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Results of reconstructed and fused NDT-data measured in the laboratory and on-site at bridges

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Abstract

Non-destructive testing (NDT) of concrete structures plays an increasing role in civil engineering. This paper presents the results of measurements carried out in the laboratory at BAM and on-site at several bridges using reconstructed and fused radar and ultrasonic echo data sets. In this context different scanning systems, developed for the on-site application of NDT-methods (e.g. reinforced concrete bridges) are introduced. The main object was the demonstration of the improved effectiveness of radar and ultrasonic pulse echo technique due to the automated measurements and the application of new software for the data processing and data visualisation. The results of these measurements show the high potential of reconstruction and data fusion for the improvement and simplification of the interpretability of large data sets measured with impulse-echo methods.
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Keywords: Non-destructive testing; Prestressed concrete bridges; Radar; Ultrasonic pulse echo technique; Data fusion; Scanning system

1. Introduction

Existing buildings consisting of reinforced and prestressed concrete involve a high maintenance to sustain their value and convenience. For instance in 2001 approx. 350 Million Euro were spent by the German Government for the maintenance of bridges and other engineering structures on federal roads. Prognoses for the future maintenance budget predict a rise of maintenance costs of about 100% during the next 15 years just to maintain the condition of the structures at the present level [1]. Big parts of the costs are caused by post-tensioned concrete bridges, which have been built between 1950 and 1970. These bridges are vulnerable to corrosion damage on tendons caused by grouting faults in the tendon ducts. In these cases the detection of corrosion affecting the tensioned reinforcement is required because the durability of the corresponding structural elements cannot be promised.

The Federal Institute for Materials Research and Testing (BAM) is dealing with the localisation of internal tendon ducts, using non-destructive investigation techniques, and with the assessment of grouting conditions inside the tendon ducts. Furthermore, non-destructive testing (NDT) methods have been applied for the localisation of non-tensioned reinforcement and to recognise irregularities (e.g. cavities, honeycombing) inside the bulk material. The research concentrates on the combined application of electromagnetic and acoustic echo methods. Therefore several test specimens were constructed and investigated in the laboratory at BAM. At the same time a scanning systems has been developed enabling these automated measurements for the assessment of post-tensioned bridges.

BAM is also deeply involved in the development and application of new techniques for data processing and data visualisation. Depending on the nature of the problem the data processing can include the reconstruction of the data sets and data fusion. By performing data reconstruction with synthetic aperture focusing technique (SAFT), the interpretability of the data, gained from different transducers, can be enhanced. The main objective of data fusion is

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the improvement and simplification of the interpretation of the measurement results gained from different methods. The complementary information of different NDT-data sets is superimposed and compressed in a single fusion data set with the aid of simple mathematic algorithms.

The main objective of this paper is the demonstration of the improved effectiveness of the NDT-methods by performing automated measurements and the application of new software for data processing and data visualisation. First, the different impulse echo methods as well as the scanner system are briefly described. Subsequently, the processing of the data sets recorded with radar and ultrasonic pulse echo technique and the algorithms of the data fusion are presented. Finally, results obtained from investigations at the test specimens and at selected reinforced concrete bridges are described and summarised.

2. Experimentals

2.1. Ground penetrating radar

Ground penetrating radar (GPR) has been established for several decades in geophysics for soil investigations [2]. With the development of high-frequency antennas, as well as efficient computer systems, it is now also possible to examine smaller structures along larger areas. Thus this method has been successfully applied to solve civil engineering problems, such as the assessment of concrete and masonry structures [3–5] and the determination of moisture content and distribution [6].

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 (transmitter), which is in most cases in direct contact (not necessarily needed) 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 at interfaces of concrete or coverings to other layers of concrete, to voids, to metal and to other inhomogeneities. The reflections are recorded by a receiving antenna (receiver), which is also positioned on the surface close to the transmitter. In most cases, transmitter and receiver are in the same housing. The transit 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. The conductivity of materials strongly affects the propagation of electromagnetic waves. For example GPR investigation is almost impossible in fresh concrete due to the high moisture content. Furthermore electromagnetic waves cannot penetrate through metal. Therefore GPR cannot be used to investigate the grouting condition inside metal ducts. However, it can be applied very effectively to locate metal reinforcement. The pace of work in comparison to the acoustic impulse echo methods is very high. The high speed is caused by the short acquisition time. Additionally a direct contact to the surface is not necessary. So the antenna can be moved over the surface continuously. For the presented investigations, radar units and antennas (middle frequencies from 900 MHz to 1.5 GHz) from Geophysical Survey Systems, Inc. (GSSI) were used.

2.2. Ultrasonic pulse echo technique

Ultrasonic pulse echo technique 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. Since the beginning of the 1990s with first experiments a large progress has been achieved to research the potential of ultrasonic echo investigations at concrete specimens. Promising results have been achieved through intensive research activities concerning time corrected superposition and the development of low frequency transducers (approx. 50–200 kHz) adapted to concrete and other building materials. Today, thickness measurements [7], localisation of reinforcement and tendon ducts [8–10] and the characterisation of surface cracks [11–13] are typical applications in practice.

The ultrasonic pulse echo technique, 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. The analysis of ultrasonic data sets is carried out in time domain. This differs from the analysis of data sets measured with the impact-echo method. The later is based on the analysis of multiple reflections and data processing is mainly performed in the frequency domain [14]. In comparison to electromagnetic waves, acoustic waves can penetrate through metal ducts. Therefore ultrasonic pulse echo techniques are very promising for investigations of the grouting condition inside metal ducts. The distance from the inhomogeneity to the transducers is determinable by using the transit time of the reflected impulse, assuming a constant propagation velocity, which also needs to be known. The pace of work is not as high as with radar which is caused by the fact that the ultrasonic echo transducer can only be moved step by step. The acoustic sensor with 24 point-contact-probes consisting of 12 transmitter and 12 receiver must be pressed onto the surface. This new developed point-contact transducers permit automated measurement without any coupling agent.

3. Data processing

3.1. General

In principle data analysis is based on the interpretation of band pass filtered and amplified data sets. There are different possibilities to visualise these data sets: Depending on the nature of the problem in most cases it is advisable to reconstruct and combine the data sets. In the following the most common variants of visualisation, the innovative data reconstruction algorithms and the efficient data fusion algorithm will be described.

3.2. Data visualisation

There are several possibilities for the visualisation of the three-dimensional 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 Fig. 1). 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 (electromagnetic or acoustic) 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 Fig. 2).

