Controlled Creating of Delaminations in Concrete for Nondestructive Testing

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Abstract

Locating and sizing delaminations is a common inspection task in the maintenance and quality control of construction and rehabilitation. Their detection is an important area of application of nondestructive testing in civil engineering (NDT-CE). To improve this application, NDT test systems and test solutions must be compared, for which specimens containing well-defined delaminations are needed to serve as a reference. Currently, there are no widely accepted procedures available for creating such flaws locally and reproducibly. This study presents procedures for creating artificial delaminations repeatably and as close as possible to natural delaminations. To produce the discontinuities only substances were used which can occur in concrete components and do not affect the application of NDT-CE methods. Ultrasonic pulse-echo (UPE) was used to test the flaws in the specimens. The delaminations were created by applying expansive mortar in prepared through holes. Three specimens with two delaminations each were built and tested using UPE.

Keywords Nondestructive testing of concrete · Delamination · Reference specimen · Ultrasonic pulse-echo

1 Introduction

Concrete is the most widely used building material today and plays an essential role in most constructions. It can be produced from locally available raw material and has manifold advantages such as high durability, safety due to its resistance, flexibility in construction and maintenance, noise reduction, fire protection, and heat capacity. Concrete's significantly lower tensile strength compared to its compressive strength is compensated by reinforcement. Dense reinforcement can make it difficult to compact concrete properly, which may lead to discontinuities, which in turn can become defects such as delaminations. If these discontinuities do not meet the acceptance criteria in previously defined specifications, they are then considered defects or flaws. Typically, in

such cases, corrosion causing substances can access the reinforcing bars and initiate corrosion, which might reduce the load capacity and durability of the structure. Consequently, flaws such as delaminations in concrete affect the structure's durability and should be identified and located during inspection.

This study focuses on delaminations as a test task for NDT-CE, as classified in the concrete structure group [1].

Delamination is characterized as a planar separation of the component parallel to the surface [2], having a lateral extension much larger than the concrete cover. Delaminations are typically found in bridge decks as a result of rebar corrosion, and these, in turn, are basic components to ensure the load-bearing capacity of a concrete bridge, as they deteriorate faster than other parts of a concrete bridge [3]. Delamination is one of the three most common deterioration types therein [4] and is even an indirect indicator of severe steel rebar corrosion [5]. Localizing and sizing of delaminations using NDT-CE depends on the validation of the test solution. A comparison of test solutions depends on comparable delaminations. This study reports procedure to produce specimens with delaminations of predefined properties in any concrete laboratory. These can be used to validate NDT test solutions and to certify NDT service providers. This will improve the practical application of NDT because it makes quantitative

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comparison of NDT-CE possible and improves the acceptance of NDT among practitioners.

Furthermore, the study shows the performance of the ultrasonic method as one of the most promising NDT methods to detect delaminations. The choice of the US method was made after trials with different NDT methods and different testing devices. The combination of the NDT method, the device and the specially developed evaluation described in this study showed the best results to detect delaminations.

The evaluation is a further development of the well-known automated ultrasonic testing and the Synthetic Aperture Focusing Technique (SAFT) reconstruction. This allows a quantitative evaluation. Thus, in this study, the extent of each delamination was indicated for each square centimeter in the relevant depth range. With the help of this application programmed with Python, elements of any size can be evaluated quantitatively.

For example, the relevance of testing grids was evidenced. During the study and the preliminary tests, the tests were performed with different grids, from 5 to 50 mm. The tests with 10 mm grids provide the best or optimal results in terms of delamination detection and data size. At an even smaller grid, e.g. 5 mm, the detection is minimally better compared to the 10 mm grid, but the size of the data and the evaluation are significantly larger.

This procedure is also applicable to evaluate other discontinuities such as honeycombs and voids. The first applications of this method on honeycombs data already show good results and can certainly be improved. Furthermore, the experience of this study can help to generate reference data for NDT detection of delaminations.

2 Delamination Properties and Prerequisites

The basic requirements for laboratory-built reproducible defects are that any concrete laboratory should be able to follow the guideline, and the defects should be of dimensions and characteristics which are as close as possible to defects occurring naturally in in-service concrete structures.

As the specimens are dedicated to being used for NDT-CE, any specific requirements for standard NDT methods should be met. Pulse-echo methods, such as ultrasonic pulse-echo or impact-echo, are especially sensitive to edge effects and dead zones. Edge effects are caused by the diffraction of waves at the edges of the specimen and should be minimized to avoid interference with signals from the built test targets. Dead zones are depth ranges close to the scanning surface where the signals of the surface wave and the echoes from reflectors are included, so that the reflector of interest is not revealed here. Essentially, the delaminations should be placed in a reasonable spacing from edges of the specimens to distinguish

the reflections from delaminations and the edges well during the evaluation of signals (Fig. 1).

As a good spacing, in the y-direction (width 80 cm), from one edge an empirical value from other successful tests (20 cm) and from the other edge the specimen thickness (25 cm) was chosen. In the x-direction (width 100 cm), a value resulted (17 cm) from the geometry of the specimen and the placement of the reinforcement, which came close to the empirical value. At the same time, the mass of the specimen should not exceed the limits of the equipment used to move it in the laboratory.

Figure 2 shows the reinforcement plan of the specimen. The reinforcement for the delamination specimen consists of reinforcement cage, including reinforcement in x- and y-direction, and bars perpendicular to larger surfaces.

3 Procedures for Creating Delaminations

Delaminations are mainly characterized by their lateral extension, concrete cover, and source of formation. They occur in bridge decks in the reinforcement layer and are typically caused by rebar corrosion [6]. The concrete cover is therefore given by the location of the rebars and the extension by their spacing.

Artificial delamination should have a concrete cover corresponding to the upper reinforcement layer, which has a rebar concrete cover of approximately 50 mm in the delamination specimen. Furthermore, the minimum lateral expansion of the delamination should be 100 mm x 100 mm corresponding to the common reinforcement mats, which simulates a realistic case.

