

# DETECTION OF CRACKS PERPENDICULAR TO THE SURFACE USING ACOUSTIC METHODS

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## Abstract

Cracks perpendicular to the surface may be initial indicators for a deterioration process of concrete structures. Moisture penetrates inside the structure and transports adverse chemicals. The paper presents an investigation about the reliability of available commercial non-destructive evaluation techniques to reliably estimate the depth of surface-breaking cracks in reinforced concrete structures. Aim of the study was the investigation of surface-braking cracks under laboratory conditions. Commercial acoustic devices as impact echo equipment, single ultrasonic transducers and arrays were applied even if they have not been developed for this purpose. The commercial software and descriptions for application was followed strictly to compare the function, precision and repeatability of the measurements. Both, perpendicular notches and cracks have been considered. The study was completed with a discussion about reference specimens. The study was the basis for formulation of gaps in research. The Electric Power Research Institute (EPRI) has initiated and funded a project [1].

**Keywords:** Acoustic test, commercial acoustic devices, ultrasonic test, crack depth, concrete specimens.

## 1. Introduction

### 1.1 Measurement task definition

Surface braking cracks can develop in concrete structures due to insufficient treatment during curing, because of differential settlement, corrosion, chemical attacks, freeze-thaw cycling, corrosion, overload or other reasons. Cracks perpendicular to the surface may an initial indicator for a beginning deterioration process of concrete structures. Depending on the environmental conditions, moisture and soluble ions could penetrate inside the structure and impair more serious damage. Cracks, perpendicular to the surface, on the other side, are necessary to activate the tensile reinforcement in reinforced concrete structures to allow the steel reinforcement bars to take over the tensile stresses. These last-mentioned cracks are usually near-surface cracks. The crack opening is limited to 0.2 mm and to only 0.1 mm in waterproof structures according to design standards. Once cracks were initiated they may allow deterioration of reinforced concrete structures, especially under adverse environmental conditions, if water with dissolved aggressive elements like chloride or sulfate ions could penetrate inside the massive concrete structure. Penetration of chlorides in a moist concrete influences the concrete properties and may change the passive alkalized film around the reinforcing bar. In these cases, after depassivation, a corrosion process starts and forms pits on the reinforcing steel surface. Carbonation may also cause reinforcement corrosion with volume increase due to penetrating carbon

dioxide from the air into a low quality concrete. In difference to chlorine induced corrosion, this would be a more regular distributed corrosion along the whole length of the reinforcing bars. To prevent fast deterioration of the concrete structure, early estimation the current depth of cracks would be of advantage. Early knowledge about crack depth allows introducing preventive or repair measures to severe cracks for service life extension of affected structures as buildings, bridges or even nuclear power plant containments.

The presented study focusses on the investigation of available commercial non-destructive evaluation techniques regarding their potential to detect cracks in reinforced concrete structures perpendicular to the surface reliable and repeatable [1]. Commercial acoustic and ultrasonic methods use commercial impact echo devices, single ultrasonic transducers and ultrasonic array arrangements including a linear array. The study focused on precision and reliable repeatability of the crack depth measurement perpendicular to the surface. Both, perpendicular notches and cracks have been considered.

## 1.2 State of the art

Most available commercial acoustic devices as impact echo equipment, single ultrasonic transducers and ultrasonic arrays including a linear array have not been developed for this purpose. Surface breaking cracks vertical to the surface are topic in many research projects. Among others, Time of Flight (ToF) based on surface diffraction of ultrasonic waves already presented by Krautkramer [2], non-linear mixing of ultrasonic coda waves, developed by Abraham et al. [3] and post-processing using the Total Focussing Method (TFM), published by Felice et al. [4] are promising methods. The TFM is an ultrasonic array post-processing technique which is used to synthetically focus at every image point in a target region [4]. When applying ToF-method to estimate the crack depth, the location of the crack must be well known to place both sensors on two opposite sides of the crack. The distance must be the same to mathematically derivate the run time of the diffracted signal and estimate the depth of the crack. What was working quite well with steel, causes difficulties in a heterogeneous material as concrete. Difficulties arise due to a relatively long micro cracking area at the crack tip that may finally lead to high deviations or errors. If the emitter is placed on a fix position on the surface and the receiver is moved along the surface over the crack and in a direction perpendicular to the surface breaking crack, the recording shows a clear indication of the crack location. In earlier research at BAM, Mielentz et al. applied single transducers for impacting and moving transducers for getting an indication of the crack depth [5], [6]. During these manual tests, noncommercial software was used for data acquisition and processing. Popovics & Zhu [7] analyzed surface waves for crack depth estimation.