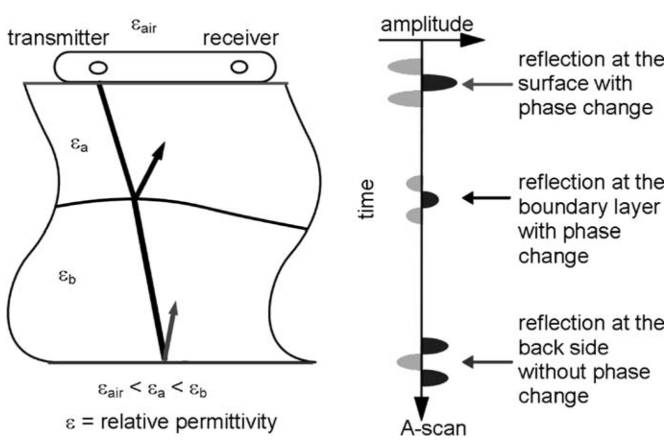

Fig. 1. A-scan (radar).

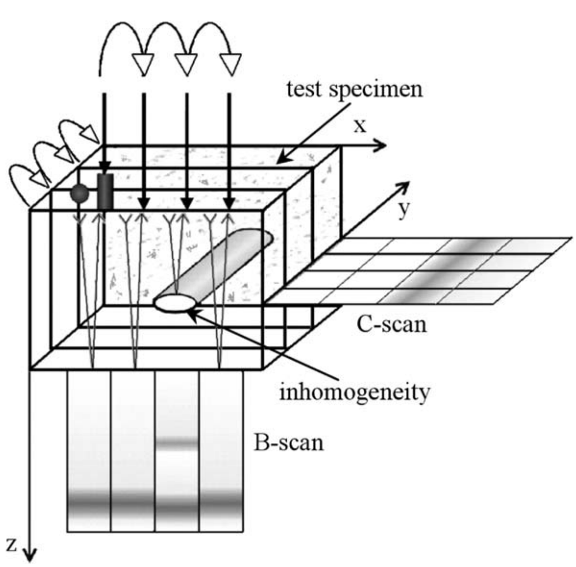

Fig. 2. Schematic illustration of B-scan and C-scan generation in a three-dimensional data cube.

For the generation of C-scans several B-scans recorded in a two-dimensional grid are combined. The resulting three-dimensional data array represents the signal amplitude as a function of its *x*–*y*–*z*-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 surface in a defined depth are called C-scans (see Fig. 2). With C-scans complex structural arrangements such as inclined reinforcements or tendon ducts can be visualised and analysed layer by layer. But especially reflectors running parallel to the surface can be displayed clearly and much better as in B-scans.

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

Further information and some examples of animated images of consecutive slices and three-dimensional movies can be found on the website www.bam.de/div-44.htm (data processing and visualisation of NDT-data sets).

3.3. Data reconstruction

In the B-scan a small reflector recorded with radar as well as with the ultrasonic pulse echo technique appears as a hyperbola caused by the opening angle of the transmitter and receiver, as visualised in Fig. 3. The reconstruction technique is based on synthetic aperture focusing technique (SAFT) and creates three-dimensional data sets in which the reflectors are focussed in their true positions. Further more the signal to noise ratio is improved. Pre-condition for the SAFT reconstruction is the knowledge of the velocity of propagation. At present, the SAFT algorithms, which were applied to the data described in this paper, only perform calculations under the assumption of a constant velocity. That means that strong variations of the velocity in depth can lead to wrong depth information. Such a variation can be caused e.g. by inhomogeneous moisture distribution.

There are various approaches for the SAFT reconstruction [15–17]. The different amplitudes of A-scans must be shifted in time and then added up depending on the lateral position of the A-scans relative to the apex of the hyperbola. At the depth and lateral position of the reflectors

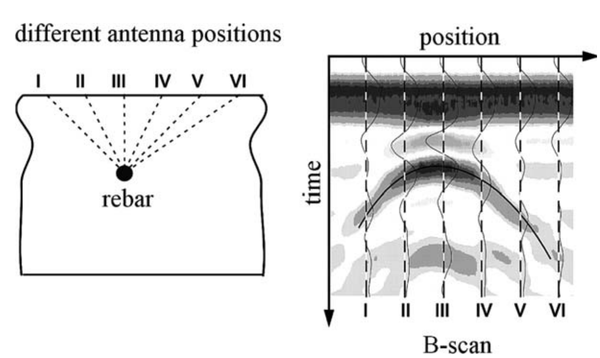

Fig. 3. B-scan of radar measurements.

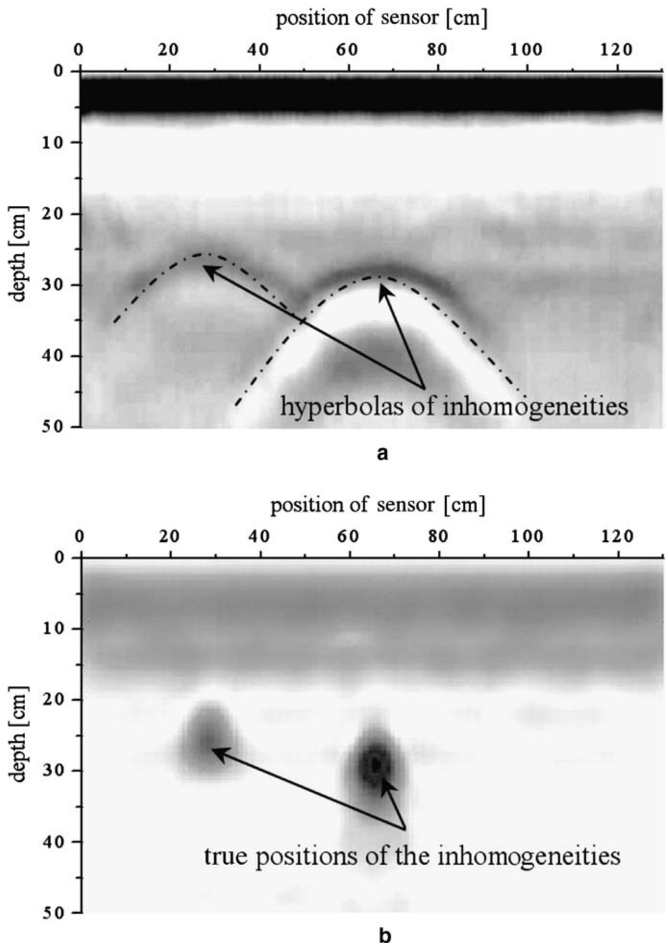

Fig. 4. Result of the FT-SAFT-reconstruction (a) B-scan of a radar measurement, (b) B-scan of the radar measurements after the reconstruction.

the high amplitudes superimpose, leading to an intense reflection. At other depth and positions, the amplitudes interfere destructively. The algorithm is realised by an outer loop over the A-scans. The pixel-driven-approach was used for the reconstruction of the ultrasonic echo data sets. Here, for each pixel in the reconstruction space, the amplitudes of the corresponding time data are added up. The algorithm corresponds to an outer loop over all image pixels. The software was developed at the IZfP Saarbrücken [18]. Radar measurements were reconstructed with the FT-SAFT (Fourier-Transform-SAFT) algorithm based on the Stolt migration [16,19]. An example of the results of this reconstruction is shown in Fig. 4, where the hyperbolas in B-scan (a) are focused to spots in B-scan (b). This software was developed at the University Kassel.

