Abridged report

for the research project
"Combination of Non-Destructive Testing methods: improvement of applicability in building/construction practice by characterization and fusion of the recorded data"

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Combination for Non-Destructive Testing: improving the field of application in buildings through characterization and fusion of the proceedings

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1 Introduction and Motivation

The application of non-destructive methods (radar, ultrasonic and eddy current fields) for the analysis of the structure condition or for the damage detection has recently gained increasing practical importance. Depending on the existing conditions an appropriate non-destructive testing method is selected, by which the given testing task can be solved at the best.

For the electromagnetic method (radar), a total reflection of the electromagnetic wave occurs at metallic internal components such as cladding tube and near-surface reinforcement. Moreover, this method allows fast data recording. For the acoustic method (ultrasonic), a total reflection of the elastic waves occurs at interfaces to media without any shear stress, so that thickness measurements of concrete structures up to 1.0 meter are possible. On metallic objects such as sheaths or armoring only about 50% of the applied mechanical energy will be reflected. Thus, even behind tightly laid reinforcement structures can still be determined. With the eddy current method the depth position of the reinforcing bars can be estimated if their thickness or the bar diameter at a known depth can be determined accurately.

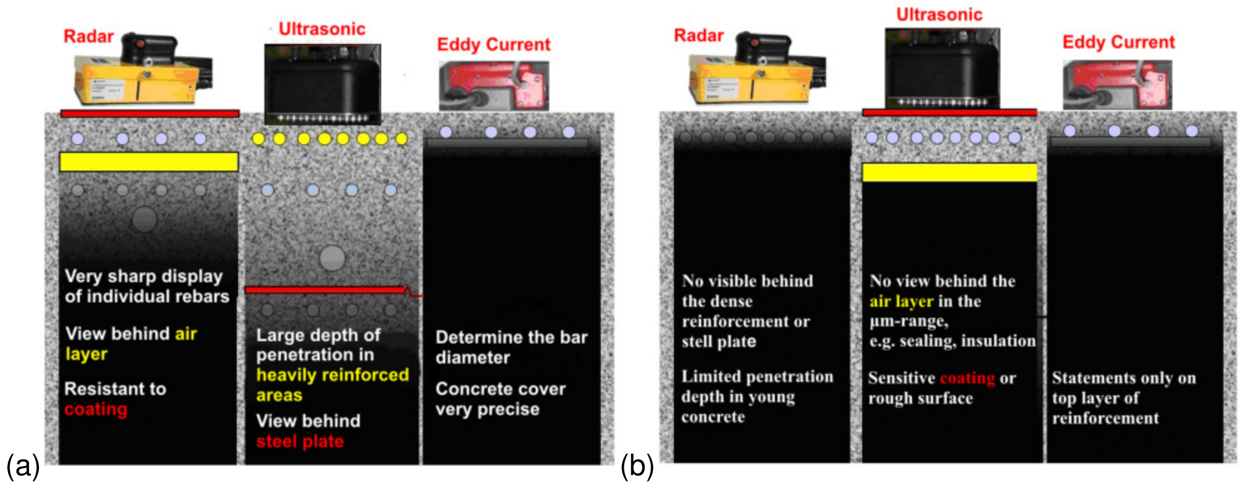

Fig 1 (a) Possibilities and (b) limitations of various non-destructive methods from [1].

Because of these few but significant characteristics of the three methods, it is clear that the combination of non-destructive methods for optimal solution of a testing task is significant to compensate the weaknesses of one method by the strengths of others (Fig. 1). In addition to the combination of methods with a separate evaluation of the results, the fusion of the processed measurement results of the three methods is a possibility to increase the value of the evaluation and to improve the reliability of the outcome.

In the research project, a methodology is developed for processing, merging and imaging of the radar, ultrasonic and eddy current data in order to increase the reliability of the records. An existing scanner (OSSCAR - OnSite scanner) is further developed so that in addition to the required recording accuracy, the congruence of measurement fields that are recorded with the three different methods, is given already during the data recording Furthermore, evaluation strategies and algorithms are developed to ensure optimal data processing. In summary, a measurement and evaluation strategy for data fusion is developed to provide guidelines for practical construction issues.

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2 Methodical Proceeding

In order to evaluate objectively the non-destructive methods radar, ultrasonic and eddy current regarding their possibilities and limitations, series of measurements were performed on a reference specimen made of polyamide with different reflectors, after the test equipment was set. With these data, recorded at a homogeneous test body, different data fusions were made with previously developed algorithms to determine optimal parameters for the data fusion. These parameters are applied to a pre-defined testing task, namely the detection of damages at element wall constructions. The fusion of data provides additional information for this task.