## 1.3 Objectives and scope

Commercial acoustic devices as impact echo equipment, single ultrasonic transducers and ultrasonic arrays including a linear array were applied even if they have not been developed for this purpose. The commercial software and descriptions for application was followed strictly to compare the function, precision and repeatability of the measurements of the crack depth. Both, perpendicular notches and cracks have been considered for comparison.

One of the project objectives was comparing measurement results on specimens with artificial notches with as realistic specimens as possible. In the scope of this study, a new type of specimen was proposed.

Finally, the research needs and needs for method optimization of commercial sensors and appropriate software were derived from the project results.

## 2. Specimens

In difference to homogeneous steel, where crack depth measurement is a standardized method [2], the heterogeneous structure of concrete, consisting of cement matrix and aggregates, is more complicated to investigate. Besides all non-regular crack growth and acoustic bridges, a characteristic for crack propagation

in concrete is the formation quite long micro-cracking section in front of the macro-crack tip. During micro-cracking the cement matrix separates from hard and brittle aggregates, while the cement matrix still forms acoustic bridges. This would require a clear definition from what point of separation or crack tip opening we call a crack a crack.

A series of specimens with known artificial notch depth was applied. The notch depth was between 15 and 150 mm. The notch depth was constant or varied from 50 to 180 mm. In some specimens, reinforcement formed acoustic bridges. Figure 1 shows one of the specimens with two notches and reinforcement.

A proposal for a new specimen was presented using a method to generate an as precise as possible crack length, here 10 cm and 20 cm according to the requirements of the client supporting this study. The general shape of the specimens was comparable to a single edged bending specimen (SENB). Grooves along both sides shall reduce the cross section area as deep as the crack shall propagate. The groove also reduces the restraint and forces the crack to grow strictly perpendicular to the surface. This was a requirement of some producers of acoustic devices for successful crack depth measurements. A short initial notch on the lower surface will guarantee the stress concentration along a line on the surface for regular crack initiation. Both measures together, notch and grooves, aim at a steady crack growth, perpendicular to the surface. Besides 5 specimens with reinforcement layers at the intended crack depth, two specimens were not reinforced at all to prevent any deviation of the crack propagation.

The width of the specimen- in this study- was limited by the maximum load in the available beam testing machine. The beam testing machine has a maximum applicable load of 100 kN. With reference to this maximum applicable load, the concrete quality of 50 cm wide specimens was chosen to be lower to enable the crack initiation. On both sides, a groove of the intended length of the crack to be produced was designed in the formwork. The set-up of the crack generation in the machine is visible in Figure 2.

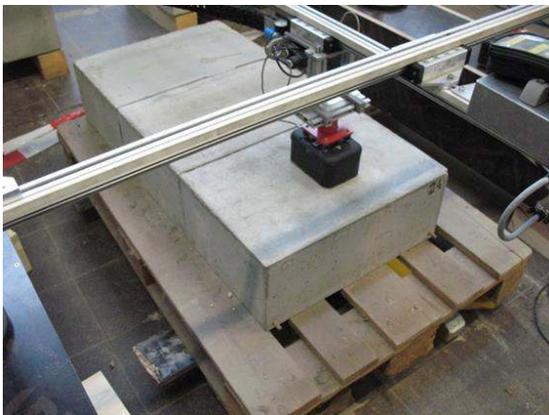


Figure 1. Test specimen with notches, see above) with and without acoustic bridges (reinforcement)

