

# Evaluation of retroreflective corner echo for detection of surface breaking cracks in concrete by ultrasound

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## Abstract

The retroreflective corner echo is used, for example, in ultrasonic non-destructive testing of metals to find fatigue cracks in tubes or shafts. If the much weaker crack tip signal is additionally detected, the crack length can also be determined. A corner reflection occurs in cases of surface breaking cracks with predominantly perpendicular orientation to the surface. The intensity of the corner reflection depends on the angle of incidence and on the ultrasonic wave mode used. For the reliable detection of vertical surface breaking cracks in metals, transversal waves are commonly used, which propagate at an angle of 37° to 53° to the inspection surface. As shown in this contribution, the wide spread low frequency ultrasonic arrays with dry point contact sources available for ultrasonic testing of concrete also allow to receive corner echoes. These devices generate transversal waves in concrete structures with a large divergence of the sound field. A series of experiments was carried out with such dry point contact arrays on concrete specimens with artificial test defects and controlled induced cracks of different depths. The ultrasonic time-of-flight signals were recorded, exported and reconstructed utilising the SAFT (Synthetic Aperture Focusing Technique) algorithm. The SAFT reconstruction parameters were adjusted to visualize the corner echo indication. As will be shown, with this targeted processing, the reproducible detection of surface breaking cracks in concrete is possible. The retroreflective corner echo can thus be exploited in civil engineering for non-destructive inspection of concrete.

**Keywords:** Ultrasonic testing of concrete, corner echo, surface breaking cracks, non-destructive testing in civil engineering (NDT-CE), SAFT (Synthetic Aperture Focusing Technique)

## 1 Introduction

A variety of studies on non-destructive testing methods for crack-depth determination in concrete has been reported. While micro cracks or cracks with small surface opening are common and classified as acceptable according to standards [1], larger cracks may accelerate the transport of gaseous and liquid substances, thus induce corrosion of the steel reinforcement and in consequence endanger the stability of the structure. Methods for crack depth measurement are in addition important in cases in which concrete structures function as a barrier against environmental hazards.

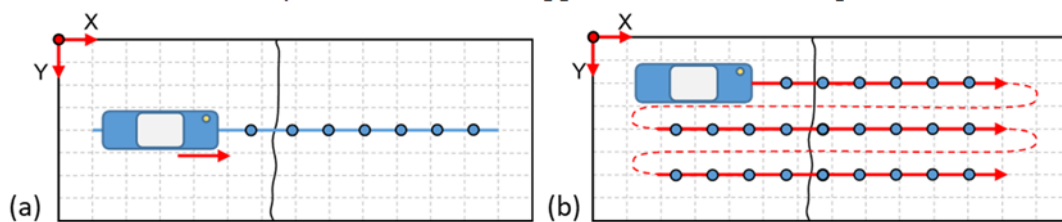
Traditional and well known ultrasonic methods for crack depth determination in concrete are based on time-of-flight (TOF) measurement [2]. Time-of-flight techniques are also applied for crack depth measurement with impact-generated stress waves [3]. The TOF method, which evaluates the first arrival of the pressure wave, which depends on the crack depth, works well with artificial defects like notches or with fully open cracks. However, in case of real cracks

with contacting surfaces, TOF often does not deliver a conclusive result. Another set of studies uses surface wave transmission for crack depth estimation [4, 5] or the diffusion of incoherent ultrasonic energy [6-8], but partially closed vertical cracks, which transmit energy, are difficult to characterise with this method. Ultrasonic dry point contact (DPC) transducer arrays for concrete provide tomographic cross-sections of the examined component by fast acquisition of multiple A-scans and post-processing of the data with SAFT [9, 10]. For example, component back-walls, reinforcement bars and horizontal delaminations were successfully imaged with shear wave arrays [11]. However, though the depth of notches was successfully imaged with DPC shear wave arrays, depth measurement of real cracks was not successful so far [12].

## 2 The corner echo method

The corner echo method, which we present in this contribution, can be used to determine whether a surface breaking crack is a through crack or not. By “through” crack we mean a full-depth crack with crack depth equal to the slab thickness. The method can also be used to find vertical cracks that are growing from the back face of the slab, and which are not visible from the surface accessible for the measurement.

