Advanced NDT Methods for Quality Assurance of Concrete Structures

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Abstract

The application of non-destructive evaluation (NDE) methods for quality assurance of concrete structures has made considerable progress recently. Driven by technology and knowledge transfer from other areas of materials testing and medicine a versatile toolbox of methods for the investigation of RC structures has emerged from research. In the area of simulation and 3D-reconstruction of ultrasonic and radar data, progress was driven by more powerful computers and development of state of the art software for 3D re-construction and visualization of data.

Bringing these developments into the state of practice, into everyday use on construction sites by trained engineers rather than researchers still remains a major challenge. To earn the trust of industry, the reliability of these non-destructive testing (NDT) methods should be established and adequately verified to prove that their application is worth the additional expense and effort.

Validation of NDT methods has to prove that the customer requirements are met by the test. A number of reference specimens have been developed over the years at BAM and other locations, acting as a standard for specific testing tasks. Those specimens are available to the NDT community for comparing their methods and instruments under independent conditions.

Résumé

La demande de non-destructif d'évaluation (NDE) les méthodes d'assurance de la qualité des structures en béton a fait récemment des progrès considérables. Poussé par la technologie et le transfert de connaissances à d'autres secteurs d'essais de matériaux et de la médecine polyvalente d'outils de méthodes d'enquête sur les structures RC a émergé de la recherche. Dans le domaine de la simulation 3D et de reconstruction des appareils à ultrasons et les données radar, les progrès ont été chassés par les ordinateurs plus puissants et le développement de l'état de l'art des logiciels 3D pour re-construction et de visualization de données.

Rapprocher ces développements sur l'état de la pratique, en usage quotidien sur les chantiers de construction par des ingénieurs plutôt que des chercheurs reste encore un défi majeur. Pour gagner la confiance de l'industrie, de la fiabilité de ces essais non destructifs (NDT) les méthodes devraient être établies et vérifiées de manière adéquate à prouver que leur demande est la valeur des dépenses supplémentaires et des efforts.

Validation des méthodes de CND a à prouver que les exigences des clients sont satisfaits par l'essai. Un certain nombre de spécimens de référence ont été élaborés au cours des années à BAM d'autres endroits, agissant comme un standard pour l'essai des tâches spécifiques. Ces spécimens sont à la disposition de la communauté NDT pour comparer leurs méthodes et leurs instruments sous conditions indépendant.

Keywords

Ultrasound, Radar, Impact-Echo, Validation, Automation
1 Validation

Validation is used in many technical fields, e.g. pharmacy, aviation, to furnish the technical proof that the customer’s requirements are fulfilled. Subject of the validation is the whole process of a successful solution for a testing problem. Well-documented validation improves the application safety for a service provider and makes his service transparent for the client. The client knows exactly what he buys and that he has full benefit from the results.

According to DIN EN ISO 17025 (DIN EN ISO/IEC 17025, 2004) Validation is the confirmation by testing to furnish the proof that the requirements for a certain intended use can be fulfilled. The client – in some cases together with the service provider – expresses his/her requirements considering all necessary boundary conditions. If a testing method – suggested by the service provider – succeeds to satisfy these requirements the validation process is completed. According to Figure 1 the validation process consists of three steps (Taffe):

- Characterization of a testing method
- Requirements of the client
- Proof that the client’s requirements have been fulfilled

![Figure 1. Validation process (Taffe)](image)

Figure 1 also shows this process: characterization is done by regular testing in research and development and evaluating the results. Calculating the uncertainty of measurement, determining the precision and accuracy and limit of detection etc. are possibilities to characterize a method under certain boundary conditions (method, device, environment etc.). The customer requirements are also expressed by the properties mentioned before. They are influenced by time, costs, accessibility etc. All this together forms the individual testing problem. A testing method under the characterized methods that is suitable for the testing problem is marked by the intersection of characterization and customer requirement. The validation is at the end of the process if the proof is furnished that customer’s requirements are satisfied.