3.4. Data fusion

By using data fusion it is possible to combine the results and thus the benefits of different NDT methods. To reach this aim any kinds of 2- or 3-dimensional data sets can be fused. The advantage of radar compared to ultrasonic pulse echo technique is that larger surfaces can be examined in short time because the radar antenna can be dragged continuously along the surface with high impulse repetition rate. But here, with increasing reinforcement density, the significance of the radar method decreases, because most of the intensity of the electromagnetic impulses is reflected at the metallic bars and thus the signals contain less information regarding structures which are located behind. The acoustic methods can compensate for this deficit, since they can penetrate through metal. Metallic structures have a nearly similar effect on electromagnetic waves (total reflectance) compared to that of air gaps on ultrasonic waves (also total reflectance). For the radar method air layers are transparent and only little intensity is reflected, so that both methods complement each other very effectively.

With data fusion, the interpretation of experimental data can be improved and simplified. Some information can be enhanced by the visualisation of data sets recorded with different methods from the same volume. Last but not least, the storage requirement for saving data sets decreases, because only the combined data set with the sum of information has to be saved.

The fusion of different data sets recorded in the same volume with one method and various configurations (e.g. sensors, polarisation) or with different methods is defined as the mathematical superposition of each data set. For this, various mathematical operations are available. Before data fusion, several data processing steps are required to adapt the data sets. For example weighting of the single data sets is possible with constant, linear and non-linear functions, e.g. for considering different reliabilities of the methods. Also signals with low signal/noise ratio and/or DC offset can be filtered. If data have been recorded with different density of data points, missing or needless data points can be interpolated or deleted, respectively, if this is a constraint for the data fusion algorithm. After processing, the different data sets can be added, subtracted or divided. Additionally it is possible to calculate the average of different data sets or to compare the data sets and include only the maximum amplitudes in the fused data set. The decision about which data fusion operation has to be used depends among others on the nature of the problem. For example it is only suitable to add, subtract and divide complete data sets. That means the data sets must have the same size. The division and subtraction are well applicable to detect a temporal change in the object in different successive measurements. Incomplete data sets can be fused with the operation which only includes the maximum amplitudes. For the data presented here, in most cases only this last operation was used to enhance the advantaged of the complementary information of the different configurations and methods.

4. Automation of test methods

The assessment of structures investigated with imaging NDT methods such as radar and ultrasonic pulse echo technique requires dense measurement grids to get optimum geometric resolutions. Especially SAFT-reconstructions of radar and ultrasonic echo data sets normally require very small scanning increments (steps) in the scale of a 10th of a wavelength. Presently, this is too time consuming for on-site measurement campaigns. Comparative studies have shown that good reconstruction results can be achieved with larger increments. That means that a step between the measurement traces of radar should be between 5 and 10 cm. The step width between the measurement points recorded with the acoustical sensors has 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.

Up to now BAM has developed three scanning systems for investigations along three-dimensional grids. The automated systems allow faster high-resolution measurements also at large areas. All components of the systems are built in modules for easy transportation and installation. Thus investigations of structures outside the laboratory can be carried out easier and more effectively. The scanning systems can be equipped with several industrial test sensors. It is also possible to install the sensors of different acoustic testing methods like impact-echo and ultrasonic pulse echo technique at the same time.

First, a small flexible scanning system was developed for automated measurements with the acoustic echo methods. This scanning system has a maximum measurement area of 1.80 m × 1.80 m on horizontal and vertical surfaces. After successful testing of the smaller system a larger and more ruggedly designed second scanning system was constructed. It allows performing measurements at large areas on horizontal surfaces up to a size of 4 m × 10 m. This system is shown in Fig. 5. The length of the two parallel tracks can be adapted to the area of investigation. Measuring widths of 3 or 4 m are presently possible. A third scanning system was set-up especially for non-destructive investigations of the outer side of box girder webs in vertical position. Fig. 6 shows a picture of this system during acoustic measurements at a web of a box girder bridge. The testing sensors can be moved along an area, which is limited by the lengths of the horizontal and the 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 track with the sensors is hung in.

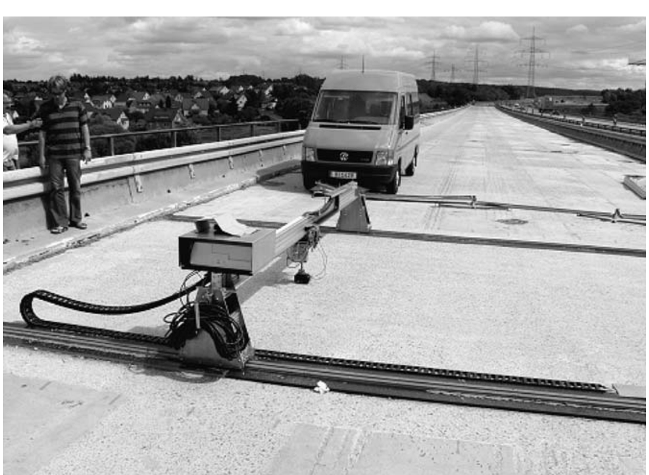

Fig. 5. Scanning system for measurements on horizontal surfaces.

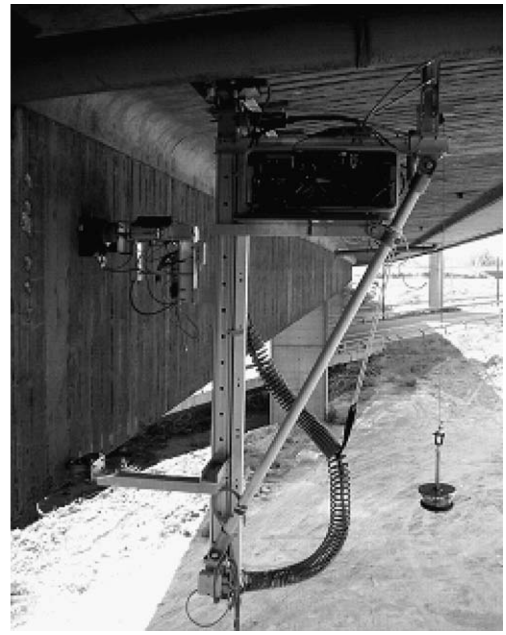

Fig. 6. Scanning system for measurements on vertical surfaces.

