Synopsis: Non-destructive testing (NDT) of post-tensioned concrete structures is both challenging and complex. Locating areas in tendons without corrosion protection (un-grouted) is technically difficult. Typically, Bridges are large structures, any testing of the complete surface with point test methods can only be done with automated systems. At present there are acoustic and electromagnetic methods which cover a large area of application and which can be used complementarily. But in most cases, only one method is applied to solve a distinct problem. In this contribution, results will be presented based on the investigation of internal structure of post-tensioned concrete bridges with three different NDT methods. Measurements with radar, ultrasonic echo and impact-echo were carried out on three bridges in Germany and Austria. Furthermore different scanning systems, developed at BAM, were applied. The main object was the demonstration of the improved effectiveness of radar, impact-echo and ultrasonic echo due to the automated measurements and the application of new software for the data processing and data visualisation. A new ultrasonic device with real-time imaging capabilities allows detailed measurements in smaller areas without special scanning devices.

Keywords: bridge investigations, data fusion, impact-echo, radar, scanning system, ultrasonic echo
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**INTRODUCTION**

The service life of post-tensioned concrete structures may be limited by corrosion of the tendons. Complete grouting of the tendon ducts reliably prevents corrosion due to the alkaline character of the cement. Grouting defects in tendons of post-tensioned concrete bridges have been identified as a not uncommon defect, especially on bridges built between 1950 and 1970. These bridges are vulnerable to corrosion damage on tendons, which threaten the durability and ultimately the safety of the structures. In these cases the detection of corrosion affecting the tensioned reinforcement is required because the durability of the corresponding structural elements is not given.

BAM has been developing methods to localise internal tendons using non-destructive investigation techniques and to assess the grouting conditions of the tendon ducts. Furthermore, non-destructive test methods have been applied for the localisation of non-tensioned reinforcement and to recognise irregularities (e.g. cavities, honeycombing) in the concrete. The research done by BAM concentrates on the combined application of radar, impact-echo and ultrasonic echo. Since 2003 these testing methods were carried out with automated measuring systems (scanning systems) for the assessment of post-tensioned bridges. The application and the results are presented in this contribution.

An ultrasonic device with real-time imaging capabilities has emerged from research. It allows much faster imaging measurements without scanning devices and is especially suited for testing smaller areas.

**EXPERIMENTALS**

**Ground penetration radar**

Ground penetration radar (GPR) has been established for several decades in geophysics for soil investigations. With the development of high-frequency antennas, as well as efficient computer systems, it is now also possible to examine smaller structures. Thus this method has been successfully applied to solve civil engineering problems, such as the assessment of concrete and masonry structures [1, 2] and the determination of moisture content and distribution [3].

Radar is a NDT technique based on the propagation of electromagnetic waves of high frequency: typically between 20 MHz and 2.5 GHz for civil engineering applications. The waves are emitted by an antenna, which is in most cases in contact with the structure under investigation and moves along the surface. The waves travel through the medium and are reflected at interfaces of materials with different dielectric properties, such as interfaces of concrete between different layers, to voids, to metal and to other inhomogeneities. The reflections are then picked up by a receiving antenna, which is also positioned on the surface. In most cases, transmitter and receiver are in the same housing. The travel time of the wave to the various interfaces and back can be related to the depth or thickness of the features of interest if the propagation velocity is known. Electromagnetic waves cannot penetrate through metal. Therefore GPR cannot be used to investigate the grouting condition inside metal ducts. However, it can be very effectively applied to locate metal reinforcement.

**Ultrasonic echo**

Ultrasonic echo is an established NDT method in material testing for the investigation of homogeneous materials like metals. And it is also one of the most applied imaging methods in medicine. In the beginning of the 1990’s first experiments started to research the potential of ultrasonic investigations on concrete specimens. Promising results have been achieved through intensive research activities and the development of low frequency sensors (approx. 50 - 200 kHz) adapted to concrete and other building materials. Today, thickness measurements [4], localisation of reinforcement and tendon ducts [5, 6] and the characterisation of surface cracks [7, 8] are typical applications in practice.

The ultrasonic echo method, as well as radar, works according to the impulse echo principle. Ultrasonic impulses are reflected at the interfaces, where the acoustic impedance of the materials changes. In comparison to electromagnetic waves, acoustic waves can penetrate through metal ducts. Therefore ultrasonic techniques are very promising for investigations of the grouting condition inside metal ducts. The distance from the inhomogeneity to the
The transceiver is determinable by using the transit time of the reflected impulse, assuming a constant propagation velocity, which also needs to be known.