This does not mean that a validation always has to be carried out at the customers testing object, in most cases this will be impossible. The idea of the process is to provide a close characterization of the method considering a wide range of boundary conditions that fit for the customer’s testing problem. In one case it might be possible to predict precisely that the customer needs will be satisfied. In another case the results, e.g. the expected uncertainty, might be too close to the customer’s defined limit and the success of a test cannot be guaranteed. In case that the characterization of a method is not sufficient, further – but few – measurements considering the unknown boundary conditions have to be carried out.
Validation has to be carried out individually for a specific testing problem because there is obviously no general validation for a testing method.

The Guide to the Expression of Uncertainty in Measurement (GUM) (Guide to the Expression of Uncertainty in Measurement 1995) provides a good methodology that can be applied in the NDT-CE field. According to the GUM the uncertainty of thickness measurement of 70 to 120 cm thickness and having areas of different reinforcement ratio was measured. The testing was performed with an automated testing device using dry point contact sensors (ACSYS A1220).

The measured data was first assessed as raw data and later assessed after improving it by creating the envelope of the transit time curve. In Figure 2 the effect of improved data analysis for different reinforcements is shown. We assess the data according to the GUM mentioned in the previous chapter the total standard deviation for the thickness measurement in relation to thickness, reinforcement and data assessment can be calculated (Gaussian error propagation) as given in Figure 2.

The results shown in Figure 2 are the results of a systematic characterization. It helps the engineer to estimate up to which depth and to which reinforcement he may expect reliable results. If the engineer just needs a quick overview to decide if thickness is 70 cm or 120 cm he may be satisfied by assessing raw data. If he reliably wants to know the slab thickness, e.g. in case of a static calculation, he will get results with a standard deviation less than 5 % only by using “improved data” (in this case creating the envelope) and up to a reinforcement of $\varnothing$ 12 mm with 15 cm spacing (upper and lower layer).

![Figure 2. Total standard deviation of thickness measurement with ultrasonic-echo (transverse waves) in relation to thickness, reinforcement and data assessment](image)

2 Reference Specimen

Improvements of NDT methods can best be shown through reference tests at suitable specimens. For this purpose, a number of large test specimens have been constructed at BAM. Well defined test problems are incorporated into those, well separated from other defects. Special care is taken of size effects, e.g. the geometry effects in impact echo. The specimens typically have a size of at least 2 x 1.5 x 0.5 m$^3$. The size is mainly limited by the ability to move the specimens with a fork lift.
In addition to the laboratory specimens, a number of larger specimens have been established for special tasks: These specimens are generally available for round robin tests or research by other interested groups upon request.

### 2.1 Large Concrete Slab

The LCS has a size of $10 \times 4 \text{ m}^2$ and a thickness of 300 mm. It contains 11 tendon ducts with well defined pre-fabricated grouting defects. There are sections where the concrete was poured in two steps, creating two layers with varying bonding between them.

There are also sections of thickness variations with different sizes and backsides. There three honeycombs hidden among other structural elements.

The entire slab is built on styrofoam with tubes running below which can be accessed to insert X-ray sources for radiography of selected sections of the LCS (Figure 3).

![Figure 3. (left) Large concrete slab on BAM campus (10 x 4 m², thickness 30 cm) (right) Large concrete slab during construction: rear section with tendon ducts, front section with thickness variations and honeycombs](image)

### 2.2 Foundation Slab

The foundation slab was established within the European Research Project RUFUS (*Re-Use of Foundations on Urban Sites*). It is a thick concrete slab of $5 \times 5 \text{ m}^2$, containing well defined variations of reinforcements and thicknesses. A strip foundation and two pile caps complement the specimen.

The BAM Test Site Technical Safety is a large area 50 km south of Berlin near Horstwalde. A facility for Research, Validation and Training in the area of NDT in civil Engineering is in the process of being established. Additional large specimens will be built there and maintained. Representative parts of structures such as bridges which are demolished have already been transported there and stored for further investigations and validation.

