

## **SCANNING IMPACT-ECHO TECHNIQUES FOR CRACK DEPTH DETERMINATION**

## **SCANNENDE IMPAKT-ECHO-VERFAHREN ZUR RISSTIEFEN-DETEKTION**

## **METHODE IMPACT-ECHO A BALAYAGE POUR DETERMINER LA PROFONDEUR DES FISSURES**

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### **SUMMARY**

Concrete cracking often results in stiffness loss and also corrosion of the steel reinforcement. The corrosion rate strongly depends on the crack width and the crack depth so there is the need to measure and to characterize its dimensions. The impact-echo technique is a useful tool for the detection of different faults in concrete structures. Unfortunately, the existing instruments and analysis tools designed for measurements were lacking of several features in the past detaining the extensive use. Therefore a new concept for impact-echo testing systems is presented. A new device was developed, which is small, robust and easy to handle. The system utilizes advanced impact generation for fast scanning techniques and reproducible impacts. The data acquisition, filtering and visualization of data are optimized for the inspection of large structures obtaining data at many measurement points. A new option is the automatic estimation of crack parameters like crack depth. In this paper fundamental principles of the different measurement techniques as well as details of the measurement system are described and some test results are shown.

### **ZUSAMMENFASSUNG**

Risse in Stahlbetonbauteilen führen in der Regel zu einem Steifigkeitsverlust wie auch zu einer erhöhten Korrosionsgefahr der eingelegten Stahlbewehrung. Hierbei hängt die Korrosionsgefahr insbesondere von der Rissbreite und der Risstiefe ab, weshalb deren Bestimmung von besonderer Bedeutung für die Dauerhaftigkeit ist. Das Impakt-Echo-Verfahren wird bei Betonbauteilen für die zerstörungsfreie Untersuchung und Charakterisierung von verschiedenen Schädigungsbildern verwendet. Aufgrund der bei großen Flächen relativ aufwändigen Versuchsdurchführung und –auswertung wurde dieses Verfahren in der

Vergangenheit jedoch nur vereinzelt eingesetzt. Daher werden in diesem Artikel neue Konzepte des Impakt-Echo-Verfahrens vorgestellt. Neben neuer Hardware wurden neue Softwarekonzepte entwickelt, welche eine objektivere und zudem weitgehend automatisierte Versuchsdurchführung und –auswertung ermöglichen. Durch die Verwendung von scannenden Verfahren als auch die Implementierung und Kombination von verschiedenen Methoden zur Signalanalyse wird die Untersuchung großer Bauteile vereinfacht. Neben den bekannten Möglichkeiten des Impakt-Echo-Verfahrens zur Bauteiluntersuchung werden insbesondere einige neue Ansätze zur automatischen Detektion und Charakterisierung von vertikal verlaufenden Rissen diskutiert.

## RESUME

La fissuration du béton armé mène en général à une réduction de rigidité et à un risque accru de corrosion des armatures. Ce risque dépend en particulier de la largeur et de la profondeur des fissures, la détermination de ces dernières est donc d'importance particulière pour la durabilité. La méthode impact-écho est utilisée pour l'inspection non destructive des constructions en béton et la caractérisation de différents défauts. A cause de l'envergure de la mise en œuvre des essais et de leur évaluation pour les grandes surfaces, cette méthode n'a été appliquée qu'occasionnellement jusqu'à présent. De nouveaux concepts pour la méthode impact-écho sont présentés dans cet article. Un nouvel appareillage et de nouveaux logiciels ont été développés, permettant une mise en œuvre et une évaluation des essais à la fois plus objectives et largement automatisées. Tant l'utilisation de méthodes à balayage que l'implémentation et la combinaison de différentes méthodes d'analyse des signaux ont simplifié l'inspection de grands éléments de construction. Outre les applications connues de la méthode impact-écho dans l'inspection des constructions, de nouvelles approches pour la détection et la caractérisation automatiques des fissures verticales sont discutées.

KEYWORDS: Scanning Impact-Echo techniques, crack determination, non-destructive testing

## 1 INTRODUCTION

Due to the demands for quality control and sustainability of structures in civil engineering, a growing market for non-destructive testing has evolved. For concrete structures, several methods are well-introduced concerning defect char-

acterisation. Ultrasound, radar, thermography, electro-potential-field methods and others are currently being used to detect voids, cracks, corrosion, etc. – with varying success. Several years ago, the Impact-Echo (IE) method, that considerably improved the detection of voids and honeycombing, was introduced by Carino et al. [1]. The strength of this method is its ability to detect voids in structures and to measure the thickness of concrete parts with good accuracy. For that reason, Impact-Echo was chosen to be the standard technology for quality control of tunnels in Germany [2]. It seems that IE is the first non-destructive technology to be part of a regulating standard for quality control in civil engineering in Germany. However, this technology is still not widely accepted due to the poor handling and limited functionality of commercially available equipment based on this approach. Moreover it was shown that single-point measurements are somehow more difficult to be interpreted compared to measurements using a scanning technique [3]. The so-called scanning IE technique was developed from measurements that were carried out by Weiler [4] and later on by Grosse and Weiler [5] as well as Kretschmar [6]. A more sophisticated approach using a static scanning frame was described by Colla et al. [3] and Lausch et al. [7]. It is obvious that the potential of this technique is currently not being used to its full extent regarding handling as well as analyzing techniques, therefore reducing the economic value of this method.

