Performance Demonstration of Non-Destructive Testing Methods

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Abstract. The civil engineering community asks for more non-destructive testing, quality control and sustainability of structures can be observed. For an economical use of non-destructive testing methods, technical information and knowledge about the capacity of existing test methods are necessary. Missing that information makes it more difficult to choose the right testing method for the investigation of concrete structures.
To ensure a better and efficient application of test methods under local conditions, performance demonstrations of non-destructive testing methods have been accomplished. For this purpose, a special specimen (“LCS”) was concreted at BAM, to carry out performance tests of echo methods. The thickness of the specimen is varying and it contains different kind of faults, such as voids, honeycombs and prestressing tendons of varying quality. While the geometry and condition of the defects is well-known the performance of test methods like radar, ultrasonic, impact-echo, thermography etc. can be compared. The research was conducted within the Research group FOR384, sponsored by the German Research Society DFG.

1. Introduction

The use of non-destructive testing-methods for structural components in civil engineering depends on the application reliability of the testing-methods, the knowledge about the application itself and the economical usage. To lead these methods to a wide acceptance in building industry, performance demonstrations have to be implemented. To use these methods for quality control it is necessary to know exactly the performance and usability of the methods.
In this study the different methods were evaluated quantitatively with the help of especially chosen tasks, checked on a reference-sample with defined flaws. This reference-specimen gives the opportunity to test structures in practice, like measuring thickness of concrete elements, locating imperfections as well as detection of position and depth of concrete cover of tendon ducts and estimation of their grouting conditions. These systematic examinations are the basis for a quantitative comparison of the results in view of the performance of the testing-methods and their modifications.
The following article shows partial results to deal with the aspects of locating parts of smaller thickness and positioning of tendon ducts.

The examinations were performed with ultrasonic echo (with transversal and longitudinal waves), impact-echo and radar by researchers of institutions belonging to the DFG research group FOR384 [1]. The results were analysed statistically and evaluated in view of the particular problem and practical needs.

2. Reference specimen

The test object (fig. 1) was named “large concrete slab” (LCS) and was designed by the Federal Institute for Materials Research and Testing [2, 3]. The LCS is a one-sided accessible concrete slab with dimensions 10 x 4 m² and a regular thickness of 0.3 m. These huge dimensions reduce the influence of the unwanted effects of geometry, which are typical for impact-echo. The LCS is mainly divided into two areas of the same size, the first half (area 1) has tendon ducts of different diameter in varying depth. The cable ducts are grouted under pressure with cement mortar, but there are areas, which are intentionally ungrouted.
The second half (area 2) contains next to other fixtures mainly a large variety of parts with smaller thickness with different characteristics made by the help of expanded polystyrene slabs (“MD1” to “MD4”), as well as precast honeycombs “K1” to “K3” (fig. 1-detail). As a reference area “RF” for the determination of wave velocity, there is one location with a steel plate at the bottom, which has a high reflection and therefore is specially suitable for calibrating the radar method.

