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Comparative Performance Tests and Validation of NDT Methods for Concrete Testing

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Abstract Validation of non-destructive testing methods is necessary to create a common basis where different systems can be compared and their applications and limitations be identified. This can be achieved through comparing the measurements taken by several systems used for a common diagnostic purpose under practical but controlled testing conditions. Well-designed small and large laboratory or field specimens promise such conditions.

The special concrete specimen (LCS) at BAM was constructed for validation purposes, in particular, to be used for evaluating the performance of echo methods. The thickness of the specimen is varying and it contains carefully designed built-in faults, such as voids, honeycombs and tendon ducts with various degrees of grouting defects. Since the geometry and condition of the defects are known, it can be used to compare the performance of radar, ultrasonic, impact-echo. The research was conducted within the Research group FOR384, sponsored by the German Research Society DFG.

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1 Introduction

For non-destructive testing-methods to receive a wider acceptance in construction industry, their reliability has to be demonstrated. To be applicable for quality control purposes, it is necessary to assess and document the applications and limitations of these methods when employed under controlled conditions on reference specimens [1]. In this study different methods were evaluated quantitatively with the well established careful selected measurement tasks, checked on a reference-specimen. This procedure opens the opportunity to answer practical questions about a specific test equipment and/or procedure such as its accuracy when used for thickness measurement, locating imperfections as well as detection of position and depth of tendon ducts and evaluation of their grouting conditions. These systematic examinations make the basis for a quantitative comparison of the results in view of the performance of the testing-methods and their modifications. A part of results obtained in this study dealing with detecting unusually small thickness of concrete sections and localising tendon ducts is presented in this paper. The results were analysed statistically and evaluated in view of certain problems and practical needs. 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 [2], the University Stuttgart (USt), the University 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).