During the automated measurements the radar antenna is moved continuously with a velocity of 0.1 m/s over the surface with a distance to the surface of 1–2 cm. The impact-echo device and the ultrasonic echo measurement head have to stop at each measurement point where the acoustic sensors are pressed onto the surface one after another and lifted after data acquisition using a pneumatic system. The ultrasonic echo measurement head of the A1220-device (ACSYS Systems), which is used for the automated measurements, has 24 point-contact-probes and requires no coupling agent as described above.

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.

5. Results of laboratory tests

Fig. 7 shows the views of a concrete test specimen with dimensions of 2.0 m × 1.5 m × 0.5 m which was used for radar and ultrasonic echo investigations. The reinforcement bars in directions of the *x*- and *y*-axes have a grid spacing of 15 cm and are built in from both sides near the surface in the left half of the specimen. Furthermore a tendon duct, including a simulated grouting fault, is built

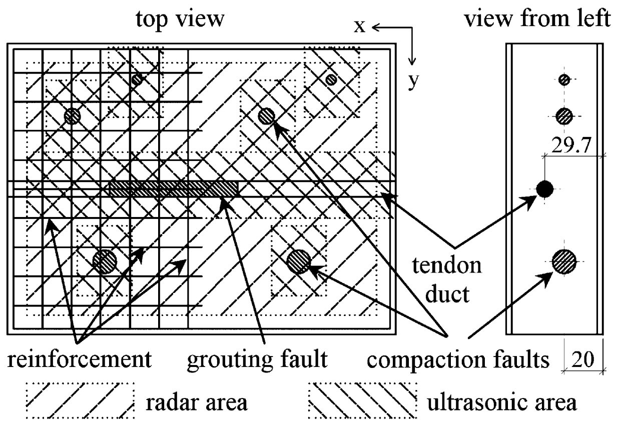

Fig. 7. Views of the concrete test specimen no. 2, size 2.0 m × 1.5 m × 0.5 m.

in. Additionally there are six compaction faults in different sizes simulated by polystyrene spheres (5 cm, 8 cm and 12 cm diameter). The radar area (see Fig. 7) was investigated with the 1.5 GHz antenna in different directions of polarisation. For this, along the whole surface of the specimen, with the antenna two data sets with traces parallel to the x- and y-axes were recorded with a spacing of 5 cm. 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 ultrasonic echo areas were tested with the point-contact transducers array using shear waves (centre frequency 55 kHz).

Fig. 8 shows the results of the combination of three reconstructed data sets. Two data sets were measured with radar in two different directions of polarisation. The third

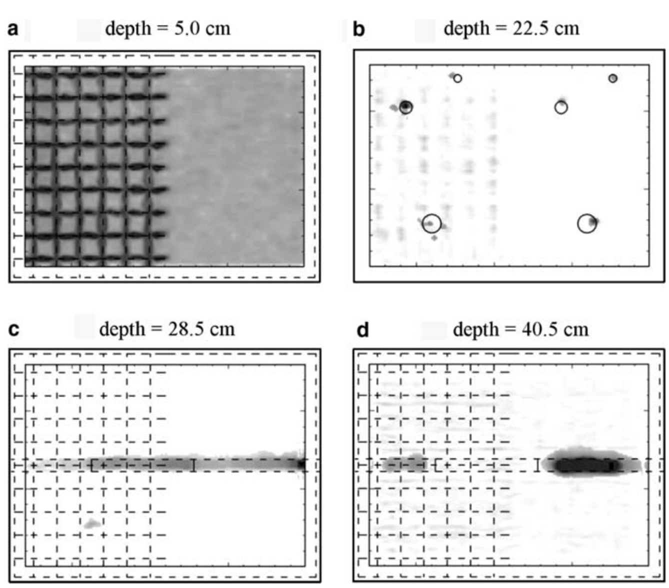

Fig. 8. Four C-scans (1.8 m × 1.3 m) representing different depth slices of the data set calculated by data fusion of two radar and one ultrasonic data sets. (a) C-scan of the fused data set at a depth of 5.0 cm, (b) C-scan of the fused data set at a depth of 22.5 cm, (c) C-scan of the fused data set at a depth of 28.5 cm, (d) C-scan of the fused data set at a depth of 40.5 cm.

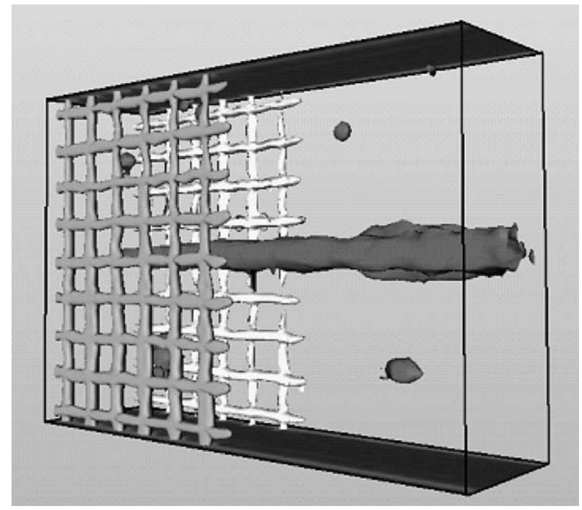

Fig. 9. Three-dimensional image of the fused data set.

is an ultrasonic echo data set recorded with the above mentioned point-contact transducers.

The C-scan (a) shows all reinforcing bars originated from the two radar data sets with different polarisation in a depth of 5.0 cm. Derived from the ultrasonic echo data set, the C-scan (b) of Fig. 8 visualises the compaction faults and the C-scan (c) the tendon duct and the grouting fault. The left area of the simulated grouting fault cannot be seen clearly because of the reinforcement above it. The C-scan (d) shows the bottom side of the tendon duct. Here, it is assumed that at this position an unintended grouting fault exists generating the high reflection amplitude on the right side of the planned grouting fault.

Fig. 9 shows a three-dimensional view of the fused data set of the test specimen. Two additional radar data sets recorded from the opposite side of the test specimen as taken before and also measured with the 1.5 GHz antenna in different polarisation, lead to a good resolution of the backside reinforcement. Therefore and as mentioned above, the reinforcement on both sides, the tendon duct and the compaction faults are visualised very clearly.