In addition, the last mentioned minimum lateral expansion was used to be detectable using ultrasonic pulse-echo (UPE). The material chosen for the specimens was reinforced concrete (RC): concrete of type C30/37 and a steel reinforcement with a diameter of 8 mm and a grid of 10 cm x 10 cm as both components are typically used in practice. The specimens and their parameters for creating the delaminations in this study are summarized in Table 1. The specimen size of 1000 mm x 800 mm x 250 mm was chosen as a compromise between the necessary size of the delaminations, their spacing to the specimen's edges, and the mass of the specimen.

Based on the positive experience made in creating cracks [7] by using the expansive mortar Betonamit, also known as soundless chemical demolition agent (SCDA) [8, 9], the same principle was utilized to create delaminations. Expansive mortar creates the force which cracks the concrete; the direction of the cracks being formed is guided by the meticulous choice of the geometry of the holes through which the mortar is applied, see Table 2 for more characteristic details. The holes for the mortar, which will be called *Betonamit holes* herein, are parallel to the reinforcing bars and are
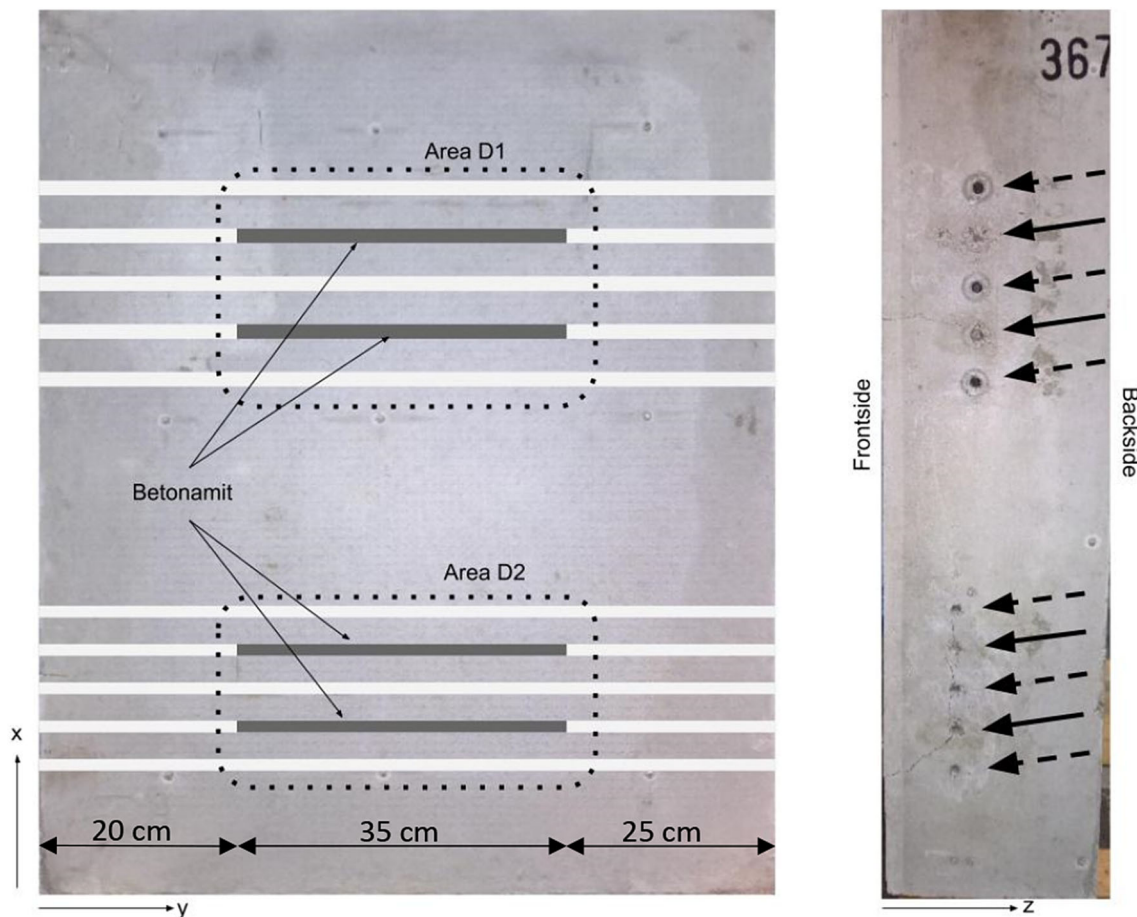
Fig. 1 Photograph of specimen #1 shows delaminations. The solid/thicker arrows point to the through holes which are aligned with the axis, parallel to the xy-surface. The continuous arrows (right) point to the holes which are partially filled with Betonamit and the dashed ones remain empty, as indicated by the dark grey area in the top view (left). Only 2 of 5 holes were filled in order not to create too much expansion pressure, so that unwanted cracks in other directions occur. The delaminations should develop in the Areas D1 and D2. UPE measurements were carried out from the front- and backside. *Copyright: Herbert Wiggenhauser, Juri Timofeev

created by embedded Polymethylmethacrylate tubes which were placed in the formwork before concrete pouring. The tubes served as markers and were stabilized with metal rods inside during the concreting process. After hardening of the concrete, the metal rods were pulled out of the tubes and the tubes were removed by drilling, creating the space through which the expansive mortar was later applied. Five parallel cavities were created parallel to the large surface of the specimen to define the plane of the delamination. The expansive mortar was filled only into the middle part of the holes where the delamination should be initiated. Each specimen has two such areas as depicted in Fig. 1.

Expansive mortar easily creates the delaminations. Various tests on specimens with and without reinforcement as well as with different holes regarding diameter and spacing revealed that it is sufficient to fill mortar into a subset of the five holes to achieve the desired result. To prevent propagation of the cracks into the nearby surface of the specimen, the

tensile forces in the concrete perpendicular to the intended delamination plane were transferred using additional reinforcement bars. In summary, procedures were implemented for building the specimen and creating the delaminations according to the description above.