Using the study of these practical building issues, the fusion algorithms and imaging parameters are optimized. For this, element walls with known flaws are investigated first.

After extensive experience has been gained through the investigations of references specimen and known element wall constructions, in the last step a working catalog is developed. This comprises documentation of the preparation steps so that they can be applied in building practice for quality assurance and state analysis of this type of construction.

3 Development of test objects

A main aspect of the non-destructive methods is the assumption of concrete as a heterogeneous material, which is practically not true. Thus it is not possible to make a general reference specimen of concrete, because of to the random distribution of the aggregate in the production process. To simplify the problem of data fusion in the first step, a homogeneous and isotropic reference body made of polyamide has been selected (Fig. 2).

Fig 2 Reference specimen made of polyamide.

After the investigations of the reference polyamide block with non-destructive testing methods well defined reference data are available.

After the possibilities of the data fusion have been determined in the first step on the homogeneous isotropic polyamide test specimen, the investigations of real components, the element walls, were carried out. The element walls were prepared properly and according to the plan, so that their structure is well known.

In this process some practice-relevant damages were incorporated into the element walls. In addition to the formation of a cone consisting of a mono-particle mixture, two different concrete mixes were used with different maximum aggregate size. Furthermore, through the application of thin films on the inner side of the concrete shell, an artificial delamination was generated. In another test specimen gravel nests were additionally incorporated as well as voids and metallic reflectors.

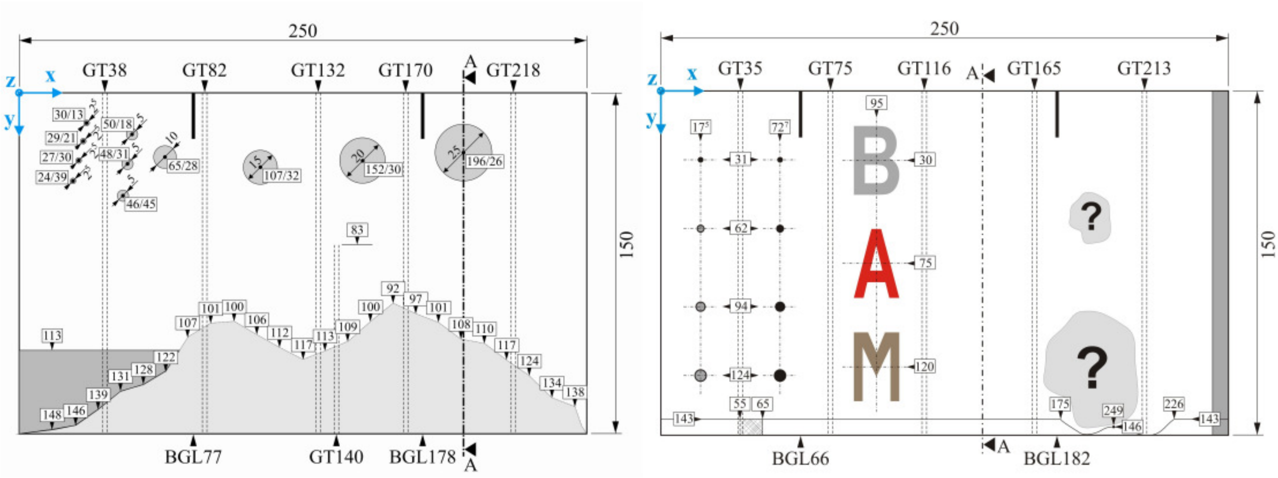


Fig 3 Schematic structure of the both element walls to be examined, from [2].

The second part of the preliminary investigations with the non-destructive testing methods is carried out at these designed test specimen with the known locations of the defects. These represent the basis of the data fusion for the selected testing tasks at real parts.

4 Used software and algorithm development

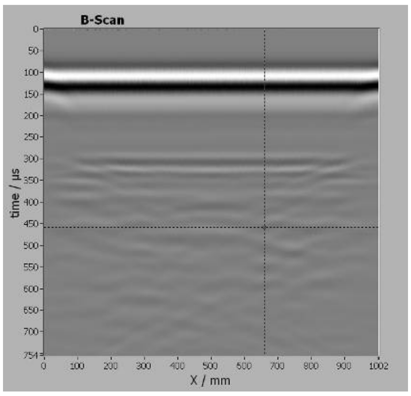
In the course of the research project, different algorithms have been designed and improved, so that they can be used for the fusion of the measured data. They are adapted to the specified testing task in order to obtain a workflow with the best possible results.