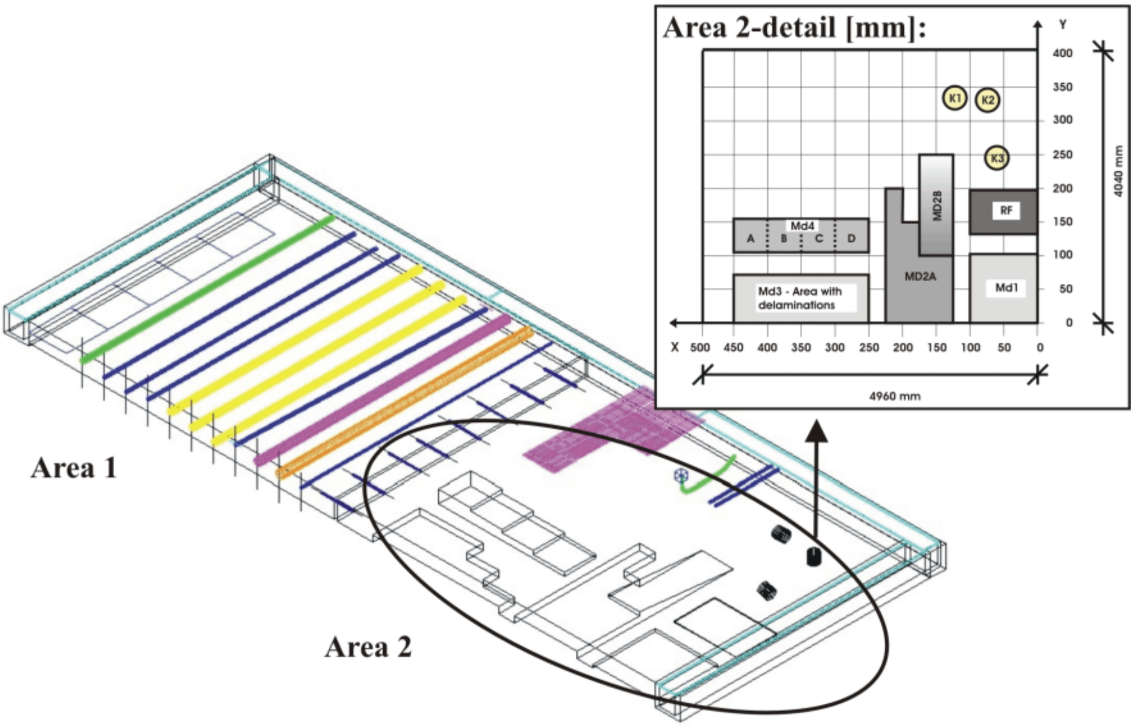

Fig. 1: Drawing of the large concrete specimen (LCS) at BAM with details of area 2 (part with artificial flaws), dimensions in mm

3. Performance demonstration

Systematic errors have to be considered for the performance demonstration of non-destructive testing methods. The quality of results depend on several factors, for example concreting, the body of tested structural elements (i.e. concentration of reinforcement, layer thickness, number and extent of inhomogeneities), test conditions (i.e. temperature, humidity), equipment (i.e. sensors, frequency range, polarisation) and a series of meterological parameters. A value of the measurement inaccuracy can be specified conditionally because the velocity varies from place to place additionally. Furthermore, the measurable extent of a flaw depends on the resolution given by physical boundary conditions like the ratio of the wavelength to the diameter of flaws and the character and intensity of the acoustic and the electromagnetic pulse. In addition, the measurable extent of a flaw depends on the measurement system and the measurement grid. A first estimate of the performance is carried out by comparing these results.

3.1 Testing methods

Acoustical and electromagnetic test methods were used. The participating institutes, the Universität Stuttgart (USt), the Universität of Dortmund (UDo), the Institute for Materials Research and Testing at the Bauhaus-University Weimar (MFPA) and the Federal Institute for Materials Research and Testing (BAM) used commercial and proprietary developed methods. As acoustical methods, the ultrasonic echo and the impact-echo method were applied.

The ultrasonic equipment of the University of Dortmund (US-UDo) [4, 5] is a commercial test system (Dr. Hillger NFUS 2300), but data is recorded by an external daq-card with a higher rate of resolution. The measurements (bistatic) were carried out using two transducers with a nominal frequency of 200 kHz (Krautkrämer G0.2R and G0.2R4). The transducers were hand-operated and coupled with glycerine. Analysis was carried out by metering the maximum values of the echo impulse [6] and additionally considering time delays.

The impact-echo methods of the University of Stuttgart (IE-USt) [7, 8] and BAM (IE-BAM-1 und IE-BAM-2) [9, 10] work with an electric controlled impactor. This testing method can be operated as a single point measurement as well as automated by measurements using a scanner. The data measured by USt were analysed with the LabView based software IEDA. Ultrasonics, radar and impact-echo measurements at BAM were accomplished by a scanner for construction sites [11]. For the ultrasonic method of BAM a dry coupled double transducer probe for shear waves was used (ACSYS A1220) [12]. Also a 3D-reconstruction analysis was applied [13]. The measured value for ultrasonic time of flight is the value between maximum of initial pulse to maximum received pulse regarding the delay.