The expansive mortar was filled in two of the five holes which form the delamination plane. The center and outer Betonamit holes were left empty. However, they act as a flaw and guide the crack propagation direction. The holes were left empty in the outer sections as shown in Fig. 1. Altogether, three samples of same dimensions of piece and cavities were prepared. The filling length corresponds to the width of the desired delamination, which is 35 cm. Table 1 includes the experimental parameters of the specimens.
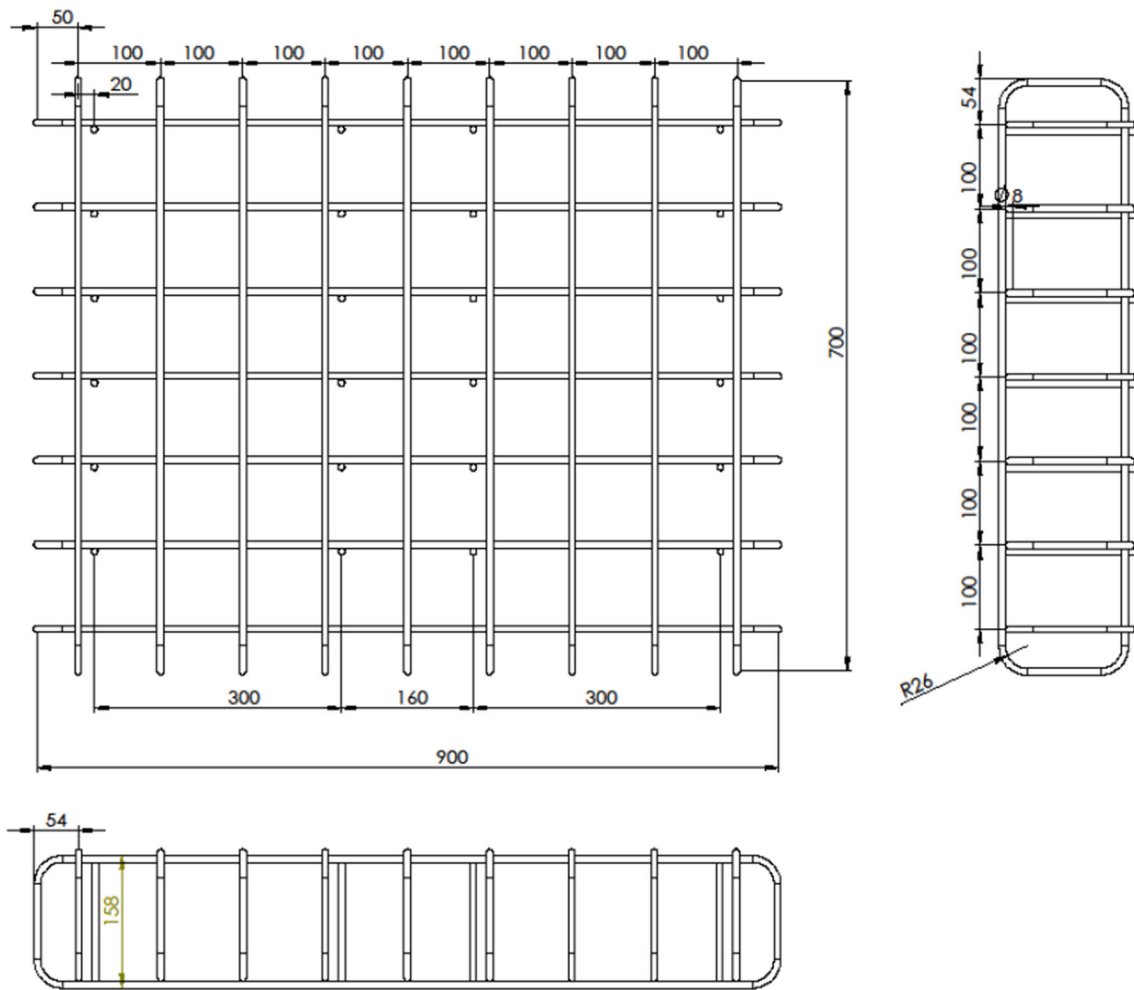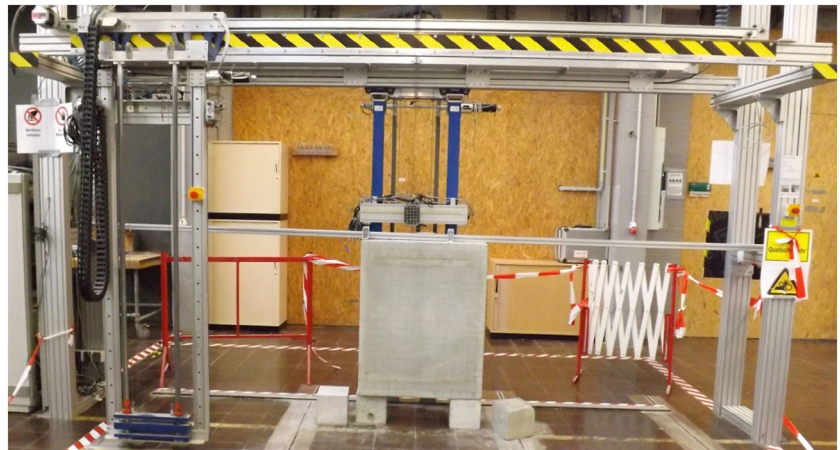
Fig. 2 Drawing of the reinforcement for the delamination specimen. The reinforcement includes the following parts: reinforcement basket consisting of stirrup reinforcement in x- and y-direction and bars perpendicular to larger surfaces. *Copyright: Matthias Behrens, Juri Timofeev