Therefore MATLAB routines were developed for preparation and fusion of the data. Moreover, the measured data were processed with ReflexW (a commercial program) for radar and with a special imaging method for ultrasonic, the SAFT (Synthetic Aperture FocusingTechnique) [3][4]. The results were fusioned afterwards with ZIBAmira, the software of the Zuse Institute Berlin (ZIB).

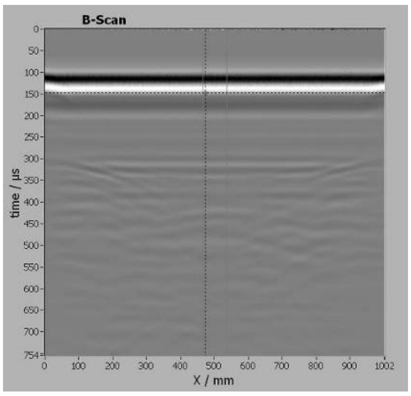
4.1 Investigations on polyamide block

The investigations of the polyamide block serve to characterize the methods radar, ultrasonic and Eddy current at a homogeneous test specimen. For this reason preliminary investigations with different parameter settings were carried out. Here, amongst other the frequency, both of the radar and the ultrasonic devices was varied. Furthermore, different polarizations of the search units and antennas were used. In addition, the ultrasonic measurements were performed with transversal and longitudinal wave search units.

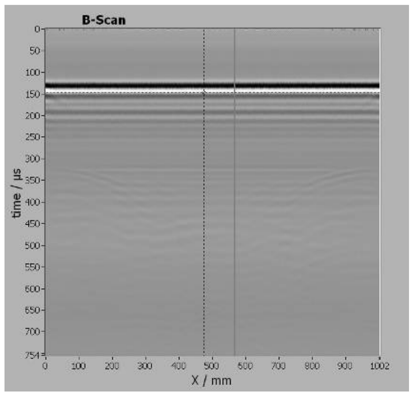
Fig 4 shows exemplarily six radargrams (radar B-image) that illustrate the effect of different antenna center frequencies and polarization.



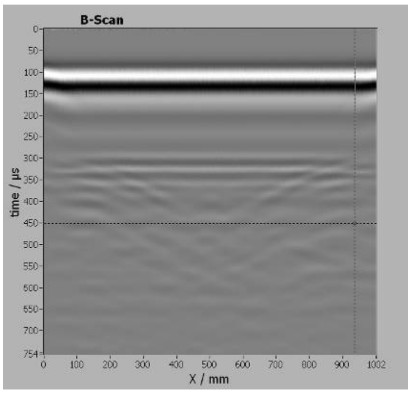
a) 1,2 GHz polarisation parallel to the x-axis



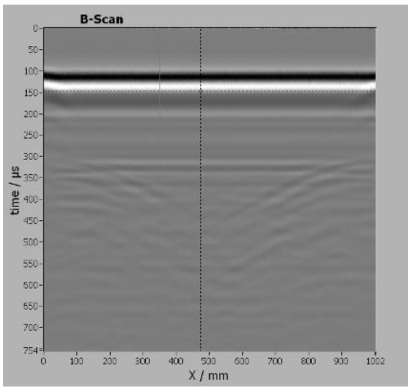
b) 1,6 GHz polarisation parallel to the x-axis



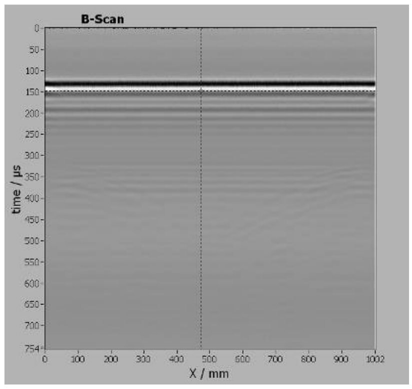
c) 2,3 GHz polarisation parallel to the x-axis



d) 1,2 GHz polarisation parallel to the y-axis



e) 1,6 GHz polarisation parallel to the y-axis



f) 2,3 GHz polarisation parallel to the y-axis

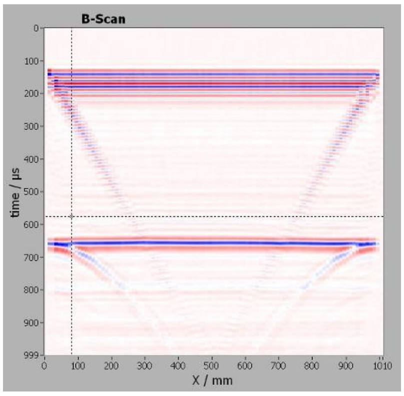
Fig 4 Radar B-images for different antenna center frequencies and polarizations; recorded at the polyamide block