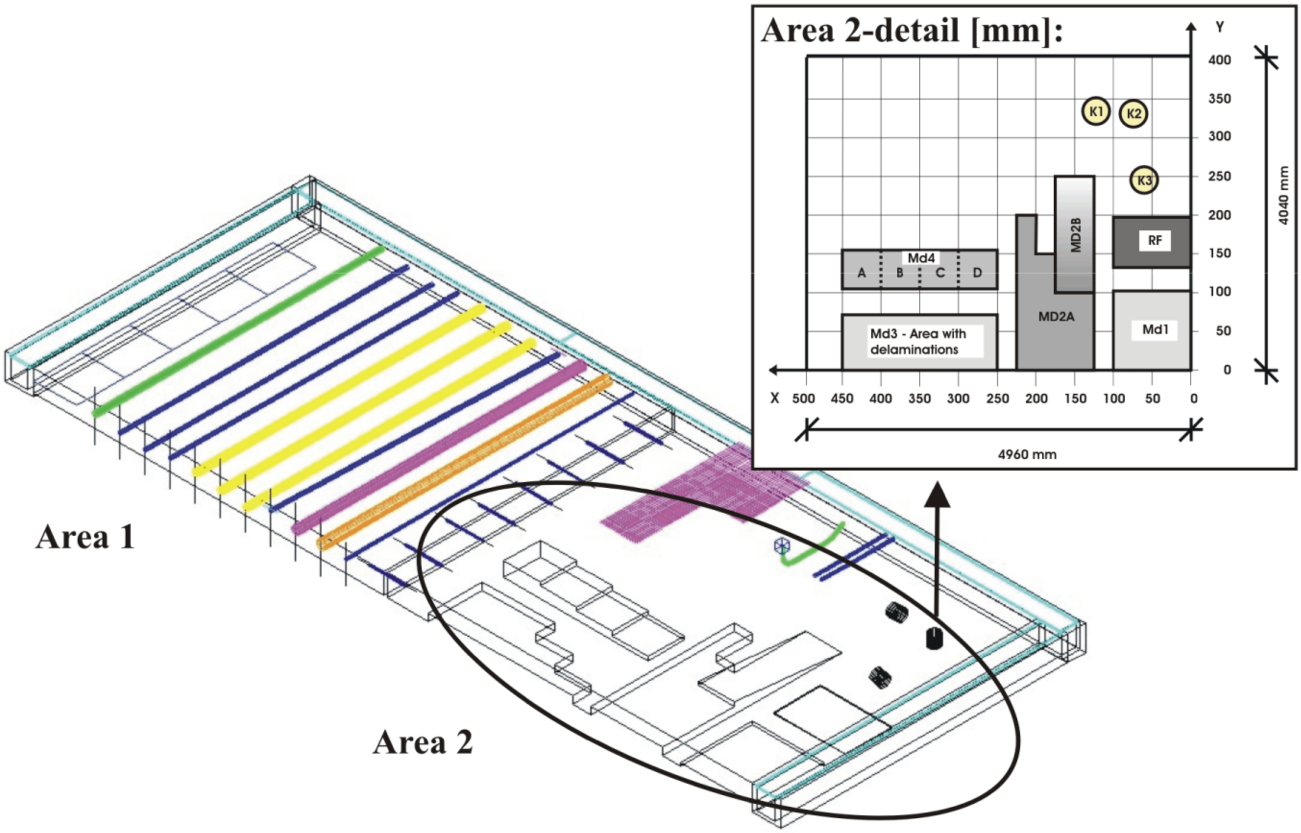

Fig. 1 Schematics of the large concrete specimen (LCS) at BAM showing the details of Area 2, dimensions are in mm. Md1: Reduced thickness, Md2A: Reduced thickness, Md2B: reduced thickness sloped, Md3: Reduced thickness with rough surface, Md4: Reduced thickness in steps, RF: Reference area with steel plate at backside. K1–K3: Prefabricated honey combs

2 Reference Specimen LCS

The test specimen (Fig. 1) designed by the Federal Institute for Materials Research and Testing [3, 4] was named "large concrete slab" (LCS). The LCS is a one-sided accessible large scale concrete slab with dimensions $10 \times 4\ m^2$ and a nominal thickness of 0.3 m built on a gravely soil bed. These huge dimensions reduce the influence of unwanted effects in the test results due to nearby edges. The LCS is divided into two areas of the same size. Area 1 includes tendon ducts of different diameter embedded at varying depths. The ducts are grouted under pressure with cement mortar, some with intentional grouting defects. Area 2 is composed of sections of varying thicknesses made using expanded polystyrene (MD1 to MD4 shown in Fig. 1). It also contains a reference area RF for wave velocity determination, a section with a steel plate at the bottom, which has a high reflection and therefore is specially suitable for calibration.

3 Performance Demonstration

A statistical analysis of performance demonstration test results was used to establish the reliability of a number of non-destructive testing methods. The influence of the quality of results has been limited to a few factors. The technological attributes of concrete and the structure were given by the specimen LCS. Varying other parameters such as reinforcement, layer thickness, number and size of inhomogeneity were not considered. 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 shape and intensity of the acoustic and the electromagnetic pulse. In addition, the measurable extent of a flaw depends on the characteristics of the measurement system and the measurement grid. A grid of smaller size provides more detailed information about the structure but the effort and therefore the cost of the inspection increases accordingly. Therefore, in deciding the number and location of test points, economical concerns have to be addressed as well. In this study a standardised measurement grid was chosen and a number of measurement points were specified, respectively.

In this paper the comparison of testing methods corresponds to measuring the same testing problems. A first estimate of the performance is carried out by comparing these results.

3.1 Testing Methods

In this study, both acoustical (i.e. ultrasonic and impact-echo) and electromagnetic (radar) tests were carried out using commercial and proprietary equipment.

The ultrasonic equipment of the University of Dortmund (US-UDo) [5, 6] is a commercial test system (Dr. Hillger NFUS 2300), but data is recorded by an external data acquisition equipment of a higher sampling rate. The measurements (bistatic) were carried out using two shear wave transducer arrays with a nominal frequency of 55 kHz (AcsysM2502). The transducers were hand-operated and couplant-free. Analysis was carried out by metering the maximum values of the echo impulse [7] and additionally considering time delays.

Another ultrasonic equipment was that of BAM with a dry coupled double transducer probe for shear waves (ACSYS A1220) [8]. Also a 3D-reconstruction analysis was applied [9]. 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) uses water coupled transducers of a bandwidth 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) [9, 10] employing proprietary software.

The impact-echo equipments of the Universität Stuttgart (IE-USt) [11–14] and BAM (IE-BAM-1 und IE-BAM-2) [15, 16] has an electric controlled impact source. 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.

Measurements using radar (Radar-BAM) were carried out using a 1.5 GHz antenna. Two data sets were obtained detecting the emitted electric field of correlating rectangular polarization configurations. Both data sets were reconstructed by 3D-FT SAFT separately and superposed afterwards [17]. Raw data have been taken to determinate the velocity of propagation at the reference position and to analyse the concrete cover.