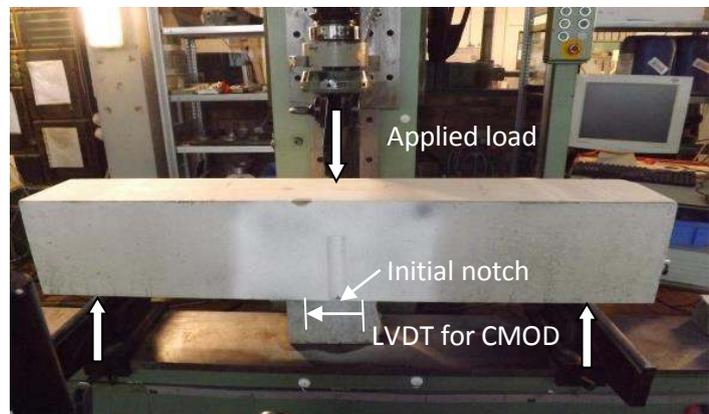


Figure 2. Test specimen during crack generation intending to create a crack depth of 20 cm. LVDTs were installed to measure Crack mouth opening displacement (CMOD)

The width of specimens was min 30 cm or 50 cm wide because of requirements for ultrasonic testing by scanning. The necessary load for initiating the crack growth was estimated based on the individual material strength tested in standard tests after 28 days.

Figure 3 shows the color-coded visualization of the groove of the unloaded specimen (left), the groove at the maximum load (middle) and the photograph of the cracked specimen (crack depth 20 cm) after unloading the specimen (right). The visualization method ARAMIS was applied to control the crack propagation during all load levels. The reinforcement was located at the end of the groove intended to stop the crack propagation.

Unfortunately, the crack tip changed the propagation direction or divided into two tips influenced by the reinforcement orientation. Only in few specimens it was possible to stop the crack propagation at the end of the groove, as the micro cracking and the internal forces caused crack propagation even without load increase.

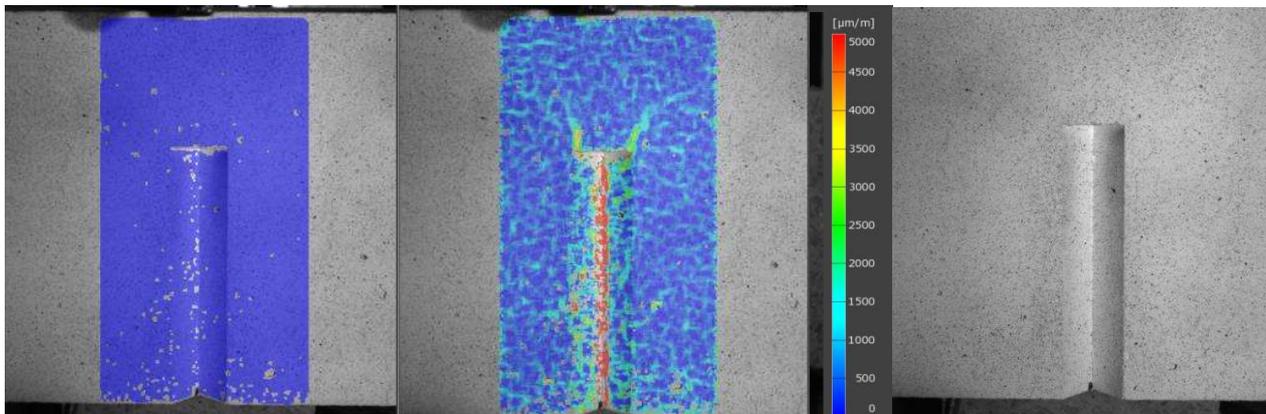


Figure 3. Visualization of the crack generation by using the color-coding strain visualization tool ARAMIS, from left to right: strains before load application, at maximum load, after unloading the cracked specimen

### 3. Crack depth measurements using commercial devices

In order to test the reliability of commercial devices under weaker conditions, we used specimens with notches in a first step. Two producers of low frequency devices promise to be able to measure crack depth reliably, but within strict limitations as perpendicular crack to the surface, no acoustic bridges due to dirt or water and only for sufficient depth and sufficient distance to the edges.