The following conclusions can be drawn from Fig 4:

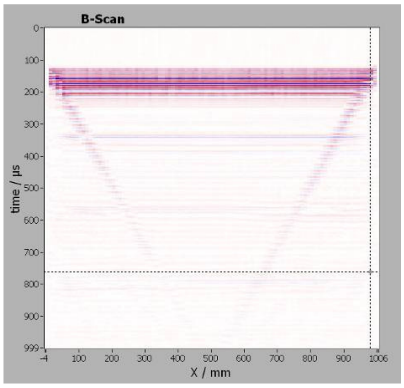
With increasing antenna center frequency (in Fig 4 from left to right), the resolution is improved, but the penetration depth of the electromagnetic waves decreases. This is visible at the weakening back wall signal at about 300 microseconds.

With an antenna polarization parallel to the y-axis, the effects of the side boundaries are much stronger defined in the radargrams than in the case of polarization parallel to the x-axis.

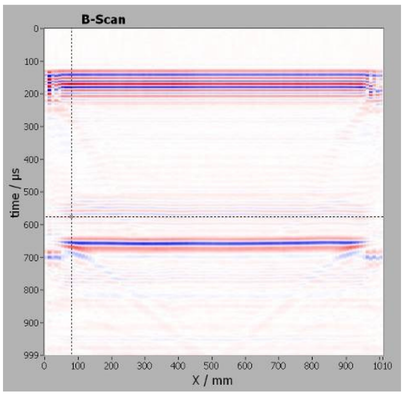
In Fig 5 several B-images of the ultrasonic method are compared.



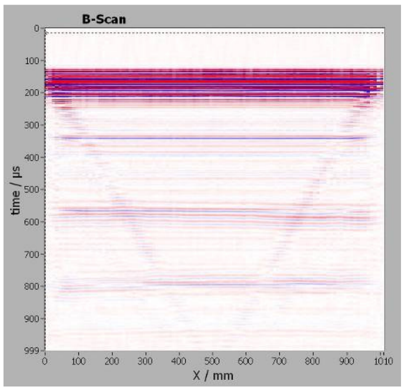
c) 50 kHz transversal polarisation parallel to the x-axis



d) 100 kHz longitudinal polarisation parallel to the x-axis



a) 50 kHz transversal polarisation parallel to the y-axis



b) 100 kHz longitudinal polarisation parallel to the y-axis

Fig 5 Ultrasonic B-images of varying center frequency, polarization and wave type; recorded at the polyamide block

The following conclusions can be drawn from Fig 5:

The comparison of the measurements with 50 kHz and transversal polarization (the left-hand column) and 100 kHz and longitudinal polarization (right-hand column) reveals that the back wall is clearly defined when recording with a transversal search unit and a center frequency of 50 kHz.

In order to combine the best properties of both methods in data fusion, the following specifications are made on this basis:

Radar:

The measurements are recorded with a high-frequency antenna (center frequency of 2.3 GHz). This offers the advantage of higher resolution. In addition, the polarization direction is set parallel to the x-axis in order to minimize the influence of boundary effects.

These parameters have the advantage of providing detailed information on the near-surface region. However, for data recorded on real objects, it is useful to adjust the polarization to the position of the reinforcement.

The radar measurement grid should be more dense compared to the grid of the ultrasonic measurement in order to optimize the measuring time.

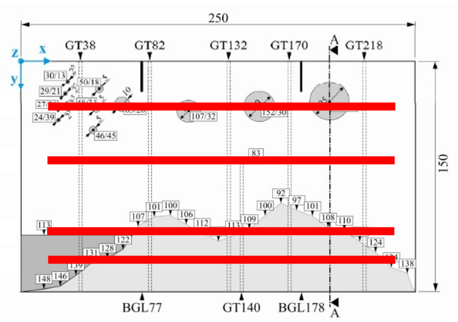
Ultrasonic:

The measurements are carried out with a transversal search unit, a center frequency of 50 kHz and a polarization parallel to the y-axis. It is beneficial for this setting, that information about areas in higher depth is obtained.