Ultrasonics, radar and impact-echo measurements at BAM were accomplished using a scanner system which is suitable for construction sites [18].

3.2 Determination of Reference Velocities

Reference parameters were measured at the section of LCS marked as RF (Fig. 1), where a steel plate was embedded at the backside of the slab at a depth of 30 cm. The velocity of the elastic waves for the ultrasonic methods and that of electromagnetic waves, and capacitivity for radar, had to be determined. The accuracy of the test results depends on 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 c of the impact-echo method was determined by the thickness equation ($T = c/2f_R$) with the measured resonance frequency 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 and measured velocities as well as the standard deviation of the results are summarized in Table 2. Ten measurements per test were used to obtain these results. Comparing the measured and calculated velocities, it can be shown that the values are slightly different even for methods using longitudinal waves.

The maximum standard deviation varies from 16 to 34 m/s, excluding radar for witch a standard deviation of 0.026×10^8 m/s was obtained. The resulting inaccuracy calculated as double standard deviation for the elastic wave based methods and radar is less than 2% and 5% respectively. The larger inaccuracy of radar measurements are caused by the influence of reinforcement.

Table 1 Testing methods

Indication	Method	Pulse/wave mode
US-UDo	Ultrasonic echo	Shear waves
US-MFPA	Ultrasonic echo	Longitudinal waves
US-BAM	Ultrasonic echo	Shear waves
IE-USt	Impact-echo	Automatic impact source
IE-BAM-1	Impact-echo	Using steel balls
IE-BAM-2	Impact-echo	Automatic impact source
Radar-BAM	Radar	1.5 GHz antenna

Table 2 Velocities

Testing method	Velocity of propagation [m/s]	Standard deviation [m/s]
US-UDo	2808.6[b]	17.8
US-BAM	2852.6[c]	29.8
US-MFPA	4456.8	34.6
IE-USt	4292.5[a]	31.2
IE-BAM-1	4163.2[a]	29.5
IE-BAM-2	4350.5[a]	25.6
Radar-BAM	1.035×10^8[d]	0.026×10^8

[a] Longitudinal wave velocity c_P of the elastic wave
[b, c] Shear wave velocity c_S of the elastic wave (for $\nu = 0.15$ equal to [b] $c_P = 4376.9$ m/s, [c] $c_P = 4445.5$ m/s)
[d] Velocity c of the electromagnetic wave, dielectric constant $\varepsilon = 8.35$ [–]

Table 3 Thickness evaluation results on MD4a-d

Method		US-UDo	US-BAM	US-MFPA	IE-USt	IE-BAM-1	IE-BAM-2	Radar-BAM	Average
MD4a	Depth z [mm]	111.0	120.0	121.0	117.0	119.0	121.0	123.0	119.0
	σ [mm]	6.0	3.0	1.0	5.0	2.0	1.0	2.0	2.9
	Δ [mm]	8.0	1.0	2.0	2.0	0.0	2.0	4.0	2.7
MD4b	Depth z [mm]	157.0	159.0	158.0	159.0	159.0	162.0	158.0	158.9
	σ [mm]	2.0	3.0	2.0	1.0	1.0	1.0	9.0	2.7
	Δ [mm]	1.9	0.1	0.9	0.1	0.1	3.1	0.9	1.0
MD4c	Depth z [mm]	198.0	202.0	203.0	199.0	200.0	205.0	205.0	201.7
	σ [mm]	0	4.0	2.0	2.0	2.0	2.0	1.0	1.9
	Δ [mm]	3.7	0.3	1.3	2.7	1.7	3.3	3.3	2.3
MD4d	Depth z [mm]	256.0	262.0	259.0	254.0	261.0	260.0	261.0	259.0
	σ [mm]	1.0	5.0	2.0	9.0	5.0	5.0	5.0	4.6
	Δ [mm]	3.0	3.0	0	5.0	2.0	1.0	2.0	2.3

3.3 Detecting Areas of Smaller Thickness

To examine their reliability, thicknesses of the sections MD4 and MD3 of the LCS were evaluated using all the test methods considered in this study. Detection of shallow sections demonstrates a common application of non-destructive testing. In addition to the thickness evaluation, the lateral dimension and accuracy of measured values were also determined. In MD4 four layers at different depths are embedded in the specimen. The measured uncertainty of all methods was evaluated based on standard deviation of ten evenly distributed thickness measurement series on each area of smaller thickness MD4a-d.