**Impact echo**

Impact echo is also an acoustic method for the non-destructive evaluation of concrete and masonry structures [9, 10], invented by the US National Bureau of Standards (NBS) in the mid-1980’s.

The impact echo method is based on the analysis of multiple reflections of mechanical waves between two boundaries. A mechanical point impact is applied to the concrete surface; thus a transient stress pulse is generated which spreads into the concrete. The impulse, travelling through the material, is partly reflected by every internal interface or discontinuity (e.g. reinforcements, ducts, defects and delaminations), but is almost completely reflected if the second material is air, as it is the case at the external boundaries of the specimen. These multiple propagations of low frequency waves between the external surfaces of the structure and any internal reflectors are picked up by a transducer, which is located close to the point of impact. A frequency spectrum analysis is performed on the multiple reflections recorded in the time domain. The calculated resonance frequencies can be used to determine the depths of the reflectors and to evaluate the integrity of the structure. For depth determination, also here the propagation velocity has to be known, e.g. has to be determined on a structure of similar material with known thickness.

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**Data visualisation**

There are a lot of different variants for the visualisation of the data of reflection measurements. In this paper, only four of them are described.

An A-scan is the result of a point measurement, whereby the amplitude and respective polarity of reflections is presented as a function of time (see Figure 1: A-scan (Radar)). If the propagation velocity of radar or ultrasonic signals in concrete is known, the time scale can be converted into a depth scale. The travel time as well as the amplitude of the reflected signal is influenced by the covered distance and by the material properties of the structures inside the concrete element.

A B-scan is the plot of a series of A-scans recorded along a line on the surface. In B-scans signal amplitudes are represented through grey/colour scales considering also polarity (see Figure 2).

For the generation of C-scans several B-scans recorded in a 2-dimensional grid are combined. The resulting 3-dimensional data array represents the signal amplitude as a function of its xyz-position. With image processing tools, this array can be manipulated to extract features corresponding to the inner structure. The image plots of the amplitudes parallel to the x- and y-axes at a constant depth z are called C-scans (see Figure 2).
With C-scans complex structural arrangements such as inclined reinforcements or tendon ducts can be visualised and analyzed layer by layer. But especially reflectors running parallel to the surface can be visualised clearly and much better as in B-scans.

Last but not least it is possible to add the amplitudes of some B- or C-Scans within a certain range. The result is a B- or C-scan projection.

![Figure 2: Schematic illustration of B-scan and C-scan generation in a 3D data cube](image)

**AUTOMATION OF TESTING METHODS: RADAR, IMPACT-ECHO AND ULTRASONIC ECHO**

Measurements for the assessment of post-tensioned structures have already been carried out by BAM in 2000 and 2001. Small areas of structures were inspected with hand measurements and first attempts to automate impact-echo testing were tried [11, 12].

The assessment of the areas investigated with these methods requires dense measurement grids. That means that a distance between the measurement traces of radar should be between 5 and 10 cm. The distances between the measurement points of the acoustical sensors have to be chosen between 2 and 5 cm. The time and the manpower requirements for the measurements are very high for this kind of investigations. The demand for higher efficiency and better performance led to the development of automated scanning systems at BAM. These systems allow faster high-resolution measurements on larger areas with radar, impact-echo and ultrasonic echo. All components of the systems are built in modules for easy transportation and installation. The scanning system can be equipped with different sensors at the same time; so it is possible to use both acoustical investigation methods (impact-echo and ultrasound) together and take advantage of the combination of the results.

Up to now the BAM has developed three scanning systems for 2D-investigations. The largest scanning system allows large-area measurements on horizontal surfaces up to a size of 4 m x 10 m. The system is shown in Figure 3. The length of the two tracks can be adapted to the area of investigation. Measuring widths of 3 m or 4 m are presently possible. The system was applied for investigations at a pre-stressed deck of a box girder bridge in Germany. Automated measurements were carried out on the top and also on the bottom side of the deck. Areas up to 4 m x 10 m were examined.