5 Investigations on the element walls

In the first step data from real test objects was obtained for the fusion: four selected measurement lines were recorded on both element walls respectively (Fig 6). The wall edge distances of the measuring lines are 15 cm in order to reduce boundary effects. Due to that, the length of each line is about 220 cm

(a)



(b)

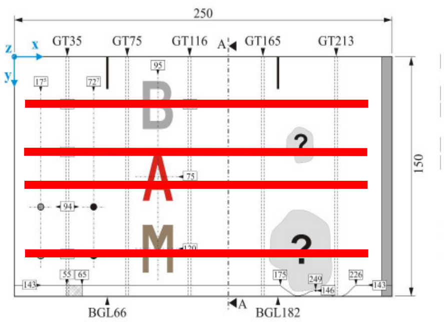


Fig 6 Recorded measurement lines on both element walls.

In the course of the project 3D measurements were performed on both element walls with the OSSCAR scanning system. A 3D data set, which was investigated more in detail, was recorded at the lower left panel of the first element wall (Fig 6a). Within this area there are three different concrete mixtures.

Based on the investigations carried out at the reference polyamide block, corresponding specifications for the measurement data recording at the element walls in 2D and 3D were given, in order to combine the best features of both methods radar and ultrasonic in the data fusion.

5.1 Results of the data fusion at the element walls

In the first step of processing, the data sets of the measurement lines of the first element wall were normalized and interpolated using MATLAB routines and subsequently the first derivative of the signal amplitudes was calculated. In the next step, the data sets are weighted and added, subtracted or multiplied. This procedure of data processing and fusion was developed using the reference measurement on the polyamide block.

The progress of the investigations and of the data fusion development is presented in the following at some examples.

<u>Fused data of line 3 of the first element wall</u>

The measuring line 3 was acquired in the area of the material cones (Fig 6(a)). In the B-image of the radar measurement, reflection hyperbolas of the near surface reinforcement are clearly visible (Fig 7 left, red ellipse). In a slightly greater depth more reflections can be recognized, which have been caused by the angle of the material cones (Fig 7 left, blue ellipse). In the B-scan of the ultrasonic measurement two areas of change of the concrete mixture through the material cones can also be seen (Fig 7 right, green ellipse).

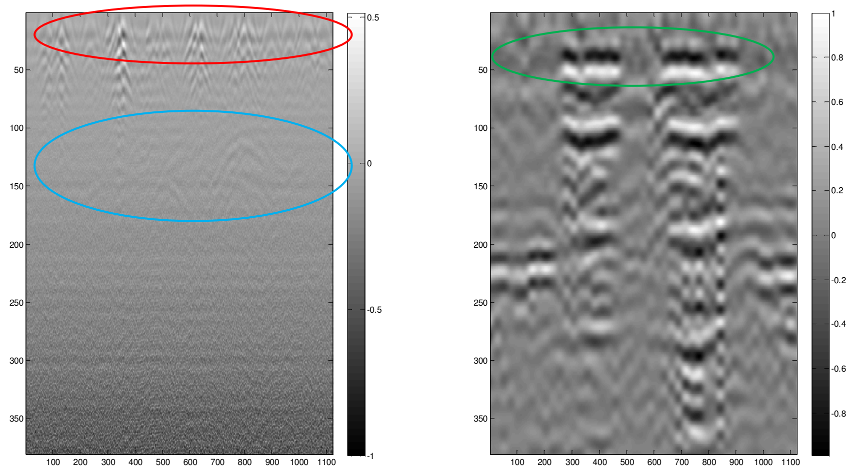


Fig 7 Interpolated radar (left) and ultrasonic data (right)