The measured and averaged absolute values, as well as the standard deviation σ for each measurements as well as the deviation Δd from the average of all determined values of all test methods are shown in Table 3.

Regarding Table 3 very small deviations were obtained between acquired values of individual methods and average of these values. All deviations from the average of all measurements by all methods are clearly smaller than 10 mm. For the areas with smallest thicknesses MD4a and -b the deviations of the values from the total average are smaller than 7%. At sections with thicker concrete cover MD4d the deviation is smaller than 2%. As expected, a higher deviation is observed at regions with smaller thickness. This is largely due to the error in measuring the time of flight by a given value of rise time, which is several percentages larger on smaller times of flight. Overall standard deviations are less than 9 mm, the maximum measurement inaccuracy is 8 mm.

These results indicate that all the methods considered to this study have a low margin of deviation and consequently are reliable for thickness measurements. The verification of the thickness by a destructive test did not take place, because the reference specimen LCS is still in use.

The reliability of the methods in determining the lateral dimensions was examined by measuring the extents of sections of reduced thickness area MD3 (Fig. 1). The location and the x- and y-dimensions of the section were unknown to the inspectors during the measurement. The results show three subareas (Sects. 1–3) of smaller thickness with different lengths for each x- and y-direction. Exemplary results of scans in x-direction are shown in Fig. 2, where the total length of each subarea is illustrated.

As shown in Fig. 2, the test results concluded a good agreement with the existing values according to the LCS plan. The measured length of the x- and y-extents on the shallow section showed a lower deviation. The deviation from given value were found to be less than 10%, on average and in some cases even lower than 4%.

The estimated areas of MD3 and MD4 as measured by radar are illustrated in Fig. 3. The apparent values rise in thickness at the transition from MD4b to MD4c is believed to have been by a reinforced bar. This figure is a good example to show how accurately the geometrical forms can be reconstructed and imaged based on the NDT results. It should be mentioned that such a high resolution pictured can only be generated using a very small measurement grid.

3.4 Detection of Tendon Ducts

To localise tendon ducts several methods can be used, most commonly used for one sided access are radar, ultrasonic and impact-echo. Only radar and ultrasonic-echo systems were able to determine the depth of and the concrete cover over the ducts. The impact-echo method as used in this study was not able to measure the concrete cover of tendon ducts.