The process of establishing this NDT-CE Research, Validation and Training Center will take several years. Interested parties are invited to participate through suggestions for specimens or in research projects.

### 3 Automation

Automation of non-destructive testing methods helps to overcome the disadvantages of manual point testing. Point measurements must be repeated several times for statistical confidence in the results. Reproducibility is not always given in rough testing environments and difficult surfaces. Furthermore test personnel get tired during long testing periods.
At BAM several automation devices have been developed for various applications: automation of point testing methods with physical contact during testing (impact-echo, ultrasonic echo) and those with non-contact testing (radar, rebar detection). The test devices are mounted on a two-axial frame which moves to a pre-defined position and triggers the measurement. Pneumatic installations are used to couple the sensors to the surface until the test is completed. The entire test procedure is computer controlled. All data about the test procedure, the test object and the applied methods is stored for documentation. Interface with test equipment is done by utilizing existing interfaces or in cooperation with manufacturers. Typical test times required for ultrasonic testing is 1.5 h/m² at a spacing of 2 x 2 cm² between test positions. Radar is much faster due to the non-contact nature of the test, at a spacing of 5 cm between lines the required time is 5 min/m².

Scanners have been developed for both horizontal (bottom and ceiling) and vertical flat surfaces. The large scanner covers an area of 10 x 4 m², smaller versions exist for 1.8 x 1.8 m² areas. Recent successful tests have supported the concept of vacuum mounting of a lightweight frame. This version does not require fixed mounting to the concrete surface (Figure 4).

Mounting and test times have been successfully reduced using lightweight frames and fast, network based programs which can be easily adapted to testing scenarios. Fully automated testing of a 10 m² area concrete area within a day is within reach. So far the biggest problem is accessibility, which should be eased by the vacuum attached lightweight scanner which can be mounted from a cherry picker of snooper truck.
4 Imaging techniques with pulse echo methods

Foundations have only one-sided access and require echo methods like ultrasonic echo for testing. The investigation of the above-mentioned slab has been carried out with an array of 24 dry point contact transducers working with transverse waves excited with a centre frequency of 15 kHz (ACSYS A1220).

For a reliable imaging of the complex geometry an automated transducer positioning system (scanner) has been used. Data (8000 measured points) have been recorded and processed with the help of a reconstruction calculation. The so-called SAFT (Synthetic Aperture Focusing Technique) focuses signals received at many positions by coherent superposition, yielding a high-resolution image of the region of interest. The following images are results of SAFT-reconstruction. Various sections through the reconstructed data volume can be processed and layers with significant reflections become obvious and visualize internal objects and geometry.

Figure 5 shows the section parallel to the surface at a depth of 75 cm. The expected reflection of the back wall at that depth is clearly visible. In upper left and upper right corner (x/y 960/860 mm, x/y 4000/850 mm) two small areas show no back wall reflection. This is where the pile heads are located because the signals propagate from the slab further into the piles and are not reflected at the depth of the back wall.

![Diagram showing the foundation slab and pile arrangement](image)

**Figure 5.** (Left) Section parallel to the surface at depth of 75 cm. (Right) Drawing of the designed foundation slab with varying thickness and reinforcement ratio.

The limits of the thickness measurement depending on the reinforcement ratio become clearer looking at cross-sections shown in Figure 8. For the high reinforcement ratio shown at the top of Figure 9 (section b-b) only in the non-reinforced sections a clear back wall signal at depth of 75 cm and 125 cm appears. In the sections with upper and lower reinforcement a strong reflection in the surface near depth is visible. A weak signal at the 75 cm section allows depth estimation up to that depth. If the 28 mm diameter reinforcement is placed only in the lower level, as shown in section c-c at the bottom of Figure 6, the reinforcement bars produce a reflection in addition to the back wall reflection a few centimetres above. Depth measurement up to 125 cm is possible with this reinforcement ratio.
Cross-section d-d shown in Figure 7 also reveals the geometry of the slab and the location of the piles. The back wall reflection at 75 cm and the bottom of the strip foundation at 125 cm are clearly visible. Also the detected width of the strip foundation of 50 cm and its location agree well with reality. The interrupted back wall echoes at the depth of 75 cm between x = 800 mm and 1100 mm and x = 3850 mm and 4150 mm mark the location of the pile heads.