The ultrasonic equipment of MFPA (US-MFPA) works with water coupled transducers having a bandwith of 180 to 580 kHz into lossless material, and about 200 kHz into concrete. The transducer for pressure waves is mounted on a 2D-scanner and operates in impulse/echo-mode. The data are analysed using 2D and 3D SAFT reconstruction (synthetic aperture focusing technique) [14,15] employing proprietary software.

Measurements using radar (Radar-BAM) were carried out with a 1.5 GHz antenna. Two data sets were obtained detecting the emitted electric field of correlating rectangular polarisational configurations. Both data sets were reconstructed by 3D-FT SAFT separately and superposed afterwards [16]. Raw data have been taken to determinate the velocity of propagation at the reference part and to analyse the concrete cover.

Table 1. Testing methods

indication	type of method	pulse/ wave mode
US-UDo	ultrasonic echo	longitudinal waves
US-MFPA	ultrasonic echo	longitudinal waves
US-BAM	ultrasonic echo	shear waves
IE-USt	impact-echo	impactor (automatic)
IE-BAM-1	impact-echo	impactor, steel balls
IE-BAM-2	impact-echo	impactor (automatic)
Radar-BAM	radar	1.5 GHz antenna

3.2 Determination reference velocities

The reference values were determined at section „RF“, where a steel plate was embedded. In detail, the velocity of the elastic waves for the ultrasonic methods and the velocity of electromagnetic waves, and capacitivity respectively for radar, are determined. The accuracy of results depends on the accuracy of these reference values. To calibrate the reference values, the depth of the steel plate in area 2 of LCS was determined exactly by an endoscopic investigation.
The reference velocity of the impact-echo method was determined by the thickness equation ($T = c/2f_R$) with the measured resonance maximum f_R and depth T of the steel plate. The reference values of radar and ultrasonic methods were determined by measuring the time of flight.
The calculated velocities are shown in table 2, including the measurement inaccuracy. Therefore, depending on the test method, the standard deviation or the approximated measurement inaccuracy with a confidence coefficient of 68 % is denoted. The measurement inaccuracy is given by observational accuracy of the onset times.

Table 2. Velocities

Testing method	velocity of propagation [m/s]	measurement uncertainty [m/s]
US-UDo	4441 [1)]	35 [4)]
US-BAM	2875 [2)]	57
IE-USt	4282 [1)]	48 [4)]
IE-BAM-1	4281 [1)]	38
IE-BAM-2	4106 [1)]	37
Radar-BAM	$1.035 * 10^8$ [3)]	$0.026*10^8$

[1)]: Longitudinal wave velocity c_P of the elastic wave
[2)]: Shear wave velocity (for $\nu = 0.15$ equal to $c_P = 4480$ m/s)
[3)] : velocity c of the electromagnetic wave, dielectric constant $\varepsilon = 8.35$ [-]
[4)] : standard deviation

Comparing the velocities in table 2, it can be shown that the values are slightly different even for methods using longitudinal waves. These differences are less then 5 % and arose by the way of determination the echo propagation time.

3.3 Detecting areas of smaller thickness

A common application of non-destructive testing is to determine sections of smaller thickness. If smaller measurement grid is chosen, flaws can be localised better, but then the process takes a longer time. To localise the thickness, section MD4 of the LCS was chosen. In this part four layers in different depth are embedded in the specimen. Table 3 shows the results of measured and averaged absolute values, the standard deviation σ of single measurements and the deviation Δd from the average of the determined values of all tested methods.