Further devices as low frequency arrays with dry point contact transducers were tested, although they were not developed for crack depth measurements and neither commercial software for processing nor visualization was applied. In a last set-up, single transducers were used, the first was remaining in a constant position while the receiver is moving perpendicular to the surface crack orientation from one side of the crack to the other side. The receiver may be replaced by a Laser vibrometer [5].

For the applications presented in other literature laboratory specimens were used regularly, often with notches instead of cracks and self-developed software for data analysis. They are not reliably adaptable to real structures with commercial devices using commercial software.

Low frequency ultrasonic echo has been applied as an appropriate method for the analysis of the inner structure and depth of concrete in the last decades. An ultrasonic wave transducer transmits elastic waves into the concrete. The receiver collects returning changed signals, refracted, diffracted and reflected at interfaces as reinforcement, anchors, back wall, surface-parallel cracks, edges or crack tips.

Only two devices on the market offer besides characterization of concrete properties an inbuilt mode for crack depth measurements. The restrictions for successful application for precise measurements required by the producers are quite limited:

1. Dry-coupling piezo-ceramic point-contact, longitudinal-wave device, 50 kHz, appropriate for crack depth measurement between 10-50 mm with a relative deviation of 1 %,
2. Dry-coupling point-contact longitudinal-wave device, 54 kHz, cracks must be strict vertical and clean, without any dirt or water, reinforcement influences the measurement result. A minimum distance to the edges of the specimen hat to be considered.

These devices refer to the former BS 1881 Part 203 (1986) that presented mathematical expressions for the estimation of vertical surface breaking cracks. The mentioned method bases on Time of Flight (ToF) measurements. Earlier studies, e.g. [4] already showed, that ToF method applied acc. to the mentioned BS results in an error of about 15% deviation, measured on specimens with cracks (notches) with different depth. The principle of ToF of the diffracted and reflected waves presents Figure 4. The transmitter and receiver are located on both sides of a crack with known location. Already in 2003, Popovics & Zhu summarized: “The time-of-flight method however is not effective when realistic concrete cracks are tested, that is when the crack tip is ill defined and the crack is tightly closed” [7]. They presented the analysis of surface wave measurements instead, as shows Figure 5. Impactors apply a point load onto the surface and receivers measure the response of the signal influenced by the surface-breaking crack on both sides of the crack in equal distance.

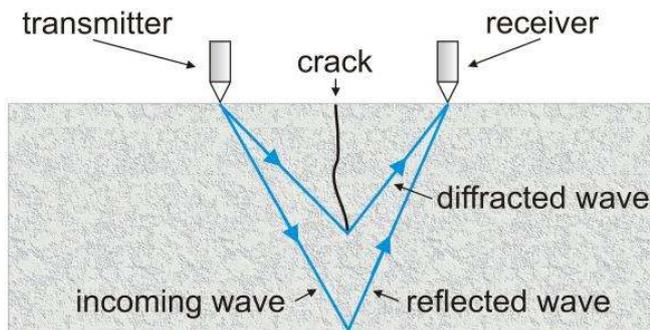


Figure 4. Sketch of diffracted and reflected wave in Time of Flight (TOF) measurements [1]

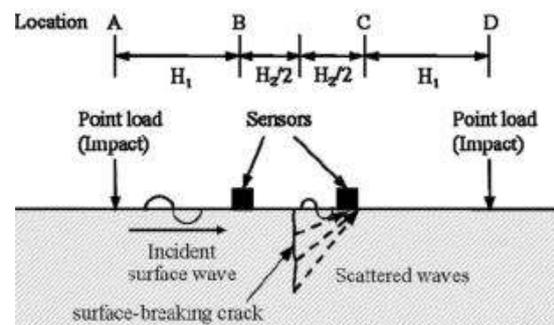


Figure 5. Surface wave measurements using impact echo measurements with indication of scattered waves at the surface-breaking crack [7]

## 4. Ultrasonic Measurements

### 4.1 Ultrasonic testing of specimens with notches

The two devices for low-frequency ultrasonic measurements work according to the principle of the time of flight (ToF) method. Both devices show the result on the screen of the device, thus a postprocessing is not possible. The results did not reach the required repeatability and reliability. The deviation from the true value of the notch depth was between 4 % and 40 %. Thus our measurements of notch and crack depth confirmed the findings of Popovics & Zhu [7]. In concrete, several influencing effects as micro cracks or acoustic bridges influence the signal to a degree that prevents reliable measurements.