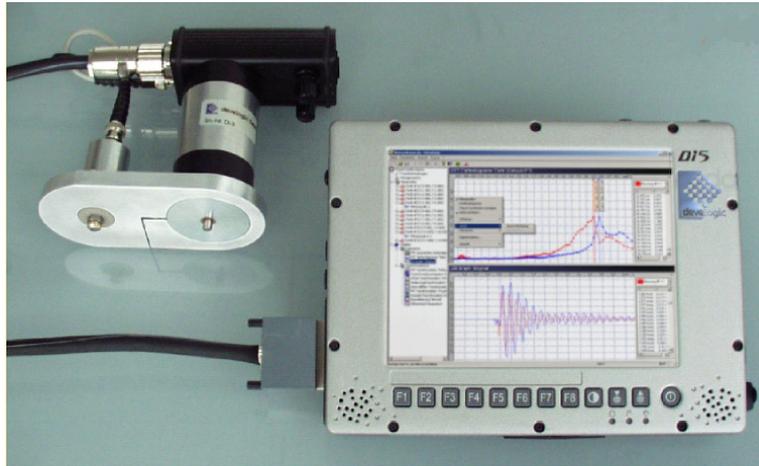
Based on the development of a new hardware [8] some improvements regarding void as well as crack detection were made, which are described in the following.

## **IMPACT-ECHO SYSTEM**

### **Measurement Hardware**

Up to now the number of commercially available Impact-Echo systems is limited. The data acquisition and analysis capabilities of these systems are very similar. With such equipment, repetitive velocity measurements are neither practical nor cost-effective although a constant velocity cannot be expected to be present in large structures. In general, Impact-Echo testing with currently available equipment takes up to two minutes per measurement point for data acquisition and verification of results. Considering the poor ergonomics of such devices, two operators are often necessary to handle the equipment. As personnel costs are crucial for in-situ measurements, reducing the complexity of the testing

process is essential for further acceptance of this technique. Otherwise, only measurements at selected single points or with relatively wide grids are feasible.



*Figure 1. DAI-1 impactor and sensor (left) together with the tablet-PC control unit (right).*

For that purpose a test system has been developed (see Figure 1). On the hardware side, the system consists of a transducer and an automatic impactor as well as a data acquisition PC-Card. The equipment is light, mobile and controlled by a rugged sub-notebook or a tablet-PC. The device is optimized for rough environments and a fast and easy data acquisition. For the detection of voids and cracks, the impact should generate a short relatively high energy but nevertheless non-destructive pulse with broad frequency content. High impact energy is necessary to detect defects and boundary surfaces in greater depth. The developed impactor operates on the basis of high speed tubular solenoids. It is equipped with an electronic control unit interfacing to external devices that allows the operator to fully control the impact generation and also gives feedback on impact time and duration. As the unit is able to deliver the exact time of impact, a second transducer so far required for velocity measurements is now obsolete [9], [10]. With the unit it is also possible to develop new fast inspection methods like the proposed methods of vertical crack detection and characterisation.

## **Measurement Software**

The Impact-Echo technique is in general a punctiform test method that means that one measurement only gives information about one point of the structure (A-Scan). To get a better a better idea of the structure it is more useful to use scanning techniques measuring at multiple points, e.g. one could look at several points in a line (B-Scan) or could measure a whole surface (C-Scan). If a

B-Scan or a C-Scan is considered, a lot of single measurements have to be made and also combined which is very complex. Nowadays this combination of the test results is often done manually that is very time consuming. The measurement software, which is presented in this paper, therefore accounts for the following aspects: easy handling for fast and competitive measurements; automatic measurement grid generation for surfaces with unlimited measurement points; flexible toolbox with mathematical functions for determining automatic and semiautomatic measurement and analysis procedures (for crack/ flaw detection and characterization); implementation of tools for the flexible graphical representation of A-Scans, B-Scans and C-Scans that will allow an easy real-time analysis during the measurement procedure.

## IMPACT-ECHO MEASUREMENT METHODS

### Standard Measurement Technique

The Impact-Echo method uses transient stress waves generated on the surface of concrete or masonry structures by an elastic impact (Figure 2). As the stress waves propagate through the material being tested, they are reflected by internal interfaces (discontinuities in the material) and external boundaries of the structure. Examples of such interfaces are delaminations, voids, honeycombing and cracks, as well as rising mains or large steel bars. In order to detect such interfaces, the emitted waves are recorded by a displacement or acceleration transducer which is placed near the impact point on the surface of the structure.