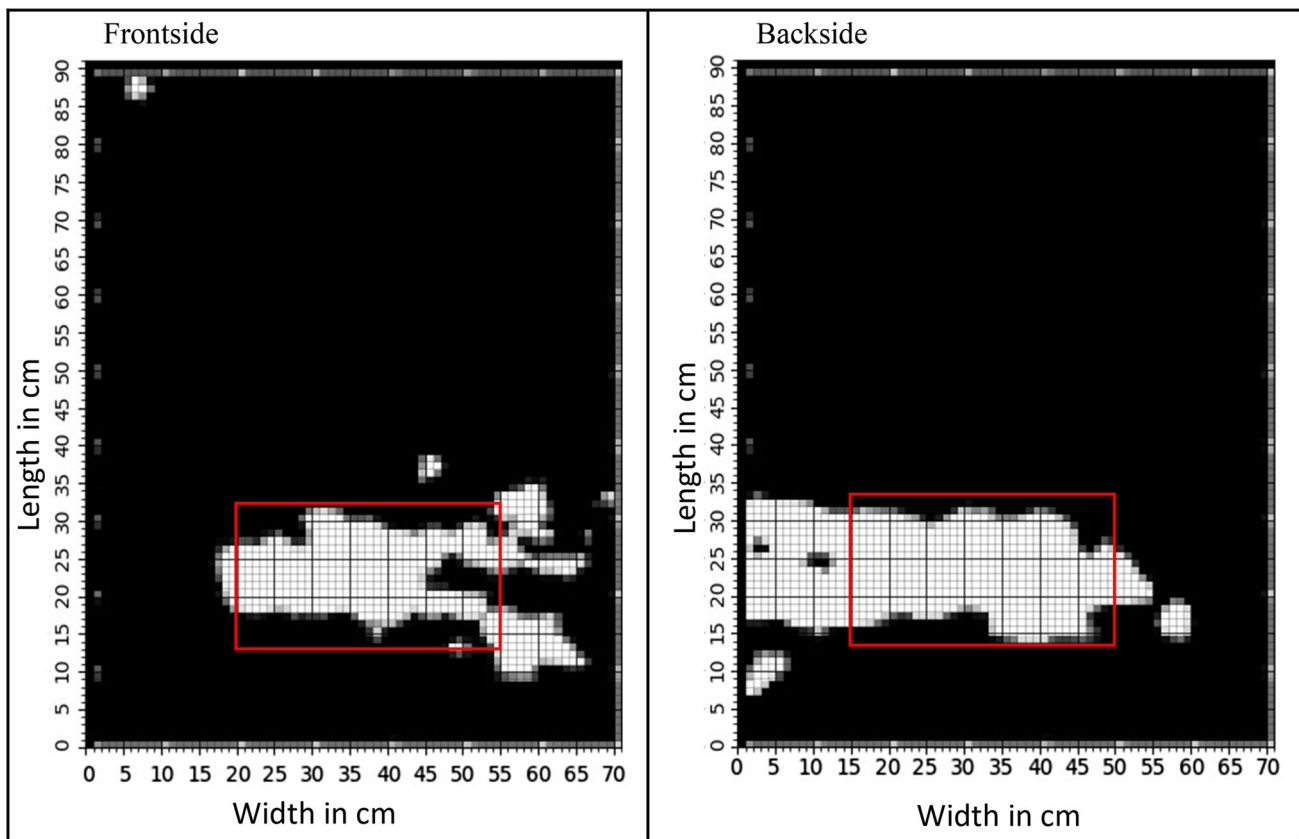**Fig. 3** Photo of the mechanical scanner, which was used for UPE measurements

Fig. 4 Result of the UPE measurements on specimen 1. Bright color indicates the delaminations. In area D2 both pictures show the delamination in the corresponding area. Regarding the width there is almost a continuous delamination, except about 10–15 cm on one side. Regarding the length, there is almost a continuous delamination at about 15–30 cm. In area D1 there is no delamination on both pictures and one possible reason is that Betonamit did not apply the required expansion pressure in this area. Both views are seen from above and are symmetrical to the y-axis, so they can be mentally folded/unfolded.

4 NDT-CE of Delaminations in Concrete

Typical NDT-CE methods for detecting delaminations are coin tap test [10], impact echo (IE) [11–14] (UPE) [15–17] and infrared thermography [18].

Scanning UPE was used to test the delaminations because it is one of the most effective NDT-CE methods for detecting delaminations and preliminary tests have indicated a promising performance. The low-frequency ultrasonic flaw detector *A1220* (also known as EyeCon), manufactured by "Acoustic Systems Ltd." [19], was used. This probe works in pulse-echo mode with shear waves and consists of 24 transducers with dry-point-contact, 12 of which serve as transmitters and 12 as receivers. Each element is spring-loaded to achieve a good coupling and to compensate for the small unevenness of the concrete surface. Shear wave probes were used in this study because of their preferable signal-to-noise ratio [20].

A mechanical scanner was used to take measurements in a predefined grid of 10 mm × 10 mm (center of the probe) in a meander pattern.

The noise level of the ultrasonic signal was determined by scanning the probe along a line where only the back-wall echo was detected. The noise level remained constant in time and amplitude, and the back-wall was detected with little amplitude variation. Table 3 summarizes the main parameters of the automated measurements.

For signal processing, 3D SAFT [21] was used to improve the signal-to-noise ratio by phase-corrected averaging, generating a voxel volume below the scanning aperture. The main parameters used for reconstruction are summarized in Table 3.

4.1 Data Evaluation Criteria for Testing Delaminations

The objective of the test set up referenced in this study is to identify, locate and size delaminations in a concrete slab of dimensions where the back-wall echo can be identified with UPE and delaminations have a lateral size exceeding their concrete cover. The delamination should be a full debonding

Table 1 The parameters and their values associated with the three test specimens for delamination

Parameter	Specimen #1	Specimen #2	Specimen #3
Size x, y, z in mm	1000, 800, 250	1000, 800, 250	1000, 800, 250
Mass in kg	464	460	464
Rebar concrete cover, diameter, spacing in mm	50, 8, 100	50, 8, 100	50, 8, 100
Size of delaminations in mm^2			
Planned (D1 and D2)	70000	70000	70000
Realized area D1 (backside)	0	108500	101000
Realized area D2 (backside)	69100	37100	201100
Betonamit holes diameter in mm	8	8	10
Concrete cover in mm			
Area D1:	80	80	80
Area D2:	100	100	100
Spacing between holes	50	50	50
Filling of Betonamit holes (1 top to 5 bottom)	No. 2 and 4	No. 2 and 4	No. 2 and 4
Fill length in mm	350	350	350

Table 2 Overview of the basic properties of Betonamit

Physical and chemical properties	Value
Application	Chemical demolition of concrete
Chemical characterization	Calcium oxide (50–100%) Portland cement, < 1% quartz (2,5–5,0%)
Form, aggregate state	Solid, powder
Smell/odour	Odourless
pH value (10 g/l) at 20 °C	> 13
Solubility in/miscibility with water	Soluble
Dangerous reaction possible with	Reaction with water and acids, corrodes aluminium