The measurement and evaluation procedure was developed using concrete specimens with the dimensions  $1.5 \text{ m} \times 0.6 \text{ m} \times 0.25 \text{ m}$  (length  $\times$  width  $\times$  thickness) with notches and cracks initiated under controlled conditions [13]. Line-scans and area scans with scanning direction perpendicular to the crack line were acquired on the top surface of the blocks using the linear array A1040 Mira (Acoustic Control Systems, ACS). The frequency of excitation was 50 kHz. The raw ultrasonic data were stored in *map mode* during the measurement and subsequently transferred to the server system of IZFP for further evaluation. The coordinate-system of the x-y plane (scanned surface) is shown in figure 1. The z-direction is pointing into the component. The zero of the coordinate system is in the left upper corner of the component surface.

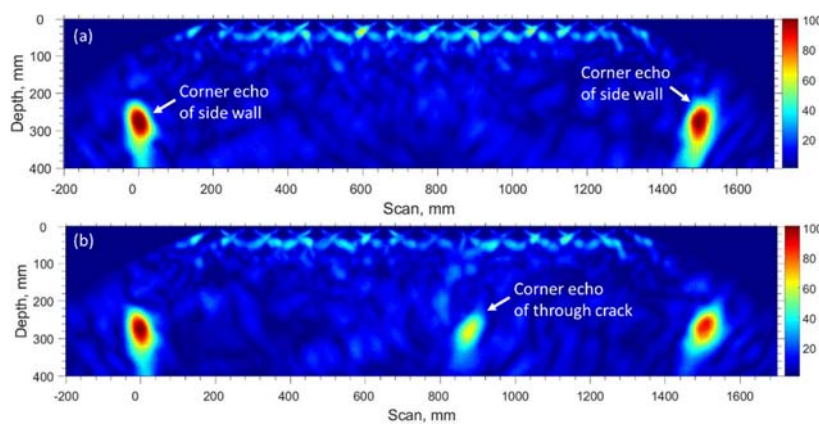


**Figure 1:** Image acquisition and scanning procedure with the linear array A1040 Mira: (a) line scan perpendicular to the crack, (b) area scan as a set of line scans.

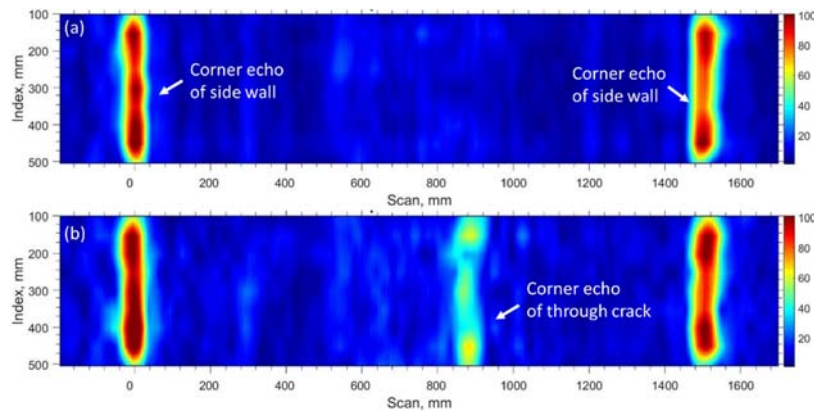
All defects, i.e. the notch and the vertical cracks with different depth, were open at the top surface of the component. The top surface of one specimen was first measured in intact state without defect. Afterwards a separating crack was generated using the method described in [13]. To confirm that the crack completely penetrated the specimen, it was turned to inspect the back surface, where the crack was visible over its full width. After the through crack was formed and verified by optical inspection, the specimen was scanned from the top surface again.

The B- and C-scans and the tomographic SAFT-images as provided by the algorithms implemented in the instrument indicate the existence of the crack or notch at the right position. The depth of the vertical crack or notch cannot be estimated from the images obtained by standard SAFT-processing, and it is inconclusive whether the crack is a separating crack or not.