Besides ToF measurements with single US-transducers, the surface of the specimens with notches (Figure 6) was scanned using the low frequency array. The measurement was carried out along a dense grid (2 cm x 2 cm). The depth of the reinforcement and the depth of the notch were visualized with a deviation of roughly 10 %. Figure 7 shows the point measurement results of the array position above the notch (A-scan) and line scans (B-scan) perpendicular to the notch as well as along the notch (D-scan). Non-commercial software developed at BAM was used for the scanner hardware control and for postprocessing and analysis the three-dimensional data sets.



Figure 6. Specimen with artificial notch used for surface scanning by means of a low-frequency US array with dry point contact (see Figure. 1)

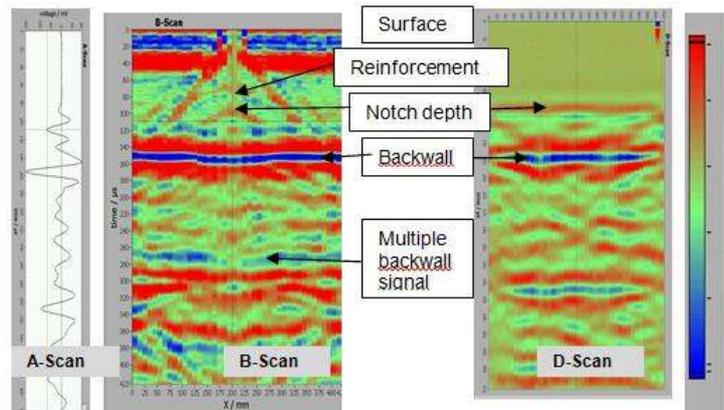


Figure 7. Results of the US-echo surface scanning of a specimen with a notch and with reinforcement perpendicular to the notch forming an acoustic bridge

A further device was tested, although it was not developed to measure crack depth. A linear array that uses an internal SAFT-algorithm was employed to check its potential for crack depth measurements. Figure 8 shows the display of a measurement with the linear array perpendicular to a specimen without initial notch, before and after cracking. Here, the signal is already processed inside the device and the online screenshot clearly images the back wall reflection. A disturbance at the vertical crack indicates that there is an irregularity as a notch. In these cases, non-commercial software was used for data processing. Further tests of repaired cracks have been presented by Friese et al. [9].

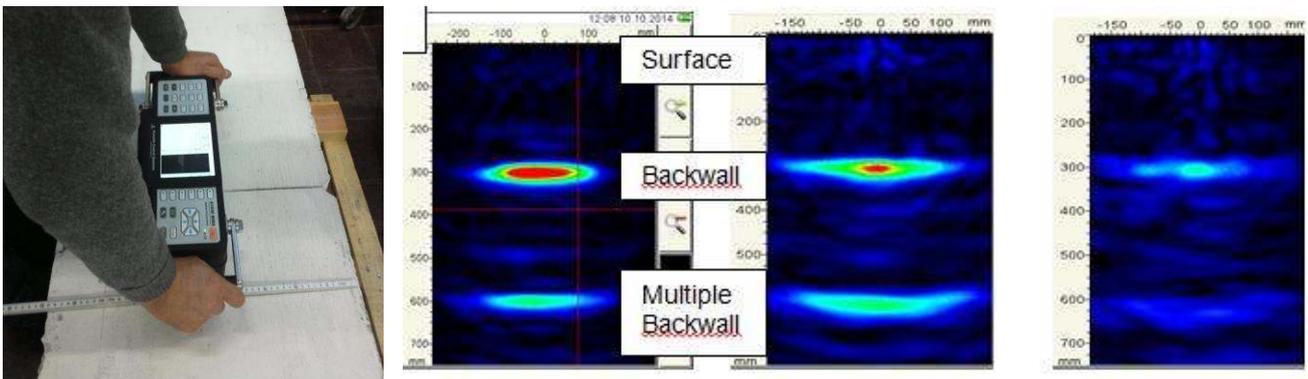


Figure 8. Example measurements applying an linear US array with internal data processing (Synthetic Aperture Focusing Technique (SAFT)): the notch reduces back wall signal, but no clear indication for crack depth (middle, right)