Table 3 UPE measurement settings and SAFT reconstruction settings

Parameter	Setting
Probe type and manufacturer	A1220, ACS
Type of wave	Transverse/shear
Center frequency in kHz	50
Shear wave velocity in concrete in m/s	2700
Measurement point grid x, y	10 mm × 10 mm
Probe alignment (polarization perpendicular to the alignment of the probe)	Vertical
SAFT reconstruction settings	
Overlap of point being focused on in x-direction	4 (Two points each left and right from the point being focused)
Overlap of point being focused on in y-direction	6 (Two points each left and right from the point being focused)
Opening angle (angle at which the waves are beamed into the concrete) in °	70
Common offset (fixed distance between the transmitter part and receiver part of the probe) in mm	60

For reconstruction, the following experience values are used for each the position being focused on: 4 points in x-direction and 6 points in y-direction. The central axis between the transmitter and the receiver of the probe was in the Y direction at 6 cm, probe edgewise, so the common offset in the Y direction was 6 cm. The opening angle of ultrasonic beam was 70°, as that of the probe

of the concrete in the realized area, so mechanical waves such as ultrasonic waves cannot transmit through them.

In this scenario, the primary criterion for data analysis is the existence of the back-wall echo of the concrete slab in non-delaminated areas. The secondary criterion is the direct echo from the delamination, which may be modulated by the shape of the flaw. A rough delamination shape may cause a weaker reflection.

Three specimens with two delaminations each were built and scanning UPE measurements performed from both surfaces which in the following are called front- and backside. Thus, for each of the specimens, the same delaminations were tested from two sides, and measurements could be compared (for different concrete covers of the same flaw). Each data set was evaluated by applying the above criteria.

Table 4 Results of the UPE evaluations for delaminations in specimen 1 (S1), specimen 2 (S2) and specimen 3 (S3)

| | Frontside (z = 0,00 m) | | Backside (z = 0,25 m) | |
| | Direct detection | | Direct detection | |
	Nominal	Quantitatively	Nominal	Quantitatively
S1				
D 1	-	No	–	No
D 2	+	Full	+	Full
S2				
D1	+	Full	+	Full
D2	+	Partial	+	Partial
S3				
D1	–	No	+	Full
D2	–	No	+	Full

The three specimens were scanned from both sides (z = 0,00 m and z = 0,25 m). In each specimen two delamination areas, D1 and D2, were evaluated. For the qualitative/nominal evaluation, the nominal classification is either visible "+" or not visible "−". For the quantitative evaluation, there are the following classes: full delamination (full), partial delamination (partial) and no delamination (no) present

Table 4 summarizes the results of the NDT-CE application for all delaminations investigated in this study. Each of the six delaminations was tested and evaluated from the front- and backside. The delaminations were analyzed by applying the criteria above.

Five of the six planned flaws could be located in the intended position using UPE as the NDT-CE method of choice. Delamination D2 of specimen S2 had only about half of the intended size. One possible reason for this is that in this area the expansive mortar was not filled properly into the holes.

Figures 4, 5 and 6 present the result of the UPE measurements evaluated by applying the data evaluation criteria described above. In Fig. 5 frontside, delaminations are in pieces and not connected with each other, because here vertical cracks run from the area of delaminations to the closer concrete surface (frontside). The vertical cracks always take the shorter path or, more precisely, the path of lower resistance. This path leads to the closer concrete surface (frontside) since the concrete strength in the specimen is almost the same. Indicated areas at the left and bottom edges are probably caused by the edge effect. Thus, the backside provides better results. In Fig. 6 frontside, the delaminations are not visible because here larger and more vertical cracks run from the area of the delaminations to the closer concrete surface (frontside). The reason is that the diameter of the boreholes, thus the amount of betonamit and thus the expansion forces were larger. Here it is particularly useful to test from the backside. In Fig. 6 backside, real delaminations are on the left and bottom edges caused by the higher expansion force of betonamit.

To detect delaminations as well as possible, only the areas around delaminations are evaluated in terms of depth, starting slightly above and ending slightly below the planned delamination. Thus, non-relevant areas or reflectors are excluded, such as the reinforcement, which is placed at a depth of approximately 5 cm.

The SAFT result is visualized by a binary depth plot, where high amplitudes in the depth range between 75 and 150 (frontside) or 150–200 mm (backside) are depicted in a bright color. All the other points are assigned black. These images show the delaminations very clearly. The criterion of back-wall echo, is less pronounced because of the interference with the reinforcement.

Data processing was performed using InterSAFT for SAFT reconstruction together with a script written in Python for classifying the delaminated areas in square centimeters.

Figures 7, 8 and 9 present the frontsides of the specimen 1, 2 and 3. These figures show surface cracks. In Fig. 9, no surface cracks are visible after the application of Betonamit, in contrast to Specimens 1 and 2.