Table 3. Results of localised areas of smaller thickness MD4a-d

Method		US-UDo	US-BAM	IE-USt	IE-BAM-1	IE-BAM-2	Radar-BAM	Average
Grid [mm]		-	20	100	20	20	2	
MD4a	Depth z [mm]	131	114	116	121	117	122	120.2
	σ [mm]	-	4.0	4.0	2.3	0.8	1.8	
	Δd [mm]	10.8	6.2	4.2	0.8	3.2	1.8	
MD4b	Depth z [mm]	168	159	158	162	156	162	160.8
	σ [mm]	-	5.0	8.0	2.4	0.6	2.3	
	Δd [mm]	7.2	1.8	2.8	1.2	4.8	1.2	
MD4c	Depth z [mm]	207	203	201	203	199	205	203.0
	σ [mm]	0.9	4.0	12	4.7	1.4	1.3	
	Δd [mm]	4.0	0.0	2.0	0.0	4.0	2.0	
MD4d	Depth z [mm]	-	262	255	261	256	257	258.2
	σ [mm]	-	5.0	11.0	8.1	2.1	4.0	
	Δd [mm]	-	3.8	3.2	2.8	2.2	1.2	

The specification of measured uncertainty of ultrasonic method of BAM is based on standard deviation on ten arbitrarily read thickness measurements respectively for each area of smaller thickness. In case of impact-echo and radar of BAM and USt these values are based on statistical deviation of all measured points within a measuring field, whereas time of flight and thickness resonance respectively were determined automatically. At the measurements of UDo in area MD4a and MD4b only single points were measured, why standard deviation is not specified. In area MD4c standard deviation is calculated by ten values measured on the same place.

Regarding table 3 very small deviations can be seen between acquired values of individual methods and average of these values. Nearly all deviations are clearly smaller than 10 mm. On the area with smaller thickness MD4a and -b the deviations are smaller than 9 %, in the majority of cases smaller than 5 %. At MD4d the deviation is about 1,5 %. It can be seen a lager deviation on smaller thickness than on larger. This is due to the error on metering the time of flight by a given value of rise time, which is percentage larger on smaller times of flight. The results shows that the used methods have a low margin of deviation and can be applied for thickness measurements reliable also on larger measurement grids. The verification of the thickness by a destructive test does not take place yet, because the reference specimen LCS is still in use.

The lateral dimension of a smaller thickness was determined in area MD3 (figure 1). During the process of measurement, for the inspectors the indication of the geometrical position and the dimension in x- and y-direction was unknown. The results show three subareas (section 1-3) of smaller thickness with different lengths for each x- and y-direction. Exemplary results of scans in x-direction are shown in figure 2, where the total length of each subarea is pictured.

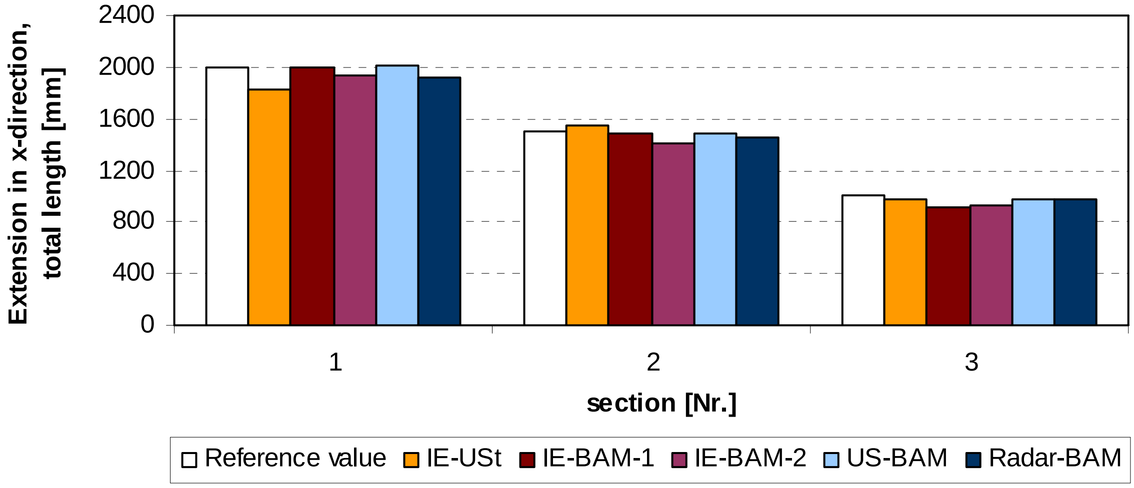

Fig. 2: Extensions (section 1-3) in x-direction of a measured flaw

The results of all tested methods show a good agreement to the existing values according to plan. The determined length of the extension in x- and y-direction on the smaller thickness part diverge less. The deviation from given value are lower than 10 %, on average even lower than 4 %.