Reliable thickness measurements have been possible up to 75 cm for areas with high reinforcement ratio (28 mm diameter at 100 mm spacing, crosswise, upper and lower reinforcement layer) and up to 125 cm with lower reinforcement ratio.

Figure 6. Section b-b, $\varnothing = 28$, $s = 10$ cm (upper and lower reinforcement)

Figure 7. Cross section d-d revealing the slab geometry and location of the pile heads

5 Impact-Echo (IE)

Impact-Echo is an acoustical test method based on mechanical excitation of sound waves in concrete (Sansalone & Streett 1997, Pessikki & Olson 1997). Resonant vibrations of the surface near the point of contact are recorded and identified by transforming the measured time signal into the frequency domain (Figure 8). Dominant frequencies are assigned to depth values by applying the well known IE formula

\[ d = \frac{v_L}{2f} \]

with $v_L$ being the P-wave velocity and $f$ the measured frequency. The wave speed must be determined at each concrete through calibration at a position of know thickness or by measuring on a core.
Impact-Echo has been successfully applied to concrete thickness measurements and defect localization in many cases. For this purpose a number of commercially available Impact-Echo devices are available. These devices are for manual point testing and can be distinguished by their impactors and sensors. Sensor coupling is assured through lead caps or plastic material, impacts are generated either through hand held steel balls of different diameters or by an electrically driven solenoid. Latter has the advantage of being easily reproducible when the IE head is not moved between subsequent impacts.

![Impact-Echo signal](image)

**Figure 8.** Impact-Echo signal: Time domain data (left) and frequency power spectrum (right). Thickness signal at 6.81 kHz, scanner resonance at 1.2 kHz

The duration of the impact ultimately determines the maximum frequency of the impact. In practical cases, the surface must be checked for dirt and soft areas. The impact will generate different waves depending upon the exact position where the hit takes place. If the impactor directly hits a hard aggregate, which may be hidden by a thin cement paste cover, the frequency range may be different from a hit into the softer cement paste.

At BAM this point method was improved into a scanning test method to visualize test results as an Impact-Echogram, similar to a B-scan in ultrasonic pulse echo or a GPR radargram. The amplitude of the frequency power spectrum is displayed colour coded or in greyscale over the position of the measurements and frequency. With automated testing in dense measurement grids Impact-Echo measurements can show very detailed the thickness of a concrete slab. When scanning is extended to a 2-dimensional grid, IE-results can be shown as 3-D images as shown in Figure 9. It was successfully shown, that grouting defects in tendon ducts can be identified by the apparent increase in thickness of the concrete slab at the position of the duct. However, validation of this test is still pending to define the limits of this test method and making it a reliable tool in quality control (Figure 10).

Impact-Echo experiments on specimens with small dimensions may be interpreted with care. Since most of the impact energy is transformed into surface and shear waves, reflections of those from nearby edges cause interference patterns on the surface. Such signals can easily being mistaken for thickness signals or void indication if not validated through measurements at different points: Those must be separated well enough to exclude that the signal is triggered by geometry effects.

Data analysis of Impact-Echo signals includes time and frequency domain filtering. Typically a high pass filter is applied to remove the signal offset and low frequency resonances within the system. A time band pass excludes signals from times where the Impact-Echo signals should have attenuated. If the time band pass is set too small, frequency resolution is lost. Wavelet analysis has been used for data analysis as well and can serve very well for time-frequency analysis. Recently, the Hilbert-Huang transform has also been utilized for the successful analysis of Impact-Echo signals (Algernon 2006).
Figure 9 Thickness of concrete slab of 5 x 4 m² (BAM reference specimen LCS. Top left: plan of section with thickness variations. Bottom left: 3D plot of measurements in very dense grid (2 x 2 cm²). Right: B, C and D Scan of same measurements with signals of various thicknesses.