5 Discussion and Outlook

The procedure for creating delaminations is the result of an empirical study in which parameters were varied and finally selected for each of the flaws. When varying these parameters, uncertainties are unavoidable, but overall, the procedures described are stable against small changes naturally occurring in a concrete laboratory. Various results and experience from preliminary tests for delaminations were integrated into the procedures to improve them. Small irregularities such as cracks on the surfaces of the specimens could mostly be avoided. However, when such irregularities
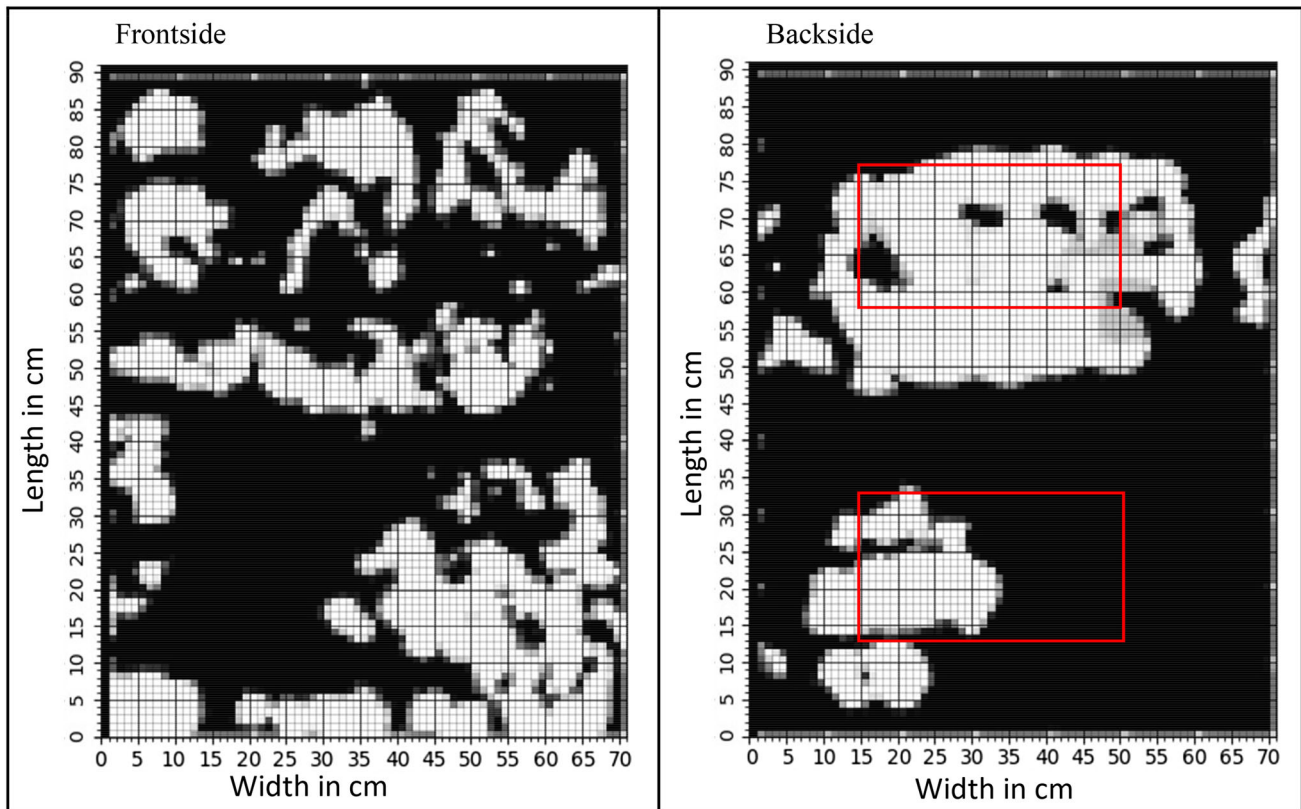
Fig. 5 Result of the UPE measurements on specimen 2. Bright color indicates the delaminations. In area D1 is the larger delamination. Looking at the intersection of both images, it is between about 10–60 cm in width and between about 50–80 cm in length. The smaller delamination in area D2 measures approx. 25 cm in width and length. This delamination has only about one half of the desired size. Possible reason is that Betonamit could not completely penetrate the two holes on one side. Both views are seen from above and are symmetrical to the y-axis, so they can be mentally folded/ unfolded

occur, they can be repaired with mortar so that the treated surfaces are more suitable for NDT measurements, e.g., for an ultrasonic probe. The reinforcement in the specimens was of the same type and dimensions typically used in engineering structures and worked as intended.

The focus of this study was on smaller or compact flaws, which are suitable for laboratory specimens but generally more difficult to detect. On the other hand, these defects are very well suited for validating the results of NDT-CE investigations to locate and size delaminations.

The results of this study support the underlying concept of creating procedures to build representative specimens with flaws for selected test tasks, which in turn can be used for validation, certification and Research & Development (R&D).

Delaminations can be reproducibly created following the steps described. The inherent uncertainty is mainly given by the inhomogeneity of concrete-geometrically quantified by the maximum aggregate size. On the testing side, the accuracy of the UPE method and the data analysis must be considered. Altogether, the uncertainties are not much greater than those because of the inhomogeneity of concrete.

If multiple delaminations create a stacked formation, then naturally, UPE can only detect the delamination closest to the surface, since delaminations are defined as flaws which cannot be passed by ultrasonic waves.

Larger holes (> 8 mm) can lead to surface opening cracks influencing the application of NDT-CE. To avoid such cracks, a reinforcement cage and reinforcing bars perpendicular to the surface were used. Nevertheless, small cracks appeared on the surface despite all the preventive measures taken.

The procedures for creating delaminations described herein have already been repeated in other NDT laboratories [22] all over the world; further tests are included in a round robin test. These tests involve research institutions and engineering companies focusing on NDT in CE. The procedures presented here should be used regularly in other NDT laboratories to compare NDT-CE solutions quantitatively and for R&D.