The second scanning system allows automated measurements on large vertical areas. It was used for non-destructive investigations at two box girder webs on concrete highway bridges in Austria. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows a picture of this system during acoustical measurements at one of the webs. In this case the scanning system was installed outside the web with the help of a sky lift, and the measurements were controlled from the ground below the bridge. For the investigations of the second web the scanning systems were also installed outside the web. In order to install and apply the scanning system a scaffold was used. The test sensors were moved along an area, which was limited by a horizontal and a vertical track. For the measurements, which could be carried out to a maximum height of 1.60 m, the horizontal leading track is mounted at a cantilever above the measuring areas. Afterwards the slide carrying the sensors is hung in. The webs at the bridges in Austria were
investigated with a length of 10 m or respectively 4 m. During the tests the bridges were under traffic, which was not affected by the measurement activities.

A web of the above mentioned box Girder Bridge in Germany was also investigated with ultrasonic echo and radar. The measurements were carried out on the inner side of the web. For the automated measurements with ultrasonic echo a small flexible scanning system was used. This scanning system has a maximum measurement area of 1.80 m x 1.80 m. For the investigations of the web the scanner could be easily transported and installed inside the box girder. Here an area of 1.45 m (height) and 4.00 m (length) could be investigated.

For the investigations of the post tensioned concrete elements industrial measurement devices were integrated in the scanning systems: a 1.5 GHz- and a 900 MHz-radar-antenna from GSSI, an impact-echo device from Olson Instruments and an ultrasonic echo measurement head of the A1220-device from ACSYS. Several software programs, developed by BAM, were working together in a network, controlling the position of the test sensors, the measurement cycle, and the data acquisition.

During the radar measurements the antenna was moved continuously with a velocity of 0.1 m/s over the surface without contact. The impact echo device and the ultrasonic echo measurement head can be moved step by step to the measurement points at the same time. The acoustic sensors are pressed on to the surface and lifted after data acquisition with a pneumatic system at each position. The ultrasonic echo measurement head with 24 point-contact-probes requires no coupling agent.

RESULTS

General

The results presented in this paper are based on the non-destructive investigation of three bridges. At first measurements on parts of the deck and the box girder web of the bridge in Germany were carried out [13]. This bridge is pre-stressed parallel and perpendicular to the bridge axis. Secondly the tension box girder webs (d ≈ 50 cm) of two highway bridges in Austria were partly investigated. The combined inspection with different NDT-methods was part of different research projects. The main objective was the demonstration of the improved effectiveness of radar, impact-echo and ultrasonic echo due to the automated measurements and the application of new software for the data processing and data visualisation.

In principle the analysis of the data is based on the presentation and interpretation of different cuts through the measured object (B-scan or C-scan). Additionally animated images of consecutive slices provide a descriptive insight into the object of investigation. This is a very useful interpretation tool especially for the investigation of tendon ducts with a change of the horizontal and vertical position. Precondition for a good visualization and interpretation is the specific data processing for each of the NDT-method. Further information and some examples of the animation can be found on the website www.bam.de/div-44.htm (Data processing and visualisation of NDT-data sets).
Radar

Each measurement area was investigated in two perpendicular directions of antenna polarization. This was done due to the effect, that reflectors, which are orientated parallel to the polarization of the electric field of the radar antenna, could be better detected than others. The analysis of the data set is based on the interpretation of B-scans and C-scans. Additionally each data set was reconstructed using the FT-SAFT software developed at the University of Kassel. This software is using the Synthetic Aperture Focusing Technique (SAFT) and allows the focusing of the reflections for scanning measurements [14]. It is possible to combine the data sets measured with the same antenna but with different directions of polarisation. There are different algorithms to compress all important information in one data set [15].

For the detection of tendon ducts and reinforcement the 1.5 GHz antenna proved to be the best suited device. It was possible to determine the thickness of concrete structures up to 50 cm. Tendon ducts without shadowing effects from the reinforcement and other tendon ducts could be detected with this antenna in a depth up to 16 cm. This means that the lateral position and the depth were identified very exactly. But as expected the resolution of 1.5 GHz antenna did not suffice to dissolve a single tendon duct with an inner width of approx. 4.5 cm between the ducts in a box girder web. With the 3D-SAFT reconstruction and the following fusion of the radar data sets, the rebar, oriented perpendicular to each other and especially those belonging to the reinforcement near the surface, could be presented with high resolution and with nearly the same amplitudes. The accuracy of the determination of the lateral position and the concrete cover was increased. In figure 5 a C-scan (slice parallel to the surface) in a depth of 7.5 cm is shown. The reinforcement near the surface is very well resolved and visible.