This means, an adapted measurement and post-processing procedure is needed in order to visualise the opening of the separating crack to the back face. To verify the crack being a through crack, one can take advantage of the fact that a vertical crack and the back wall of the component form a right-angled corner. Such a corner functions as a retroreflector for acoustic waves impinging from any direction. The corner echo was subject to numerous studies in connection with detection and sizing of cracks in metals [14]. For the shear vertical (SV) waves commonly used for metal inspection, the strongest reflection is obtained under an angle of  $37^\circ$ - $53^\circ$  of the incoming wave [14]. Using the shear horizontal (SH) waves generated by the Mira array, the corner echo can either be visualised by choosing appropriate positions of the Mira instrument relative to the corner and/or by distinctively limiting the angles of the reconstruction.



**Figure 2:** SAFT-B-Scan of one scan line ( $y = 450$  mm) on the specimen without defect (a) and with separating crack (b). The opening angles of SAFT reconstruction were limited to  $\pm [40^\circ-70^\circ]$ .



**Figure 3:** SAFT-C-Scan, reconstruction angles  $\pm [40^\circ-70^\circ]$ , of the specimen without defect (a) and with separating crack (b). The depth of the C-scan interval was set from 240 mm to 270 mm.

Figures 2 and 3 show SAFT B- and C-scans of the component without defect (Figs. 2(a) and 3(a)) and with separating crack (Figs. 2(b) and 3(b)). The indications at the left and the right side are the corner reflections of the left and right side walls of the concrete specimen. They appear at  $x = 0$  mm and  $x = 1500$  mm at a depth of 250 mm (i. e. component thickness). While the test specimen without defect does not show any other high intensity indications except those from its side faces, the images of the component with separating crack present an additional indication at the  $x$ -position of the crack and a  $z$ -position equal to the specimen thickness. The images were obtained with programs written in MATLAB (MathWorks) by IZFP.



The indication of the corner echo can be used to decide whether a crack is a separating crack or not. It can further be used to detect cracks which are open to the back-wall surface. Respective tomographic images of test specimens with different thicknesses and different crack depths have confirmed the applicability of this method.

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### References

- [1] Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings; German version EN 1992-1-1
- [2] British Standard BS 1881, Testing Concrete, Part 203, 1986. Recommendations for measurement of velocity of ultrasonic pulses in concrete
- [3] M. Sansalone, J.-M. Lin, and W. B. Streett, *ACI Materials Journal* 95 (1998) 168-177
- [4] J.S. Popovics, W.-J. Song, M. Ghandehari, K.V. Subramaniam, J.D. Achenbach, and S.P. Shah, *ACI Materials Journal* 97 (2000) 127-135
- [5] E. Ahn, H. Kim, S.-H. Sim, S.W. Shin, J.S. Popovics and M. Shin, *Sensors* 18 (2018) 2793
- [6] S. K. Ramamoorthy, Y. Kane, and J.A. Turner, *J. Acoust. Soc. Am* 115 (2004) 523-529
- [7] Chi-Won In, Kevin Arne, Jin-Yeon Kim, Kimberly E. Kurtis, Laurence J. Jacobs, *Journal of Nondestructive Evaluation* 36 (2017) 4
- [8] A. Quiviger, C. Payan, J.-F. Chaix, V. Garnier, J. Salin, *NDT&E Int.* 45 (2012) 128-132
- [9] V.G. Shevaldykin, A.A. Samokrutov and V.N. Kozlov, *Proc. IEEE Ultrasonics Symposium 2002*, 793-798
- [10] A.O. De La Haza, A.A. Samokrutov, P.A. Samokrutov, *Construction and Building Materials* 38 (2013) 1276-1291
- [11] Pangil Choi, Dong-Ho Kim, Bong-Hak Lee, Moon C. Wong, *Construction and Building Materials* 121 (2016) 81-91
- [12] M. Friese, F.U. Vogdt, H. Wiggenhauser, *Beton- und Stahlbetonbau* 106 (2011) 471-480
- [13] H. Wiggenhauser, C. Köpp, J. Timofeev, H. Azari, *Journal of Nondestructive Evaluation* 37 (2018) 67
- [14] H. Krautkrämer, *Ultrasonic Testing of Materials*, Springer, Berlin, 1990, and citations therein.