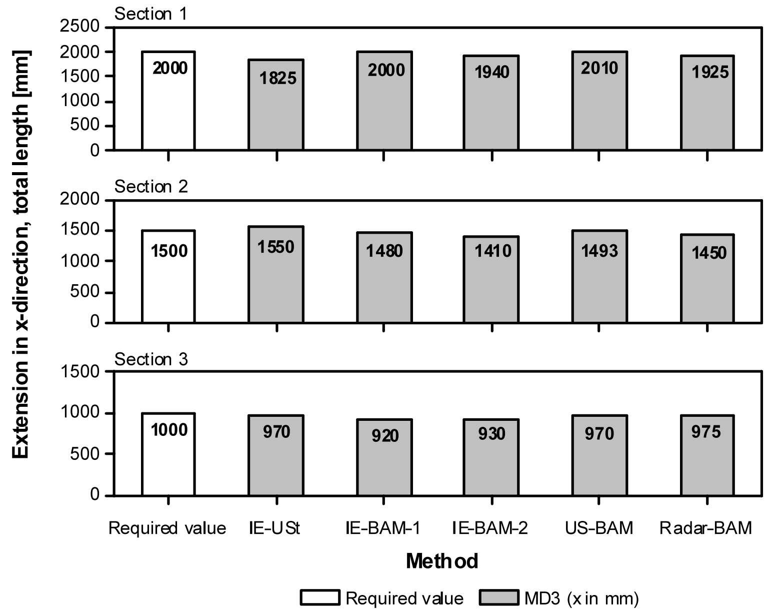

Fig. 2 Extensions (Sects. 1–3) in x-direction of a measured flaw

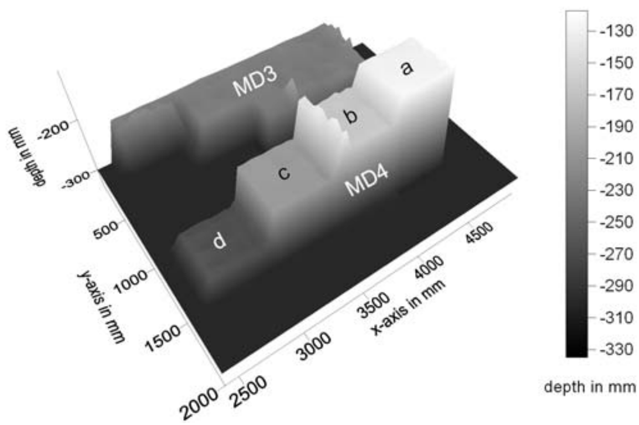

Fig. 3 Extensions of MD3 and MD4 measured by radar

The accuracy in localization of ducts was investigated on Area 1 of the LCS. A small measurement grid of 2 cm was chosen, whereby a good resolution was obtained. Only the results obtained on two tendon ducts are presented here. The position of peak values on three points ($y = 1000$, 2000 and 3000 mm) of tendon duct HR-E1 and HR-E2 are displayed in Fig. 4.

According to the construction 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 at a depth of 110 mm.

A good accuracy can be observed on the results in Fig. 4. The deviations between detected and given values are lower than 100 mm. In comparison, the estimated x-positions obtained by the radar system were slightly inaccurate. These systematic deviations may be related to large absolute x-coordinate values. The point of origin is at a distance of 5 to 10 meters. The standard deviation is calculated as ±23 mm maximum.

The results of detecting the concrete cover are shown in Fig. 5. The accuracy decreases as the depth of the tendon duct increases, the variation of the values measured by radar are larger compared to ultrasonics.

Quantitative conclusions regarding the grouting defects (ungrouted areas) inside tendon have not yet been made and need more thorough investigations.

4 Summary and Outlook

To establish the reliability of non-destructive testing methods, it is necessary to compare the results of different measurement systems used under comparable conditions on well-defined reference specimens. The accuracy of these methods can be deduced by examinations on concrete structures with reference specimens, like the "large concrete slab" LCS at BAM.

Four measurements tasks were selected: i) thickness measurements, ii) lateral dimension measurements of reduced thicknesses, iii) locate tendon ducts and iv) determine the concrete cover of tendon ducts. At a reference point of known thickness, the NDT systems used had to be calibrated.

The reliability of several impact-echo, ultrasound and radar systems was evaluated in this study. The results of the experiments verified that among the methods considered in this study, ultrasonic-echo, impact-echo and radar could be applied for locating shallow thickness sections and tendon ducts. All these non-destructive testing meth-