![Figure 5: C-scan (parallel slice to the measurement surface) in a depth of 7.5 cm from the reconstructed fused radar data (the outer reinforcement layer of a box girder web in Austria)](image)

Impact echo

In Figure 6 two different projections of impact echo data sets are shown. These are the results of measurements on the deck of the box girder bridge in Germany. On the right side a B-scan projection is presented. The backside, which partly does not run parallel to the surface, is clearly visible in a frequency of approx. 9 kHz. This frequency is equivalent to the thickness in the middle of the deck (approx. 24 cm). The lateral position of the tendon duct could be determined by displacing of the backside reflection. In Figure 6 on the left side a C-scan (slice parallel to the surface) in the depth of the backside is shown. The positions of the tendon ducts are clearly visible from \( y = 3.7 \text{m} \) to \( y = 5.4 \text{ cm} \). The high intensity between tendon ducts no. 5 and no. 6 is caused by a drainage pipe. From the topside of the deck the tendon duct could not be detected directly, only through the apparent increased thickness of the deck. For that reason the determination of the depths was not possible. From the bottom side of the deck the tendon ducts could be detected directly and the depths could be determined. Indications of grouting faults, which are indicated by high reflection intensity, were not found. The thickness of the box girder web in Austria (approx. 50 cm) could be confirmed. But the tendon ducts were not located. Further research is urgently needed here.
Ultrasonic echo

The interpretation of the ultrasonic echo measurements is based on 3D-reconstructed data, calculated with a SAFT-program of the Fraunhofer-Institute Non-Destructive Testing (IZFP) in Saarbrücken. By the use of this calculation the signal-to-noise-ratio is increasing considerably [16].

Tendons in the investigated building structures could be localised with the applied ultrasonic echo equipment up to a measurement depth of 40 cm. The ultrasonic waves are also reflecting on fully grouted tendon ducts, but with a low intensity. Therefore the lateral position of the tendon ducts could be reliably identified by means of reflections from tendon ducts and the shadowing of the back wall behind them. If the reflections from the tendon ducts are more intense than the noise of the concrete texture it is possible to specify the concrete cover of the tendon ducts. Figure 7 shows that also tendons arranged behind others were reproduced at the investigated webs at the bridges in Austria. The application of ultrasonic echo on larger areas allows the visualisation of perpendicular arranged reinforcement bars. In comparison with radar the display of the non-tensioned reinforcement detected with ultrasonic echo is more diffuse and incomplete. On the other hand the thickness of the structures up to 60 cm could be determined.

For the assessment of the grouting conditions of the tendon ducts the arrangement of the tendons in the building structure and the kind of tendon have to be taken into account for the interpretation. Furthermore the intensity of
Reflection depends on the arrangement of the strands in the tendon duct, on the coupling of the ultrasonic transducers, on the structure surface and on the distance between the tendons and the surface. Significant rising of the reflected signals, which is expected in the case of non-grouting, are noticed at tendons in one of the webs at the bridges in Austria. In parts the tendon sections with high reflectivity correspond to the length and the arrangement of coupling between tendons. The reflectivity of two at the depths of 22 cm to 28 cm detected couplings is shown in Figure 8. Furthermore some sections of tendons have been detected, which could not be clearly defined. Here, further investigations are recommended.

Data fusion, combination of different methods

In chapter 4.2 an example for the fusion of two radar data sets was shown. In addition to this, it is also possible to combine data sets measured with different NDT methods, like radar and ultrasonic echo. Both methods complement one another as it is shown in Fehler! Verweisquelle konnte nicht gefunden werden. (slice perpendicular to the surface).

The B-scan is part of the fused data set. Radar and ultrasonic echo data sets, measured on the box girder web in Germany, were combined. The multitude of reflections of rebar near the surface and the reflection of the tendon duct on the left side of the B-scan were measured mainly with radar. The radar measurement in this depth range is more suitable and useful than ultrasonic because of the enhanced resolution, especially for the detecting of metallic reflectors. The reflection of the backside and signals of the rebar on this side, both at the depths of 45 cm - 60 cm, were exclusively measured with ultrasonic echo. For the radar these reflectors are too deep to get a significant reflection. By the combination of the radar and ultrasonic echo data sets it is possible to compress information in one data set. This allows the complex visualisation and interpretation of one data set measurement on the box girder web with ultrasonic echo and radar.
ULTRASONIC LINEAR ARRAY

To accelerate the data acquisition, a special transducer array was developed in co-operation between BAM and ACSYS [17][18]. It consists of 10 elements with 4 dry point contact shear wave transducers each working at a centre frequency of 50 kHz and polarization perpendicular to the long side of the array. The distance of the transducer elements can be varied between 25 and 40 mm (figure 10, prototype at BAM).