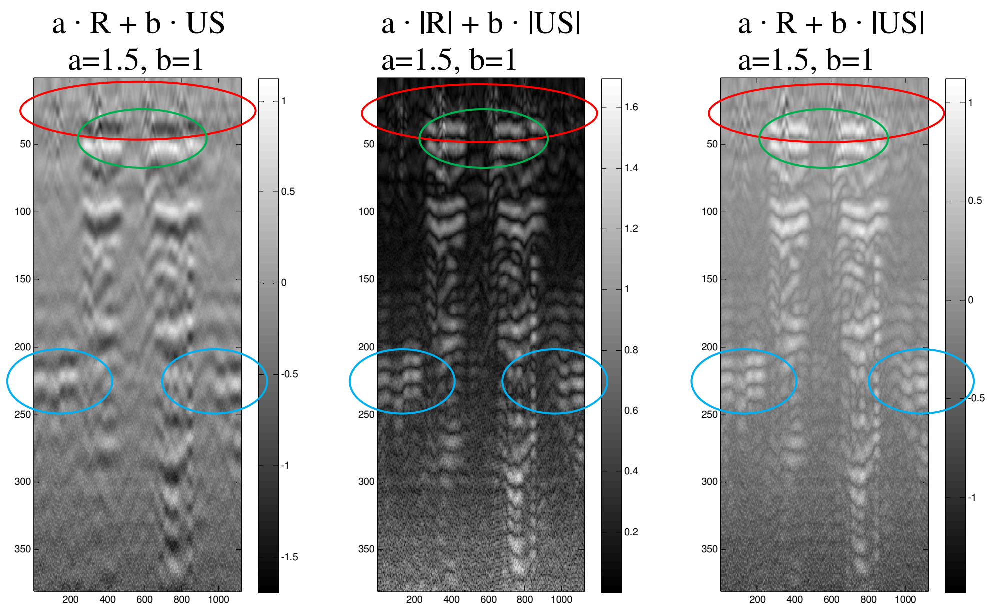


Fig 8 Measured data for line 3 of the first wall element.

After addition of both data sets (radar data weighted 1.5x), reflection hyperbolas of the reinforcing bars from the radar measurements are clearly recognizable in the resulting B-images (Fig 8, red ellipse), as well as the regions with a different concrete mix by the material cones within the introduced site-mixed concrete (Fig 8, green ellipse). The back wall reflection is also clearly visible, but only in the area of the concrete mix 1(Fig 8, blue ellipse).

In summary, it is clear that by the fusion of the data with a corresponding weight, added value in the display of B-images is achieved. However, it may also come to the degradation or even loss of information, e.g. if the acoustic bond between the introduced core concrete and the concrete shell is missing. The back wall of the element wall in the area behind will be no longer visible. The greatest information content is provided by the B-images of data sets addition.

<u>Fused data of line 2 of the second element wall</u>

a) b)

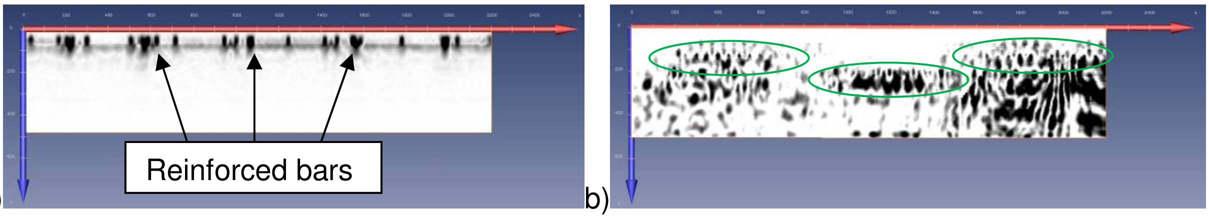


Fig 9 Processed a) radar and b) ultrasonic data of the measuring line 2.

In the B-image of the radar measurement (Fig 9a), the reflections of the near-surface reinforced bars are clearly visible. Beyond a depth of about 80 mm, a plane reflection appears which is caused by the back wall of the front shell of concrete.

In the B-image of the ultrasonic measurement noise at two different depths (80 mm and 220 mm) is recognisable (Fig 9b, green ellipses). This could be caused by a lack of acoustic bond between the introduced core concrete and the concrete shell of the wall element.

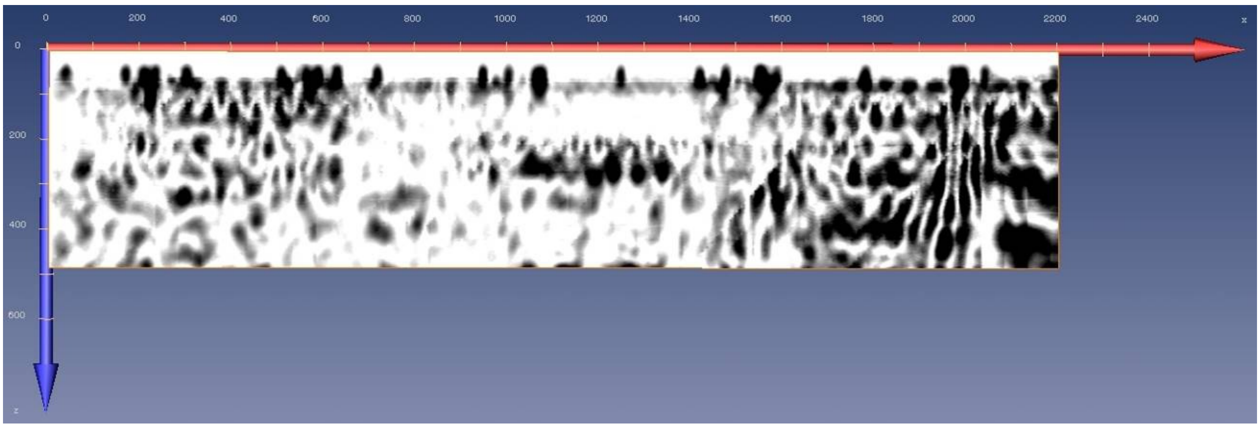


Fig 10 Addition of the measurement data for the line 2 of the second element wall.