3.4 Detection of tendon ducts

The localisation accuracy of ducts was investigated using area 1 of the LCS. In this area the methods were tested to detect tendon ducts and to classify ungrouted ducts. Here, the research on two tendon ducts are described exemplarily. Measurements using the described methods above were accomplished with a small measurement grid (≤ 2cm), whereby a good resolution was obtained. The position of peak values on three points (y = 1000; 2000 und 3000 mm) of tendon duct HR-E1 and HR-E2 are displayed in figure 3. According to the plan the tendon duct HR-E1 has a diameter of 80 mm and a concrete cover of 170 mm; HR-E2 has a diameter of 40 mm and is located to a depth of 110 mm.
The results show a high accuracy (the measurements were carried out with the same scanner equipment). The deviation between detected and given values are lower than 100 mm. Comparing results the determined x-position with the radar system is slightly inaccurately. These slight systematic deviations may be related to large absolute x-coordinate values. The point of origin is at a distance of 5 to 10 meter.
To determine the concrete cover only the ultrasonic and the radar methods can be used. Due to the technique the impact-echo method is not able to detect the depth of tendon ducts. The results of detecting the concrete cover are shown in figure 4. The accuracy decreases with the depth of tendon duct similarly to above, so that the variation of the values measured by radar are larger as by ultrasonics.

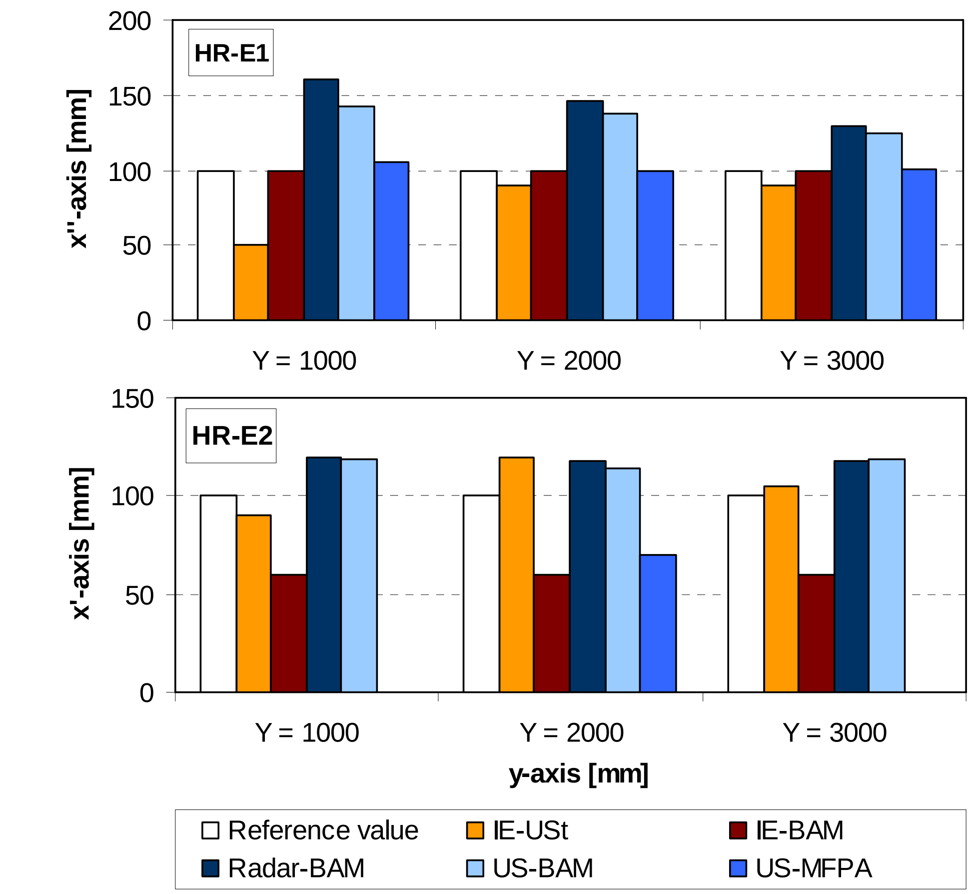

Fig. 3: Localising tendon duct (HR-E1 and HR-E2), relating to relative coordinate x^{I} and x^{II}