Figure 10. Impact-Echo testing of grouting defects in ducts. Top: drawing of defect location. Middle: B-scan along duct. Bottom: C-scan showing apparent increase of slab thickness at defect locations. (BAM, unpubl.)

6 Ground Penetrating Radar (GPR)

Ground Penetrating Radar has emerged from geophysical applications and has become a versatile and powerful instrument for civil engineering applications. GPR can be applied in general without surface preparation by sliding the antenna over the surface. The fast data collection allows covering a large area in reasonable time (Figure 11).

Due to the nature of electromagnetic waves it can be used for concrete and masonry structures but radar waves cannot penetrate metals. Any metallic layer, e.g. a metal sheet or a metallic tendon duct is an impenetrable boundary. However, reinforcement which leaves gaps between the rods can be passed by radar waves within limits.
The propagation of electromagnetic waves in solids depends on the dielectric constant (relative permittivity $\varepsilon_r$) of the material. The permittivity of the material basically describes how the dielectric field in the material is following the applied electric field of the waves. The permittivity is a complex number. The real part determines the propagation velocity in the material

$$v_L = \frac{c_0}{\sqrt{\varepsilon_r}}$$

with $c_0$ being the velocity of light in vacuum. The imaginary part is largely responsible for the frequency dependent attenuation of the radar waves.

\[\text{Figure 11. Radar parabola signature when passing over reflector}\]

Radar waves are polarized, having the effect of a preferred direction. This is especially true for linear objects like reinforcing bars, which show up with highest intensity when the polarization of the antennae is parallel to the direction of the rebar. For this reason the localisation of rebars should always be performed using both polarization directions (Figure 12). This is done by scanning a surface in two perpendicular directions and combining the two data sets.

\[\text{Figure 12. Influence of polarization on the detectability of tendons}\]
The availability of antennas with different frequencies allows choosing the penetration depth in accordance with the requirements of the test. Low frequency antennas penetrate deeper into the material, but have lower depth resolution. High frequency antennas have a higher depth resolution but less penetration depth.

For application on structures mostly bow-tie antennae types are used. They can be slid over the surface for conducting the test. Horn antennas are mainly being used for road and train track measurements. They have a distance of several decimeters from the surface and can be mounted on vehicles for fast inspection.

Typical applications for radar on concrete structures are (Maierhofer et al. 1995):

- Location and concrete cover of reinforcement
- Location and concrete cover of tendon ducts
- Thickness measurements of beams and slabs
- Moisture detection areas
- Localization of voids
- Localization of delaminations
- Measurement of the thickness of layers

Conducting radar tests and the interpretation of the results is supported by advanced instrumentation which is commercially available. More important are powerful computer systems which can handle large amounts of data in reasonable time. Software tools for different purposes have been developed and are available for service providers or research.

GPR applications for non-destructive testing in civil engineering have been a success story for many years now. More and more information has become available and known about the capabilities and limitations of such systems.

New systems emerging from research will bring array systems into the market, allowing to scan a wide path with one sweep. An early system of this type has been developed by the Federal Highway Administration in the nineties (Scott et al. 2000).

7 Conclusions

Quality control of concrete structures benefits from the development of advanced NDT methods. The main areas of development and research are:

- Validation of methods for specific testing task
- Reference specimens are important as a scale against which developments can be quantified. Also for validation a selection of well defined specimens is indispensable.
- Automation is a key topic in the development of advanced NDT methods. It enables scanning of large areas and overcomes the limitations of manual operation
- Imaging techniques on the basis of large data sets open new opportunities to make NDT results easily readable by engineers.

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