The near-surface reinforcement and the continuous reflection at a depth of 80 mm can be clearly seen in the B-image after the fusion (Fig 10).

<u>3D data fusion at the measuring field of the first element wall</u>

Data from a measuring field with the size of 100 x 50 cm has been recorded in the area of three different mixtures of the in situ concrete, in order to obtain values of a real test object for the three-dimensional data fusion. The obtained measurement data were fused with the ZIBAmira program. The fusion of 3D data sets was carried out only with the processed data.

These were added and radar data received a weighting of 1.5 times compared to the ultrasonic data.

In the following the results of 3D measurement for radar and ultrasonic for the measuring field 1 of the first element wall are shown as C-scans (Fig 11).

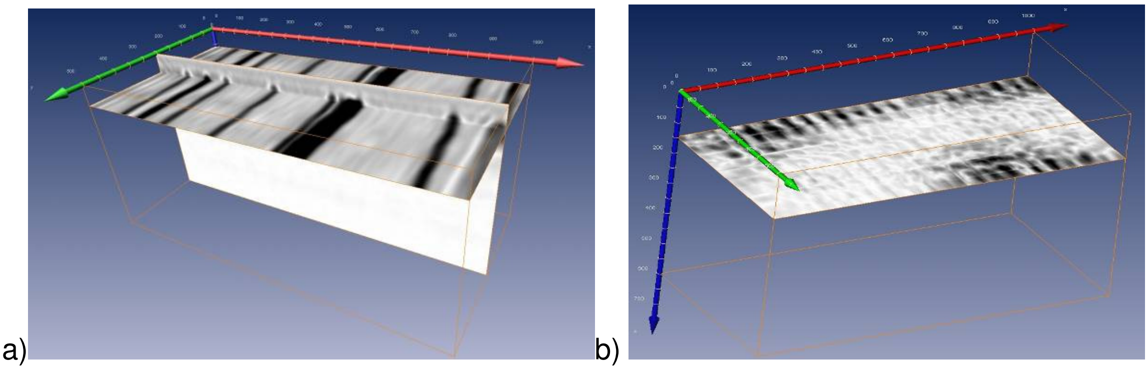


Fig 11 C-scan of the near surface a) radar and b) ultrasonic measurement.

The result of the fusion of the data from the radar and ultrasonic measurement is shown below as an isosurface in Fig 12. The reinforced bars which lie close to the surface are clearly visible here. Furthermore, reflections of the material cones and the back wall are visible. In general, the detection and the mapping of the component objects in the three-dimensional fused data cube are more difficult to do than 2-D data acquisition and merging.

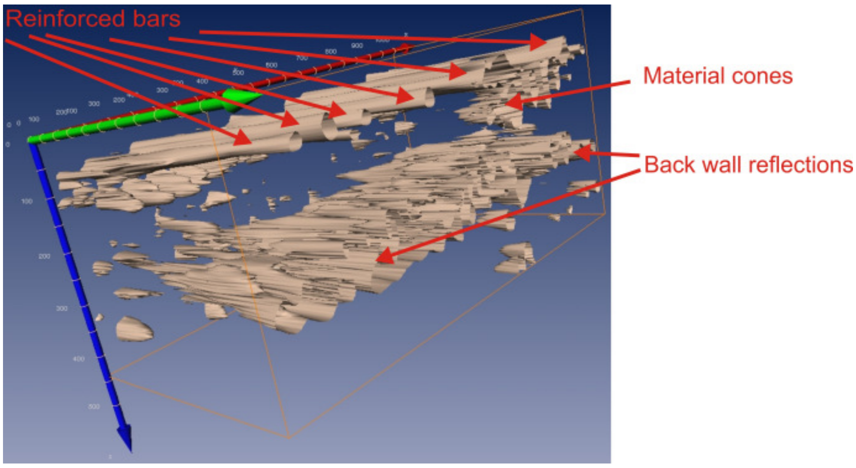


Fig 12 3D representation of the fused radar and ultrasonic data sets of the measuring field 1 at the first wall element.