## 4.2 Ultrasonic testing of specimens with cracks

All available ultrasonic devices were applied to the cracked specimens. Although the location of the cracks on the surface can be visualized, the repeatability of the depth estimation was not reliable enough. Although the low frequency arrays with point contact transducers and the ultrasonic linear array was not developed for crack depth measurements, it was included in the study.

As mentioned above, the application of commercial crack depth measuring devices did not lead to the expected precision during the measurement on the available notched and cracked specimens, as well. Under real conditions on site, the inspector does not know in advance, whether he will meet the limits of the device defined by the producers regarding crack depth, i.e. if the crack is propagating perpendicular to the surface or

whether the crack would be located in the required distance to edges. Real crack formation and orientation depends on the cause, as e.g. shrinkage, chemical deterioration, load or settlements.

Here, we want to present an example of more successful testing of the crack depth obtained by US-scanning techniques. A low frequency ultrasonic array with dry point-contact transducers was applied with a small measurement grid size of 2 cm and 2 cm line spacing. A specimen with two reinforcing bars was available for comparison of the influence of acoustic bridges on reinforcement reflections and diffraction of waves due to the crack (Figure 9). In this specimen, the corrosion of one rebar caused a crack on the surface along its whole length. The other rebar has served in an earlier corrosion experiment as cathode and was not corroded. The concrete around the second rebar is not cracked.

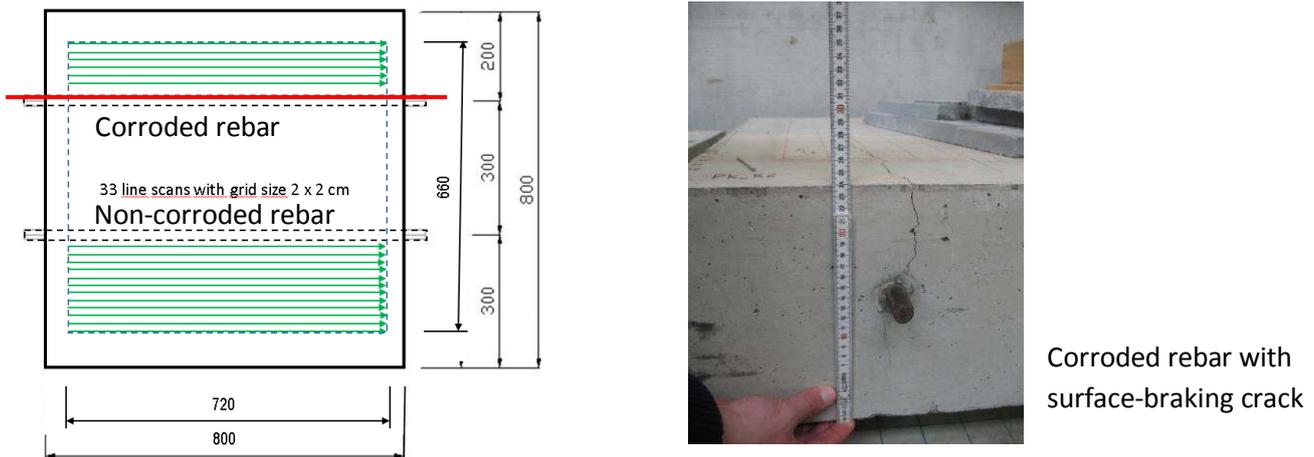


Figure 9. Specimen with two reinforcing bars: the upper bar was artificially corroded, corrosion caused a crack along the whole length of the rebar. The second embedded rebar was not corroded and serves for comparison

