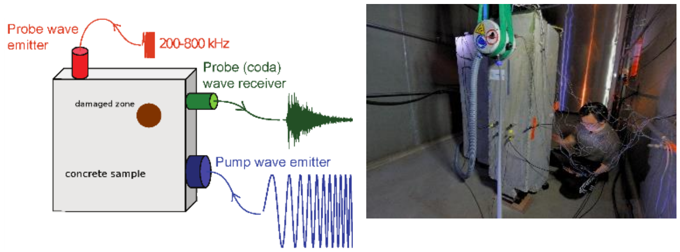

FIGURE 1: NCWI EXPERIMENTAL SET-UP. Left: SCHEMATIC PRINCIPLE. RIGHT: DETECTING A CLOSED CRACK IN A POST-TENSIONED SLAB.

4 EXPERIMENTAL CONSIDERATIONS

Most experiments so far have relied on commercial equipment which is fully enough for laboratory experiments. For monitoring of real structures dedicated, robust, energy efficient and compact equipment is required. Transducers for embedment in concrete as shown in

Figure 2 might be a part of the solution, minimizing environmental influence and ensuring robust and durable coupling to the structural concrete.

The appropriate frequency range has been discussed in a couple of publications. A summary and recommendations (multiple scattering regime 50 – 150 kHz for structural concrete are given in [3] and [14].

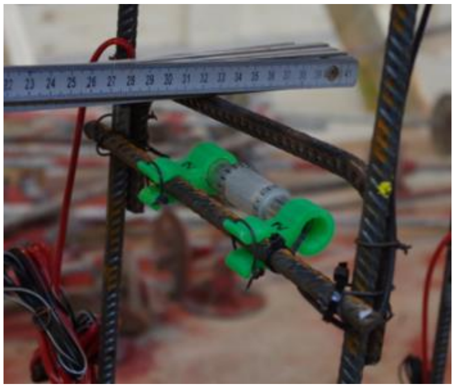

FIGURE 2: ULTRASONIC TRANSDUCER FOR EMBEDMENT IN NEW AND EXISTING CONCRETE ELEMENTS [12].

5 IMAGING

When monitoring larger structures, imaging procedures are required, which project the data and features acquired by a specific transmitter-receiver combination to the correct position on or inside the structure. Methods conventionally used for ultrasonic echo experiments are not applicable here.

Recently, simple straightforward imaging methods have been proposed, assigning the evaluated features to the center between transmitter and receiver [13] or the line connecting them [14], followed by spatial interpolation. While these approaches are very fast and suitable for online monitoring and able to delineate zones of compression, tension or damage, they have very limited resolution and potential of quantification.

More sophisticated methods are using realistic estimates of the spatial sensitivity of all transmitter and receiver combinations, followed by an inversion procedure to reveal more subtle details of damage and, after calibration, material parameters. While earlier approaches have used a diffusive model to calculate the sensitivity kernels, radiative transfer has been shown to be a more accurate solution, especially for early time windows and small transmitter-receiver spacings [15].

Those diffusive or radiative transfer kernels are used to invert the observations from various combinations of transmitter S and receivers R: the apparent relative velocity changes from surface sensors $dv/v_{app}(S,R,t)$ are inverted to local velocity changes in the 3D medium $dv/v(x)$, and apparent decorrelations $K_d(S,R,t)$ are inverted to yield local density of scattering cross section change $\sigma(x)$, related to structural changes. Local relative velocity changes are dimensionless and related to change of stress, humidity or damage. Density of scattering cross-section change have the dimension of a surface per volume (m^2/m^3) and can be visualized or imagined as a density of microcracks, even that in some cases structural changes are not associated solely to microcracks but also to geometrical changes or moisture evolution.

Meanwhile, these ideas have been used to map stress and damages with sparse transducer networks even in structures of significant size [16]. However, for very large and/or complex shaped structures manageable but sufficiently accurate solutions have yet to be found.

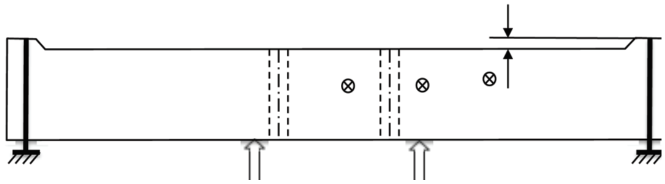

FIGURE 3: FRONT VIEW OF THE SETUP OF LOAD EXPERIMENT ON A 6.1 X 0.8 X 1.6 M³ BEAM [16]. ULTRASONIC TRANSDUCERS ARE DISTRBUTED ON TOP.