6. On-site tests at post-tensioned concrete bridges

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 [20,21]. In the following results of the automated application of radar and ultrasonic pulse echo technique on post-tensioned concrete bridges in 2003 and 2004 are presented. The combined inspection of several bridges with NDT-methods took place in the frame of research projects.

Each measurement area was investigated with the same radar antenna in two perpendicular directions of antenna polarization as described above. With the ultrasonic echo each investigation area were only measured once.

For the interpretation of the investigations the raw and the SAFT reconstructed radar data and the SAFT reconstructed ultrasonic echo data were considered. Finally the fused data were analysed. Especially for the investigation of tendon ducts with a change of the horizontal and vertical position the animated images of consecutive B- or C-scans provide a descriptive insight into the object of investigation.

6.1. Investigation of a post-tensioned bridge-deck

Automated measurements with different NDT-methods were carried out on a bridge deck of a highway bridge. The bridge itself is a cantilever concrete unicellular box bridge built in 1966. A cross-section of the superstructure of the bridge is shown in Fig. 10. The bridge deck is transverse pre-stressed by tendons, each consisting of 12 strands in a duct with a diameter of 45 mm. The distance between the ducts is 75 cm. An area of 4 m × 10 m on the top of the deck and an area of 3 m × 10 m on the bottom side of the deck, from the inside of the box girder, were examined. For this, a 1.5 GHz radar antenna from GSSI, an impact-echo device from Olson Instruments and the ultrasonic echo measurement head with shear wave probes from ACSYS were used. The carriageway surfacing was removed before the investigations were carried out.

All processed data of radar and ultrasonic pulse echo technique provide information about the horizontal location of the tendons and the thickness of the construction element. Seen from the bridge deck, the concrete cover about the tendon ducts varies from 8 cm to 15 cm. The depth, at which the reinforcement and tendon ducts are

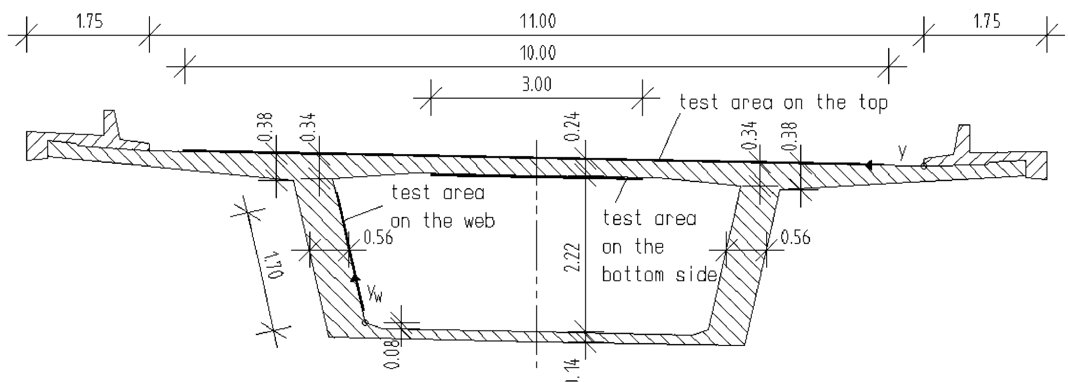

Fig. 10. The cross-section of the superstructure of the highway bridge.

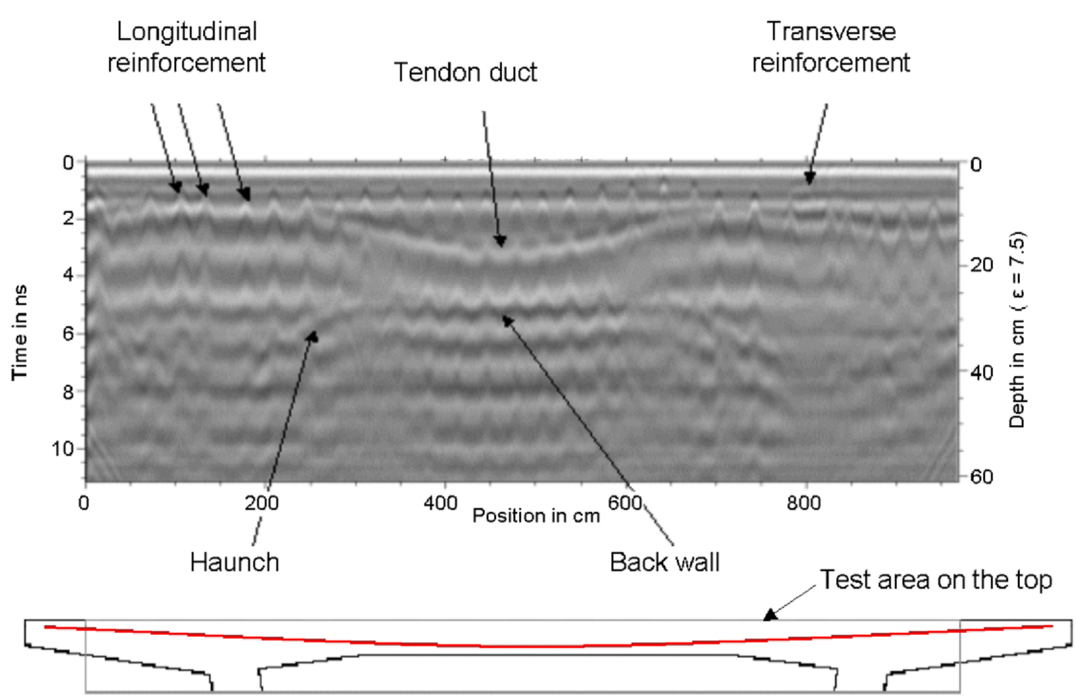

Fig. 11. B-scan, data collected with 1.5 GHz radar antenna (scanning direction parallel to a tendon duct, polarisation perpendicular) measured from the top of the bridge deck.

located, can be accurately indicated by the raw data sets of radar. As an example in Fig. 11 the location of one of the transversal tendon ducts is imaged in a B-scan.

The accuracy of the determination of concrete cover thicknesses above the tensioned and the non-tensioned reinforcement is increased by the SAFT reconstruction of the data. The data fusion of the reconstructed radar data sets, measured on the same test area and with the same radar antenna but in two perpendicular directions of antenna polarization, allows imaging the perpendicularly arranged bars in one reinforcement layer in one C-scan. This is demonstrated in Fig. 12. This figure shows the SAFT-C-scan at a depth of 4.5 cm processed from the measurement data taken from the bottom side of the bridge deck. The ultrasonic waves are also reflected at fully grouted tendon ducts, but with a low intensity. Therefore the lateral position of the tendon ducts could be reliably identified by means of analysing the reflections from tendon ducts and considering the shadowing of the backside 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.