Numerical modelling and simulation of the flaw production and their testing applying NDT-CE could provide valuable insights.
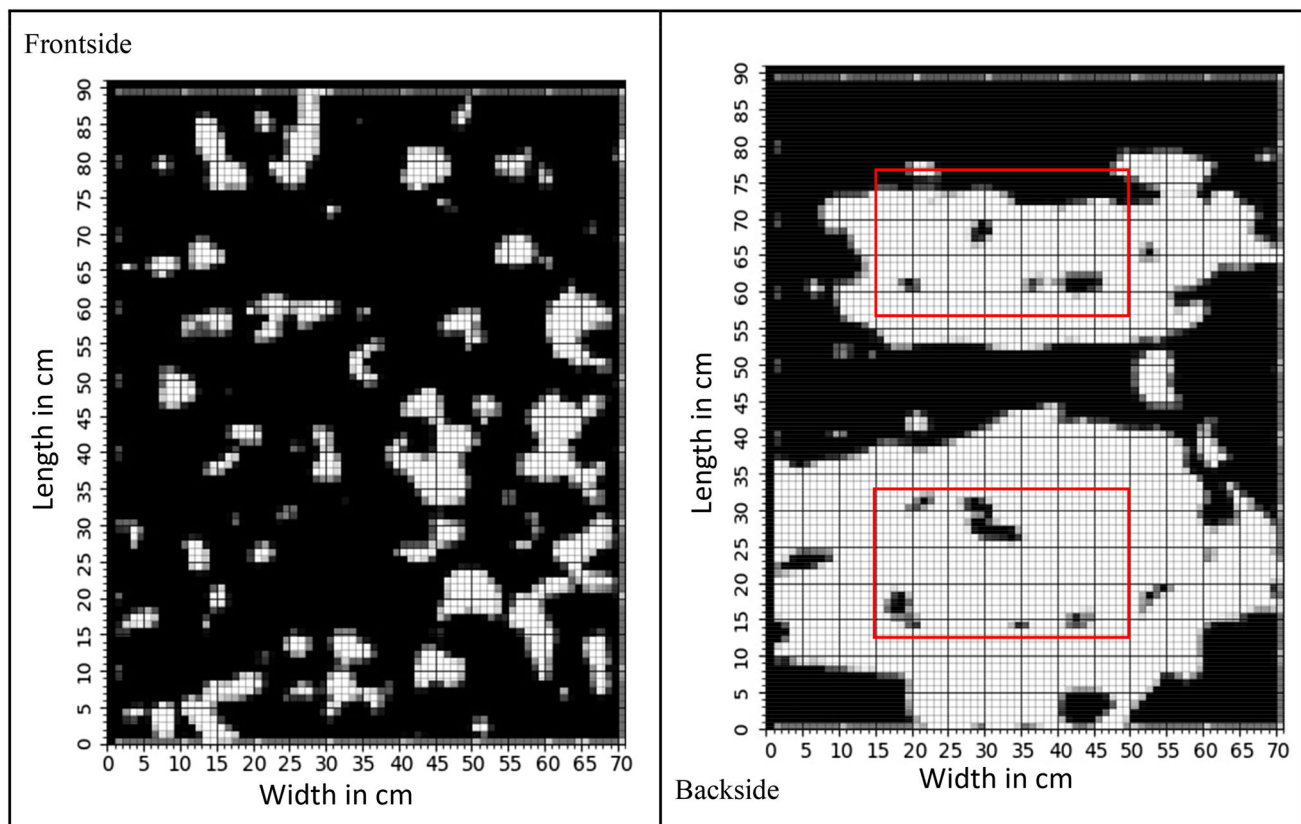
Fig. 6 Result of the UPE measurements on specimen 3. Bright color indicates the delaminations. Only the backside shows delaminations. One possible reason are vertical cracks in case of the frontside, probably due to the larger hole diameter, 10 mm instead of 8 mm. The backside shows two delaminations. In area D1 the delamination is between about 10–65 cm in width and between about 55–75 cm in length. In area D2 the delamination is larger. The D2 delamination is in the complete width, i.e. 70 cm, and between about 0–40 cm in length. Both views are seen from above and are symmetrical to the y-axis, so they can be mentally folded/ unfolded

6 Conclusions

Procedures to create artificial delaminations as close as possible to natural ones have been developed and successfully applied to three specimens. The delaminations produced in this way were mostly detected using UPE according to previously established criteria.

The recipes which make it possible to generate artificial delaminations can be repeated relatively easily in any qualified NDT laboratory. The resulting specimens are suitable for common NDT methods on the one hand and transportable on the other hand. The specified dimensions of the delaminations could usually be achieved and unwanted cracks could largely be avoided.

For this purpose, Betonamit and through holes were used, based on the positive experiences of the author with vertical cracks. Filled and unfilled holes were used to limit the expansion direction of delaminations.

The method with boreholes and Betonamit can, in principle, also be used for other shapes of delamination, such as curved delaminations, which are often of interest in practice.

Automated testing using UPE was carried out, and SAFT as well as established criteria were used for evaluation. Thus, for each square centimeter, it could be shown whether delamination was present or not. For the six delaminations investigated here, it was also possible to show the scale of the delaminations for the areas investigated, i.e. in the respective depth range and, for this depth, also the specific position in the plane. This experience underlines the power of the ultrasonic method in general and of the evaluation method developed in this study, especially considering that the cracks involved are horizontal cracks with a width that is in the range of tenths of a millimeter. Such cracks could not previously be generated in a controlled manner for NDT application, nor could they be detected with the ultrasonic method as precisely as in the study.

Despite the in-depth study of the direct and indirect indicators of delamination, some questions remained unanswered.

Fig. 7 Frontside specimen 1: surface cracks. The surface cracks are visible in delamination 2. The dots on the surface are a 10 cm grid
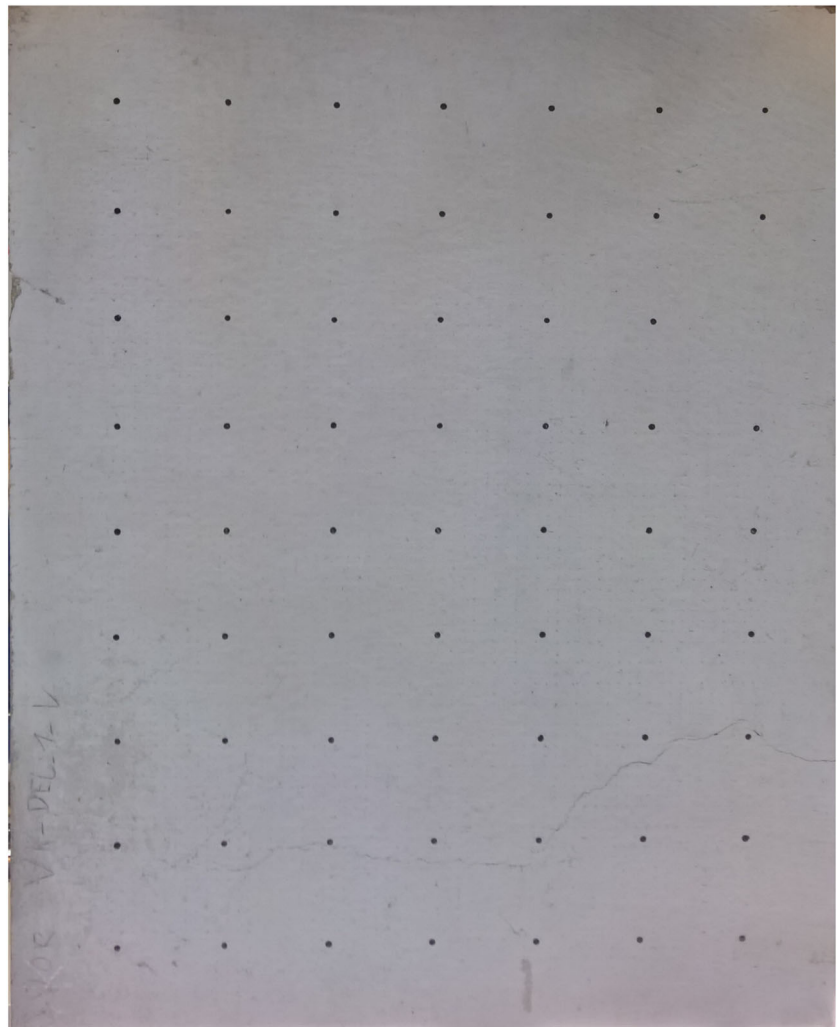
For example, it is especially difficult to detect delaminations when several of them are below each other or under vertical cracks. Nevertheless, there were the first positive experiences concerning the detection in such cases.