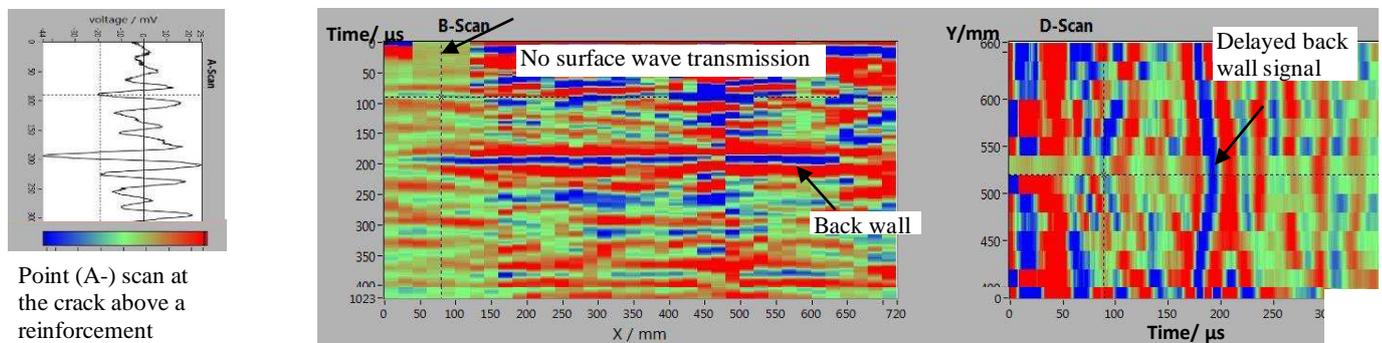


Figure 10. Example: Ultrasonic array measurement above a crack caused by corrosion of a reinforcing bar. The line scan (B-) scan is perpendicular to the crack and to the corroded reinforcement. The transverse image (D-Scan) crosses the corroded reinforcement

The measurement results from the scan with the low frequency ultrasonic array along a surface above the crack is presented in Figure 10. The phase of the received signal of the reinforcement (example see in a point (A-) scan, left) does not have a phase shift. As in case of reflection from steel, the phase would have shifted, this signal very probably originates from a diffracted wave. Where the crack is located below the array no surface wave is transmitted as visible in the line scan (B-scan) The back wall signal is clearly at 24 cm (at  $\sim 190 \mu s$ ). The detail of the D-scan showing the cut through the 3D-data-set perpendicular to the B-scan and crossing the reinforcement shows a delay or seemingly a displacement of the back wall signal.

## 5. Conclusions

The study was the basis for formulation of gaps in research and development of specimens and requirements for commercial software development. The following research needs for further development of Non-destructive evaluation have been derived:

1. Reference specimens would allow an appropriate comparison of the potential of non-destructive testing devices for measuring the crack depth.
2. Promising results were obtained in scanning the surface at the crack. None the less, scanner and its control as well as the applied software for data analysis are not commercial.
3. Further initial research is promising and needs an integrated project of experts from several leading institutes to further increase the reliability of crack depth measurements with the intention to standardize and commercialize the most appropriate methods.

While the measurement of crack sizing is well established for homogeneous steel, it is much more complicated to measure the depth of surface-breaking cracks in heterogeneous concrete. The heterogeneous structure of concrete consisting of a cement matrix and aggregates does not allow a precise crack depth generation. In concrete, the open macro crack with separated edges may be as long as the damaged micro-crack below the macro-crack. The area of micro-cracks diffracts parts of the ultrasonic wave but at the same time there are unknown acoustic bridges due to aggregates, dirt or reinforcement. It is assumed that unknown micro-cracks and acoustic bridges are responsible for the poor repeatability of the ultrasonic measurements. So far, no definition of a crack tip is agreed. The definition of a crack could, e.g., consider width of the crack on the surface or limit of the Crack Mouth Opening Displacement (CMOD) between 0.1 and 0.2 mm, which are terms and values that are known requirements in structural engineering standards.

Scanning of the surface and other methods under research as set-ups with at least one moving transducer may offer some chance for crack depth measurements [1]. Methods, like the one applied to crack depth measurement in steel structures uses multiple reflections from the crack edges and back wall, might be transferred to low frequency measurements and concrete structures [2]. If the side is accessible, methods like ultrasonic mixing [3] or using an array with postprocessing [4] may lead to more reliable standardized or commercial methods

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