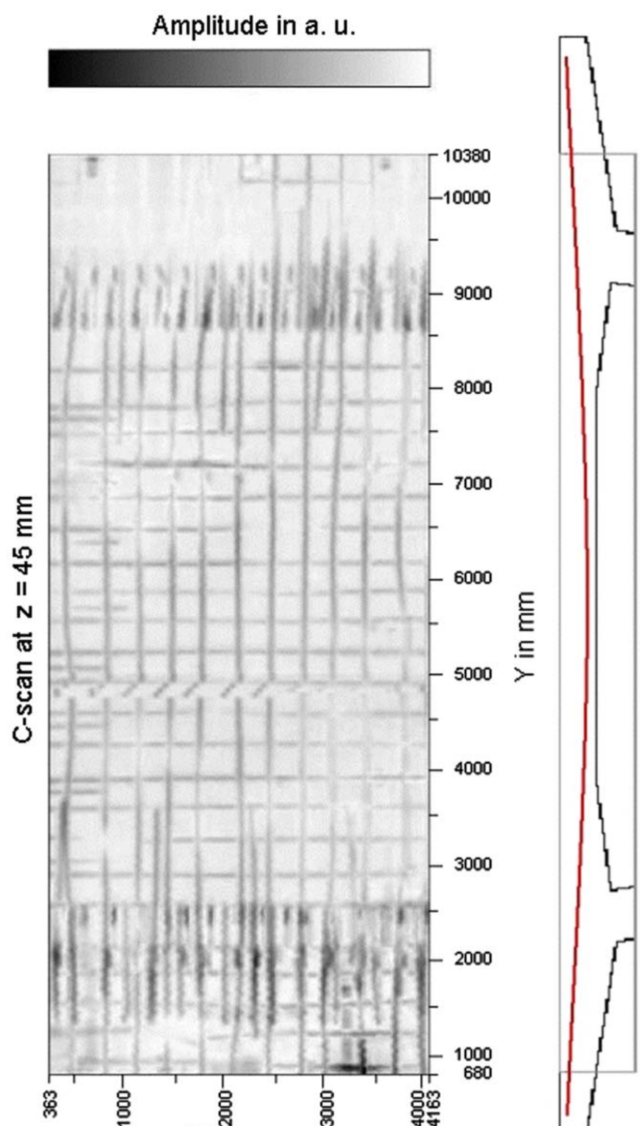

Fig. 12. Radar, SAFT-C-scan at a depth of 4.5 cm (upper reinforcement layer) of the reconstructed and superimposed radar data.

In Fig. 13 the tendon ducts detected by the ultrasonic echo measurements on the bottom of the bridge deck are shown. The image taken from the left part of the test area is a projection of data sections in measurement depths from 11.4 to 12.1 cm processed with SAFT. The image on the right is a section at a depth of 8 cm resulting from the measured ultrasonic echo data without reconstruction calculation. Perpendicular arranged reinforcement bars could also be localized with ultrasonic pulse echo technique. But the main reason for applying acoustic methods is to assess the condition of the tendon ducts, especially to localise grouting faults. In the case of the investigated bridge deck no clear indications of grouting defects could be given. Taken cores and endoscopic inspections after the non-destructive measurements confirm these results. Apart of one very small air inclusion the cores indicate fully grouted ducts.

6.2. Investigations of webs of box girder bridges

Normally the webs of box girders are thicker then the slabs and the arrangements of the longitudinal tendons differ considerably from those of the transversal tendons. Therefore the investigations of these structures are more complex also with regard to the application of NDT-methods. Automated investigations of larger areas of box girder webs were previously carried out by BAM at three different occasions.

At first an area of 1.45 m (height) and 4.00 m (length) of a web of the box girder bridge in Germany (which was already mentioned in chapter 3.1) was investigated with radar (1.5 GHz- and 900 MHz-antenna) and with ultrasonic pulse echo technique. Furthermore two webs of different highway bridges in Austria were investigated with automated measurements using radar (1.5 GHz- and 900 MHz-antenna), ultrasonic pulse echo technique and impact-echo. These measurements were carried out on the outer side of the webs over a length of about 4 and 10 m, respectively. The measurements were controlled from the ground below the bridges. During the tests the bridges were under traffic. The thickness of all three webs is nearly 50 cm. For the pre-stressing of the structures different methods were applied.

For the detection of tendon ducts and non-tensioned reinforcement with radar the 1.5 GHz antenna proved to be the best suited device. Tendon ducts without shadowing effects from the reinforcement and other tendon ducts could be detected in depths up to 16 cm. The lateral position and the depth could be identified very exactly. But the resolution of the antenna did not suffice to dissolve single tendon ducts with an inner lateral distance of approx. 4.5 cm between the ducts in a box girder web.

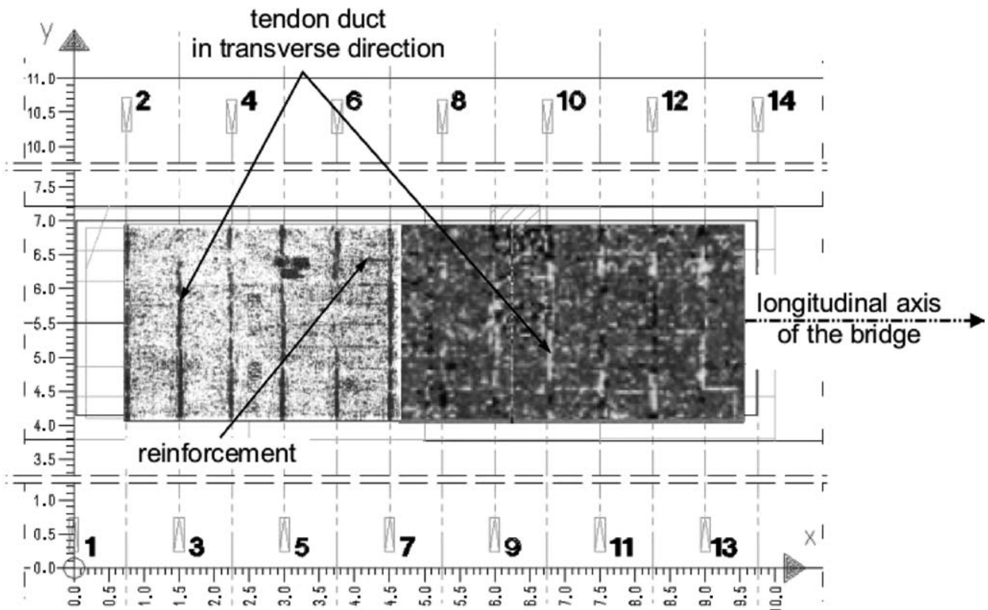

Fig. 13. Test area on the bottom side of the deck with SAFT-C-projection at depths from 11.7 cm to 12.1 cm (left) and a C-scan at the depth of 8.0 cm (right) from ultrasonic echo data.