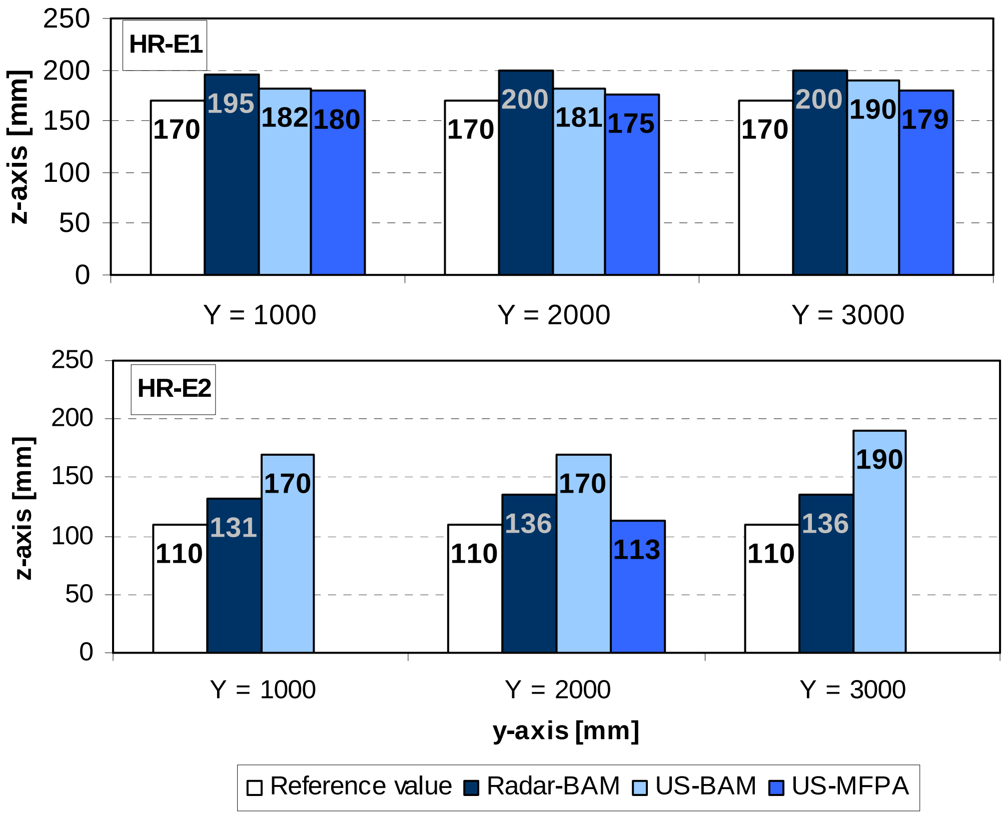

Fig. 4: Concrete cover of tendon duct (HR-E1 and HR-E2)

4. Summary and outlook

Comparing the described non-destructive testing methods repetition measurements have been carried out. The examinations demonstrate that all these methods could be applied for localising parts of smaller thickness and tendon ducts. With the used non-destructive testing methods highly accurate measurements with small deviations within a few millimetres are possible, if scanning methods are used. On single point measurements the inaccuracy is in the order of about 1 cm. The accuracy of these methods can be deduced by examinations on structural elements with reference specimens, like the “large concrete slab” LCS. A comprehensive evaluation including the quantification of ungrouted ducts and the localisation of honeycombs will be reported later.
To verify the results taking test cores is still necessary. Improving the technique and increasing the capability and usability of non-destructive testing methods, destructive testing can be reduced to a minimum.

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