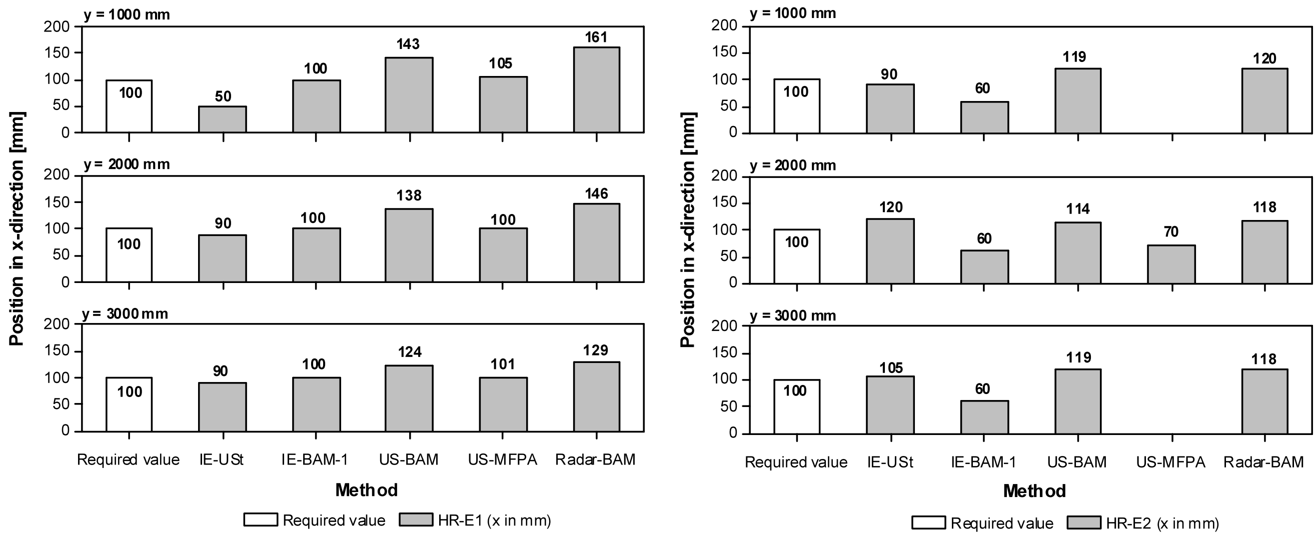

Fig. 4 Localising tendon ducts (HR-E1 and HR-E2), relating to relative coordinate x^{I} and x^{II}

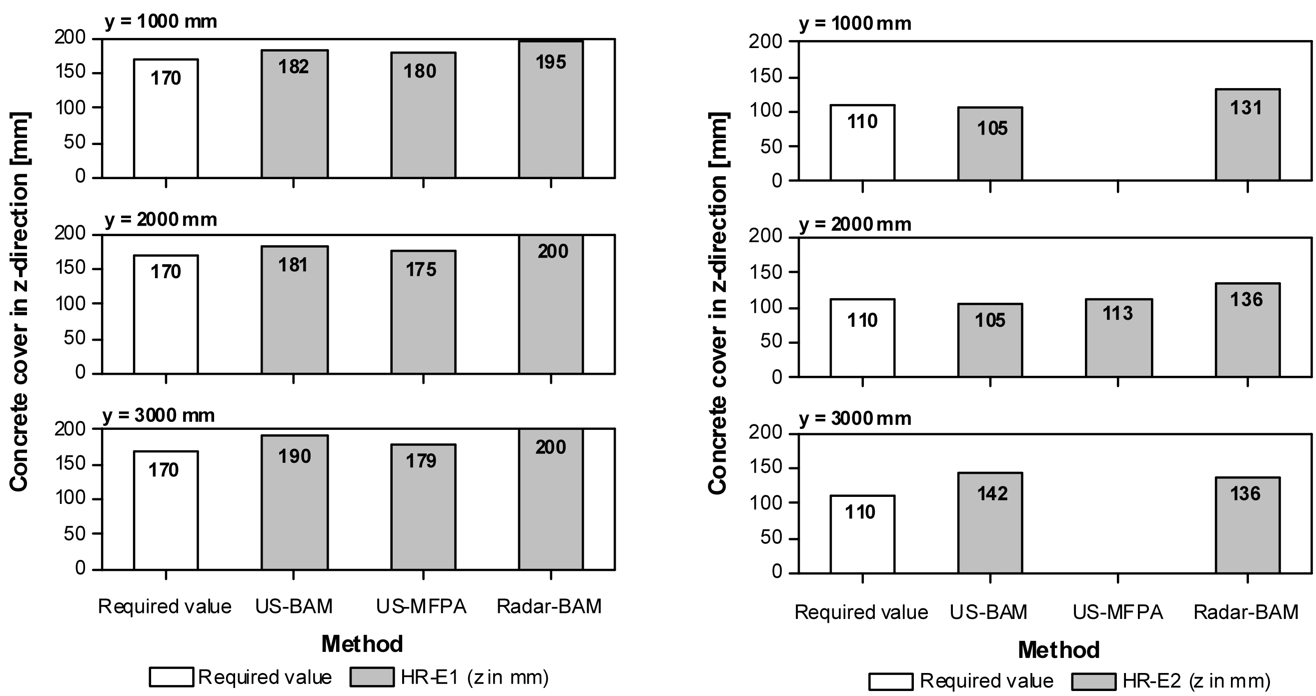

Fig. 5 Concrete cover of tendon ducts (HR-E1 and HR-E2)

ods were able to measure the dimensions with small deviations. Regarding present investigation a good accuracy of a few millimeters is possible, if scanning methods (small grid size) are used. On the basis of single point measurements, the inaccuracy was found to be in the order of about 1 cm, relating to thickness the deviations are smaller than 7%.

This study proves that NDT methods can perform reliably in measuring such quantities as thickness and lateral dimensions of flaws.

Future studies should include the evaluation of grouting conditions of ducts quantitatively. In addition, honey combs must be studied by varying size, shape, density and concrete cover over a wide range. Today, a reliable identification of honeycombs is technically not possible.

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