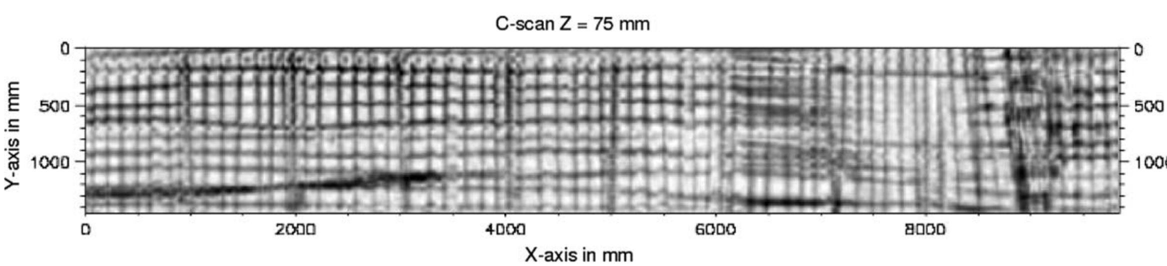

Fig. 14. C-scan in a depth of 7.5 cm from the reconstructed fused radar data sets (the outer reinforcement layer of a box girder web in Austria).

The imaging and the interpretation of data from the non-tensioned reinforcement is substantially improved by the fusion of the reconstructed data sets measured in two polarisations. Rebar's, oriented perpendicular to each other and especially those belonging to the reinforcement near the surface can be presented with high resolution and with nearly the same amplitudes. In Fig. 14 a C-scan in a depth of 7.5 cm is shown.

Also by the application of ultrasonic pulse echo technique the visualisation of perpendicular arranged reinforcement bars can be partly detected. In comparison with radar the display of the non-tensioned reinforcement detected with ultrasonic pulse echo technique is more diffuse and incomplete. But an advantage of ultrasonics is the point that also bars in depths, where the absorption of the electromagnetic waves is to high, could be detect.

The tendon ducts in the investigated building structures could be localised with the applied ultrasonic echo equipment up to a measurement depth of 40 cm. Fig. 15 shows that also tendons arranged behind others could be visualised at the investigated webs of the bridges in Austria. Also the back side reflection of structures with thicknesses up to 50 cm could be detected.

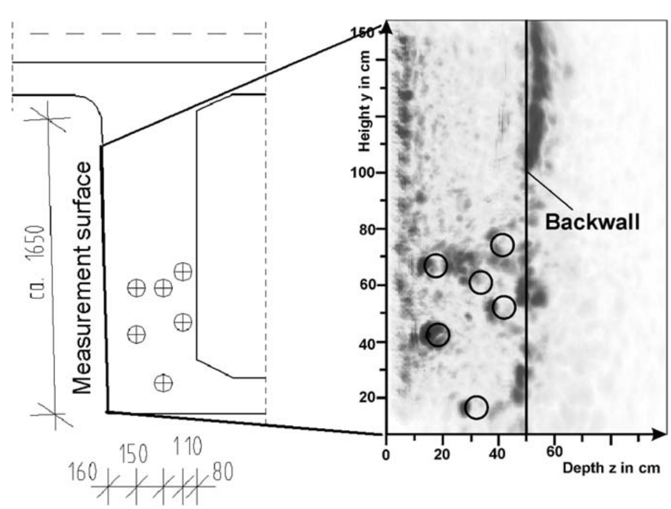

Fig. 15. Arrangement of tendon ducts in the cross section (at $x = 6000$ mm) of a box girder web in Austria, left: according to construction plan, right: located at a SAFT-B-projection by ultrasonic pulse echo technique.

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 has to be taken into account. The intensity of reflection depends on the arrangement of the strands inside the tendon duct, on the coupling between the ultrasonic echo transducers and thus the structure of the 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, is noticed at tendons in one of the webs at the investigated bridges in Austria. In parts the tendon sections with high reflectivity correspond to the length and the arrangement of a coupling area between tendons. The reflectivity of two detected couplings at depths of 22–28 cm is shown in Fig. 16. Furthermore some sections of tendons have been detected, which could not be clearly defined. Here, further investigations are recommended.

In the following two examples present the useful fusion of the two data sets of radar and of ultrasonic pulse echo technique. In Fig. 17 a B-scan parallel to the bridge axis for the investigated web of the box girder bridge in Germany is presented. 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 echo 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 depths of 45–60 cm, were exclusively measured with ultrasonic pulse echo technique. For radar these reflectors are too deep to get a significant reflection.

Fig. 18 shows a comparison of data sets consisting of two reconstructed and fused radar data sets measured with different polarisations, the reconstructed data set of ultrasonic pulse echo technique and the fused data set as a combination of both of them. In this case the arrangement of the tendon ducts at the left part of the measurement field can be seen by radar more clearly. The reflections of the tendon ducts at the right part, in the coupling area, are more significant by ultrasonic pulse echo technique. The lower reflection intensity of the electromagnetic waves in this area and in this range of depth results from the denser outer reinforcement above the tendon ducts and their shadowing effect.

7. Summary and outlook

In this paper radar and ultrasonic pulse echo technique were applied for manual measurements on test specimen and for automated assessment of post-tensioned concrete bridges in Germany and Austria. The main task was the proof of the capability of radar and ultrasonic pulse echo technique in combination with an improved data processing for the investigation of concrete structures. The measured data sets, recorded with radar in different transmitter and receiver configurations and with different ultrasonic echo arrays, were reconstructed, using the

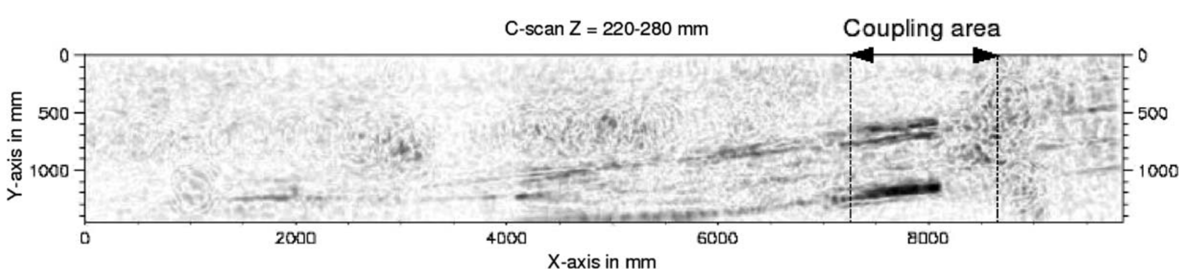

Fig. 16. SAFT-C-projection parallel to the measurement surface at the depths of 22–28 cm from the reconstructed ultrasonic echo data (tendon ducts in a box girder web in Austria).