However, there are limitations when the specimens are produced and verified. The following procedures need to be studied in future work more detailed: The expansion of Betonamit and the resulting forces, and the appearance of vertical cracks, in particular. This is not only dependent on the quantity and care taken in filling the holes. The expansion force also depends on the packaging and on the time after which Betonamit is used after opening the packaging. Even if Betonamit is repacked in vacuum, it slowly and continuously loses its expansion force. This makes it technically and economically difficult to produce reference specimens with delaminations. The safest method to successfully produce the specimens is to test the expansion force of Betonamit on other specimens with comparable concrete strength before using it in the reference specimen. These functional tests of Betonamit must be immediately followed by the final application in the reference specimen.

Several factors affect the quality of delaminations. The specimens produced according to the procedure instructions by several international participants show that it is not only the execution quality but also the local conditions that are important. In particular, the concrete technology and the locally available resources for the concrete play an important role. For example, the form of the aggregates, i.e. crushed or uncrushed, proved to be important for the path of the cracks. The recipes of the reference specimens were with unbroken aggregates, and it turned out that these were not available everywhere, so that broken ones were used, which probably also affected the cracks.

The UPE method proved to be effective. Several devices from different manufacturers were used in preliminary tests. In addition, various methods were used to evaluate the data. The results presented in this study show the best combination to test and evaluate the data resulting from this project. Nevertheless, in addition to UPE, other techniques were used in
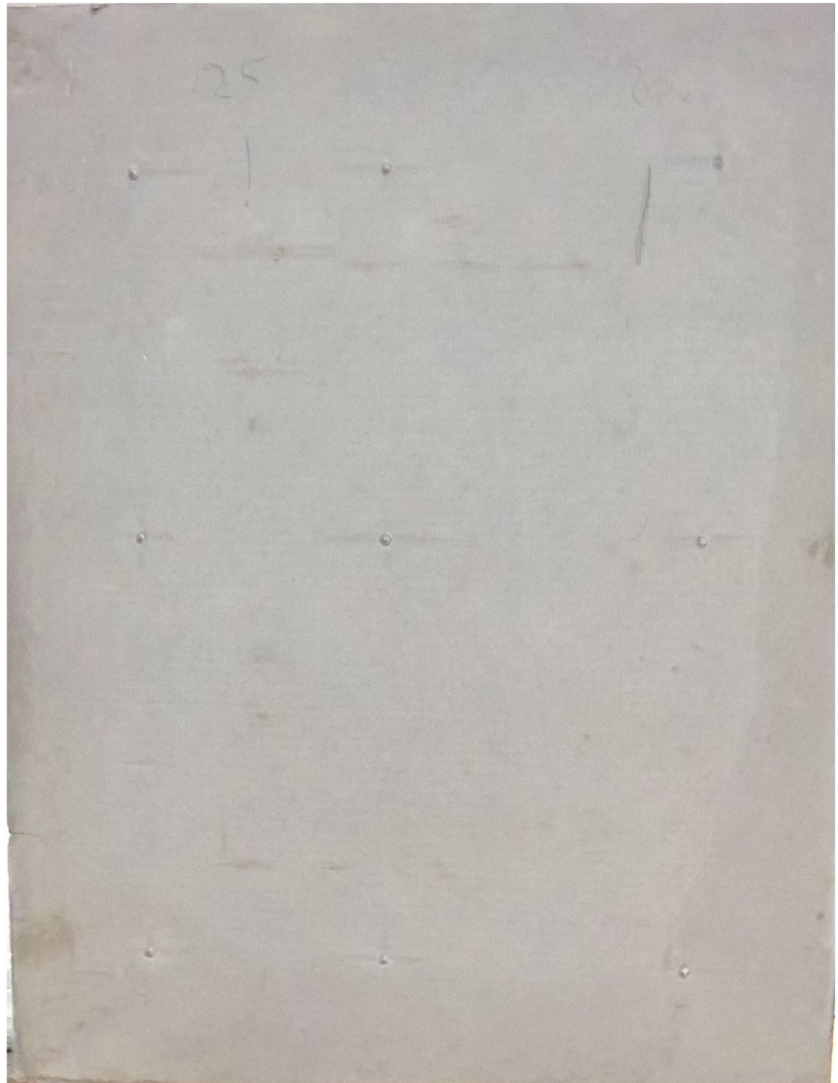
Fig. 8 Frontside specimen 2: surface cracks. The surface cracks are visible in delamination 1

the preliminary studies: time of flight diffraction (TOFD), ground penetrating radar (GPR) and reverse time migration (RTM). These did not prove to be effective in detecting delaminations.

The procedures developed here now make it possible to compare and improve NDT test systems regarding the testing task of delaminations. This serves NDT-CE in particular and quality assurance in CE in general. Improving NDT can, in turn, make infrastructure, such as bridges, safer.

Fig. 9 Frontside specimen 3. Unfortunately, no cracks are visible here. The cracks to the surface after the application of Betonamit were not visible, in contrast to specimen 1 and 2

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