5.2 Investigations on a concrete slab

To examine other possible application areas of the 3D representation of a fused data set, measurements with the OSSCAR scanner system were carried out at another reference block, using the non-destructive testing methods. Recorded data sets were subsequently processed and fused with ZIBAmira.

Fig 13a shows the internal structure of the test body before it was concreted. The measuring field was selected in such a manner that the near-surface reinforcement mesh covers half of the measuring field. The casing tube extends over the entire concrete slab length, and the reinforcement mesh extends over the entire back wall of the slab.

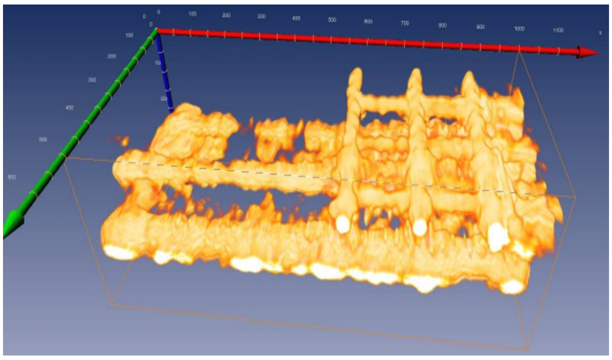
a)  b) 

Fig 13 a) Internal structure of the investigated concrete slab and b) isosurface of the fused 3D data sets.

Fig 13b pictures the result of fusing the data sets as an isosurface. The near-surface reinforcement mesh is clearly visible. In a somewhat greater depth the casing tube is imaged. At a depth of about 200 mm, a plane reflection can be seen, which is caused by the back wall of the concrete slab.

From this investigation it is clear that for concrete construction types other than element walls, a gain of information is possible with the 3D representation of the fused data sets.

6 Summary and Conclusions

To achieve the best results in this research project, a selection has been made, which instruments should be integrated in the scope of the fusion of measurement data. The selection of a measuring instrument was made based on the following criteria:

- Applicability of the instrument in practice
- Compatibility with the OSSCAR scanner
- Suitability for the inspection task

A great advantage in the selection of measuring instruments, which are mostly used as single instruments, is the compatibility with the OSSCAR scanner. Thus, all three systems can be controlled with the OSSCAR scanner. This is an important criterion for data fusion, since only with automated data recording; the strict congruence of the measured fields is given. In addition, the scanner measurements meet the requirements for accuracy of measurement.

A crucial point for the research project is the combination of information from the various methods. At the beginning of the research project no suitable software for this purpose was available.

For this reason, algorithms which enable data fusion with different approaches have been developed in an early stage of the project on the basis of commercially available MATLAB software.

Regardless of the actual algorithms the following steps are always necessary for data fusion:

- Recording the data in a compatible grid
- Eliminate systematic deviations (DC Shift, etc.)
- Shortening the time axis
- Scaling and interpolation of the measured data
- Data fusion with different algorithms

At a later stage of the project the commercial software ZIBAmira (Zuse Institute Berlin - ZIB) was used. With it, fusion of 3D data sets was also possible. In order to obtain significant results with this software, the measured data were processed prior to the fusion.

As a result of the research it can be said that a significant increase of information value can be achieved by the fusion of data sets of radar and ultrasonic measurements and the use of the eddy current method for determining the concrete cover. However, this can vary greatly, depending on the testing task and the type of investigated concrete components. Thus, fusion of radar and ultrasonic data of element walls does not necessarily improve the information content because of possible delamination of the inserted core concrete in the concrete shell. However, if the element wall is homogeneous and the in-situ concrete, which is filled into the concrete shell has an acoustic bond with the element wall, possible interferences such as gravel nests can probably be seen after data fusion.

The application of the fusion on other structural components of civil engineering can provide a significant improvement in information gain regarding the internal structure (chap. 5.2). With the use of the eddy current method the concrete cover of the near-surface reinforcement and thereby the propagation velocity of the radar waves can be determined. This allows more accurate position determination of structural elements in their depth.

During the project, knowledge was collected, which serves as the basis for the application of the data fusion techniques at real test elements. The application of the fusion at element walls is possible and can increase significance of the data. But it may happen that afterwards the fusion information is disturbed by a lack of acoustic bond. Here further investigations would be needed, like the fusion of such data with additional records of a lower-frequency radar antenna. By appropriate weighting of the individual data sets, it is possible to obtain information about the structure from the fused data set also behind existing delaminations.

In addition, further investigations on the fusion of data recorded on engineering structures (such as bridge elements or concrete slabs with prestressing) would be of interest. Therefore, the data fusion and the resulting improved information value of non-destructive methods could be applied to other concrete construction types.

7 References

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