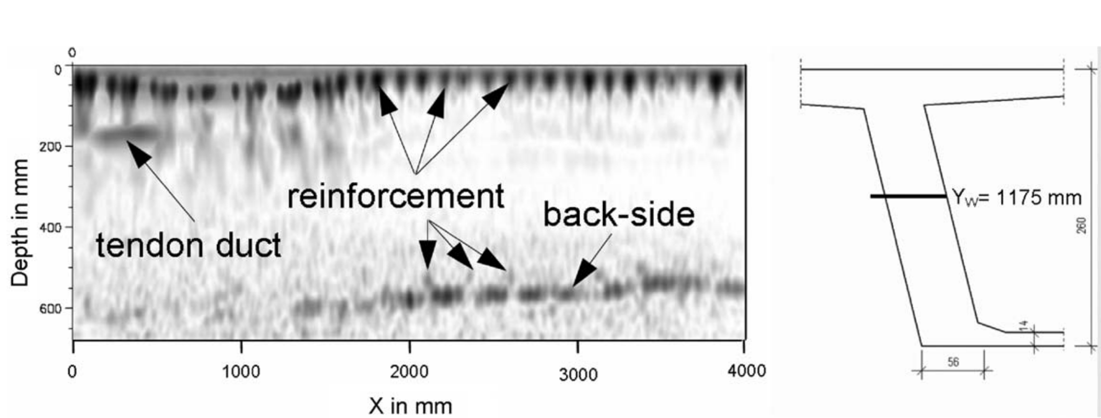

Fig. 17. B-scan through the box girder web of the bridge in Germany at the level of $y_W = 1175$ mm from the fused dataset of the reconstructed data of radar and ultrasonic pulse echo technique.

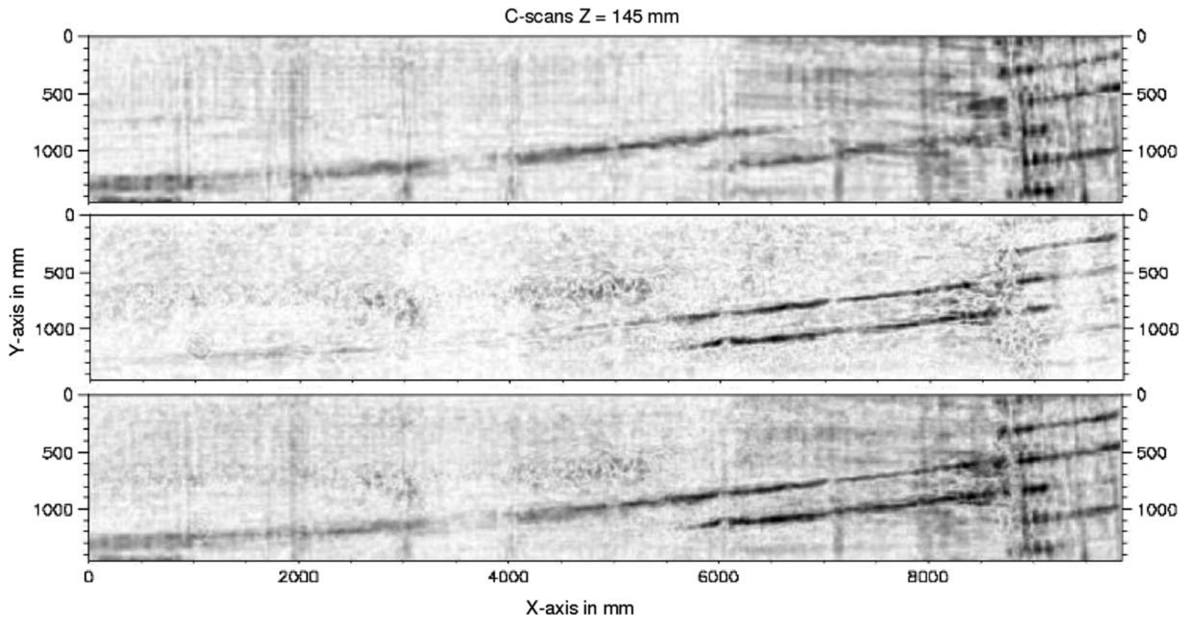

Fig. 18. Arrangement of tendon ducts in longitudinal sections at a depth of 14.5 cm at the box girder web in Austria, C-scan from the reconstructed fused radar data set (top), C-scan from the reconstructed ultrasonic echo data set (middle), C-scan from the fused data set of the reconstructed data of radar and ultrasonic pulse echo technique (down).

Synthetic Aperture Focusing Technique, and combined with different algorithms. The fusion of radar data sets measured with two different directions of polarisation leads to a result which is independent from the polarisation of the antennas. This is especially important if longish reflectors orientated in different directions (here: rebars and tendon ducts) have to be detected and visualised. 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 pulse echo technique at measurement depths up to 40 cm. With the ultrasonic echo measurements, carried out from only one side of the structure, it was possible to detect the backside of the structure with depths up to 60 cm in areas, where the backside is not shadowed by tendons. Because of the limited penetration depth of the 1.5 GHz antenna the backside could not be detected with radar. Additionally the position of couplings between tendons could be determined and hints to not completely filled tendon ducts could be given with ultrasonic pulse echo technique. The combination of reconstructed radar data sets with reconstructed ultrasonic echo data sets allow the compression of all important information in one data set and the compensation of the disadvantages of one method in comparison to another. A maximum of information is gained about those structures containing a high reinforcement density and/or air voids and gaps. The presentation of fused data sets simplifies the data interpretation especially for those, who are no specialised experts.

One disadvantage is that there are no automatic algorithms for the weighting of the data sets, considering e.g. reliability of the data, before the fusion. At present the results of the fusion depend also to some extend on the experience the user has.

The scanning systems developed at BAM show a reliable performance under field conditions. They allow non-destructive measurements on areas up to 4 m × 10 m with a high positioning accuracy. 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 multiple test sensors.

Further research is required to investigate the side conditions for the application of the methods in order to make the results more reliable.

The consideration of further methods (e.g. like the covermeter or others) to get more information about measurement objects will be subject of future investigations.

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