Each element contains not only the 4 transducers but also the electronics needed for generating, receiving and digitizing signals. From the transducer element to the controller unit built into the array and from the controller unit to the computer, only digital data is transferred.

During operation, the transducer elements are switched as a multistatic array, that means one element acts as transmitter and all others as receiver, then the second element acts as transmitter and so on (figure 11). Another benefit apart from the fast data collection – a complete sweep is finished in less than a second – is the fact that one gets information from many different sound paths. After a complete sweep is done at one position, the data is transferred to the computer, instantly reconstructed applying the SAFT algorithm and displayed as cross-section below the linear array. The data measured along a line can be combined to one data set and be shown as longitudinal as well as cross sections, corresponding to ultrasound B- and C-scans.

It’s also possible to evaluate the data with other algorithms such as FT-SAFT (Fourier Technique SAFT) reconstruction calculation, which allows real 3D imaging and phase analysis [19, 20]. In figure 12 one practical application is presented as example. The aim was to verify the position of tendon ducts inside a girder, of 60 cm thickness. The data was collected along one 1.16 m long line with a step width of 2 cm. The linear array was positioned perpendicular to the line, thus, the shear waves were polarized parallel to the duct.

The result of the 3D-FT-SAFT reconstruction is shown in figure 12: The cuboid at the right

(a) represents the reconstructed volume (surface: 0.40 m x 1.26 m, depth: 0.70 m). The other parts of the graph represent the different sections, which can be interactively adjusted by three plains:

b) Depth section (C-scan parallel xy) in showing the upper tendon duct
c) Cross section (B-scan parallel xz) showing two tendon ducts
d) Longitudinal section parallel (B-scan parallel yz)

The result clearly indicates two tendon ducts in the depth of 18 cm and 40 cm. The back wall echo at z = 60 cm is clearly visible. There are probably reflection signals from the top as well as from the bottom side of the tendon ducts. This corresponds to earlier results of acoustic imaging of tendon ducts [21].
Radar, impact-echo and ultrasonic echo were applied for the automated assessment of post-tensioned concrete bridges. The tensioned and the non-tensioned reinforcement at a transverse pre-stressed bridge deck were investigated with NDT methods. Further automated measurements were carried out on three pre-stressed box girder webs, one in Germany and two in Austria. The reinforcement bar, which is arranged perpendicular could be visualised with a high resolution. For these purposes the radar datasets, collected within two perpendicular polarisation directions, have been reconstructed and fused with each other. The tendons in the investigated building structures could be localised with the 1.5 GHz-antenna at measurement depths up to 16 cm and with ultrasonic echo at measurement depths up to 40 cm. With the measurements, carried out from only one side of the structure, it was possible to detect the backside with ultrasonic and impact-echo up to a depth of 60 cm in areas, where the backside is not shadowed by tendons. Additionally the position of couplings between tendons could be determined and hints to not completely filled tendon ducts could be given. There is still need for further research concerning the detection of grouting faults with impact-echo and ultrasonic-echo.

The scanning systems developed at BAM show a reliable performance under field conditions. They allow non-destructive measurements on areas up to 4 m x 10 m. The time and effort could be considerably reduced by automation in comparison with manual measurements. Potential for further investigations arises from a shorter installation time of the scanning systems and from simultaneous measurements with several test sensors.

A new device allows much faster collection of data and imaging of concrete volumes. This device is commercially available and can be operated easily on site with real-time results.

ACKNOWLEDGMENT

The investigations on the box girder bridge in Germany were realised in cooperation with the Federal Highway Research Institute and the ASV Fulda (the office for transportation) in Germany. The Ministry of Traffic, Building and Housing Industry funded this research project. The automated measurements on the two box girder bridges in Austria were carried out with the Vienna City Administration. Further the teamwork of the colleagues at BAM, division IV.4 and several FOR384-partners contributed to the success of these research projects. Part of the research work was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) within the scope of the Forschergruppe FOR 384 (Non-destructive evaluation of concrete structures using acoustic and electromagnetic methods).
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