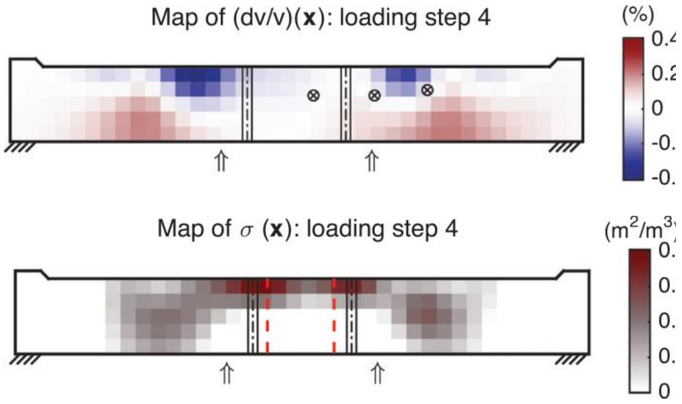

FIGURE 4: MAPS OF VELOCITY CHANGE(TOP) AND MICROSTRUCTURAL CHANGES (EFFECTIVE CROSS-SECTION, BOTTOM) FOR A SPECIFIC LOADING. FROM [16].

4. CONCLUSION AND OUTLOOK

The last comprehensive review on ultrasonic monitoring of concrete structures by CWI is just a few years old. However, science and applications as well as the interest gained from potential users have made very good progress. Meanwhile methods have been proposed to improve the experiments e g. by embedded transducers, to get additional insight into the connection between ultrasonic features and material parameters and condition e. g. by nonlinear CWI as well as to improve the imaging of larger structure by a radiative transfer approach and inversion.

As some of the basis connections between material, structural and ultrasonic parameters are not yet fully understood, the authors think that lab studies on a larger scale, connected to simulations in the material and ultrasonic domain (“digital twins”) would be beneficial. However, the first practical applications on real structure can be envisaged soon.

ACKNOWLEDGEMENTS

The authors acknowledge the contributions of various colleagues within their institutions and the cooperation with external partners – too many to be fully listed here.

REFERENCES

[1] ASTM C597 – 16: Standard Test Method for Pulse Velocity Through Concrete

[2] DIN EN 12504-4: Prüfung von Beton in Bauwerken - Teil 4: Bestimmung der Ultraschallgeschwindigkeit

[3] Thiele, M., Experimental investigation and analysis of damage evolution in concrete due to high-cycle fatigue loading. PhD Thesis, Technische Universität Berlin, Berlin (in German) (2015).

[4] Planès, T., E. Larose, A Review of Ultrasonic Coda Wave Interferometry in Concrete. Cement and Concrete Research 53 (2013): 248–55.

[5] Payan, C., V. Garnier, J. Moysan, Potential of Nonlinear Ultrasonic Indicators for Nondestructive Testing of Concrete. Advances in Civil Engineering, Volume 2010, Article ID 238472, 8 pages. Doi:10.1155/2010/238472.

[6] G. Poupinet, W. L. Ellsworth, J. Frechet, Monitoring velocity variations in the crust using earthquake doublets: an application to the Calaveras fault, California, J. Geophys. Res. 89 (1984), 5719–5731.

[7] R. Snieder, A. Grêt, H. Douma, J. Scales, Coda wave interferometry for estimating nonlinear behavior in seismic velocity, Science 295 (2002), 2253–2255.

[8] 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 (2009), 1853-1856.

[9] Grêt, A., R. Snieder, J. Scales, Time-lapse monitoring of rock properties with coda wave interferometry. JGR: Solid Earth, 266 111(3) (2006), 1–11.

[10] Zhang Y., O. Abraham, V. Tournat, A. Le Duff., B. Lascoup, A. Loukili, F. Grondin, 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), 1038-1045 (2012). Doi: 10.1016/j.ultras.2012.08.011

[11] Legland J.-B., Y. Zhang, O. Abraham, O. Durand, V. Tournat, Evaluation of crack status in a meter-size concrete structure using the ultrasonic nonlinear coda wave interferometry. JASA, 142 (2017), 2233. Doi: 10.1121/1.5007832

[12] Niederleithinger, E., J. Wolf, F. Mielentz, H. Wiggenhauser, S. Pirskawetz, Embedded Ultrasonic Transducers for Active and Passive Concrete Monitoring. Sensors 15, Nr. 5 2015): 9756–72.

[13] Niederleithinger, E., X. Wang, M. Herbrand, M. Müller, Processing Ultrasonic Data by Coda Wave Interferometry to Monitor Load Tests of Concrete Beams. Sensors 18, Nr. 6 (2018): 1971.

[14] Fröjd, P., P. Ulriksen, Detecting Damage Events in Concrete Using Diffuse Ultrasound Structural Health Monitoring during Strong Environmental Variations. Structural Health Monitoring (2017), 147592171769987.

[15] Planès, T., E. Larose, L. Margerin, V. Rossetto, C. Sens-Schönfelder, Decorrelation and Phase-Shift of Coda Waves Induced by Local Changes: Multiple Scattering Approach and Numerical Validation. Waves in Random and Complex Media 24, Nr. 2 (2014): 99–125. doi: 10.1080/17455030.2014.880821.

[16] Zhang, Y., T. Planes, E. Larose, A. Obermann, C. Rospars, G. Moreau . “Diffuse ultrasound monitoring of stress and damage development on a 15-ton concrete beam”. JASA 139, 4 (2016), 1691-1701. Doi: 10.1121/1.4945097