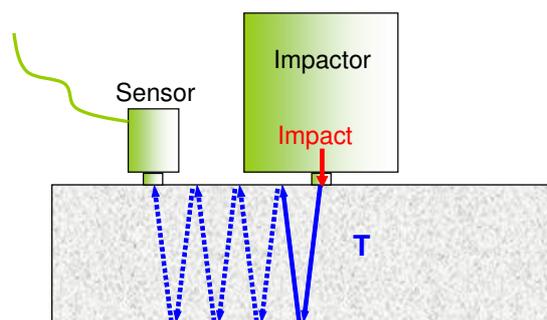


Figure 2. Principle of impact-echo measurements to detect boundaries or voids.

The depth of any internal flaws or external interfaces can be determined by analyzing the recorded signal and its characteristic frequency spectrum (FFT) using the following simple equation

$$d = \frac{v_p}{2 \cdot f_R} \quad (1)$$

where  $d$  is the depth of the interface or void,  $v_P$  is the measured compressional wave velocity and  $f_R$  is the resonance frequency in the spectrum corresponding to the period  $T$  of the wave. Usually the resonance frequency is the dominant frequency in the spectrum. Together with the previously measured compressional wave velocity of this structure, the depth of the void can be evaluated from equation (1).

### Principles of Crack Detection using Impact-Echo

One principle of crack detection using the proposed test setup is similar to time of flight techniques [11], [12]. A signal emitted by the impactor will be detected after a certain travel time  $t$  and with a certain amplitude or energy, respectively (see Figure 3). If a surface crack with a tip depth  $d'$  is present between emitter and sensor, a time delay  $\Delta t$  occurs in the signal with the following relation to the original travel time  $t$ :

$$\Delta t = (t_1 + t_2) - t \quad (2)$$

With knowledge of the wave speed of the compressional wave  $\Delta t$  will correlate with the crack tip depth. Unfortunately, the time delay depends very strong on the material filling the gap between the crack edges since there is usually not only air in between. Additional effects are caused by the reinforcement able to bridge the crack flanks.

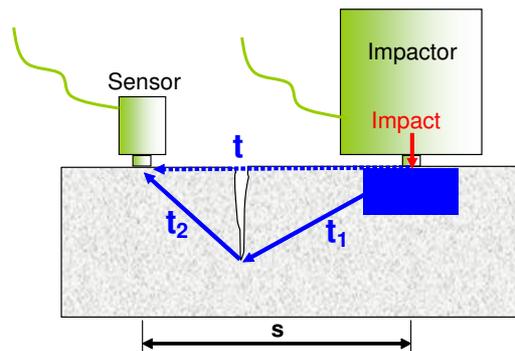


Figure 3. Principle of IE measurements for crack detection with the time of flight method.

Therefore it is appropriate to use the energy of the emitted signal as recorded by the sensor ensuring that the emitter produces a highly reproducible constant signal. This is especially true for the used electronic impactor. Tests have shown that the cumulative energy (samplewise addition of the squared amplitude of the received signal) is a good discriminator between concrete surfaces with and without cracks. The peak amplitude of a time signal travelling across a crack is delayed and the overall energy is significantly lower compared to a

wave travelling along an undisturbed surface, because a part of the impact energy is reflected at the crack surface. Figure 4 shows the principle of this technique that can be used for automatic crack detection and in future developments for a determination of other crack parameters like crack depth and width.

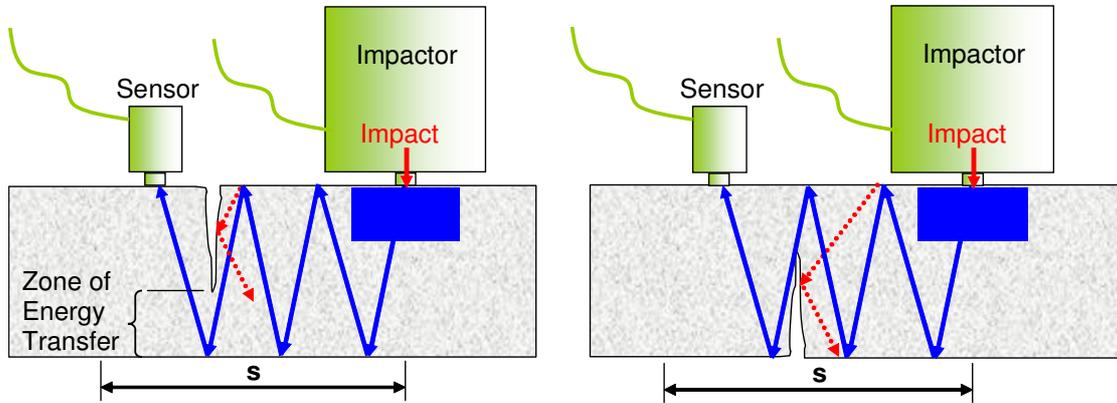


Figure 4. Principle of IE measurements for crack detection considering signal amplitude and signal energy as criteria.

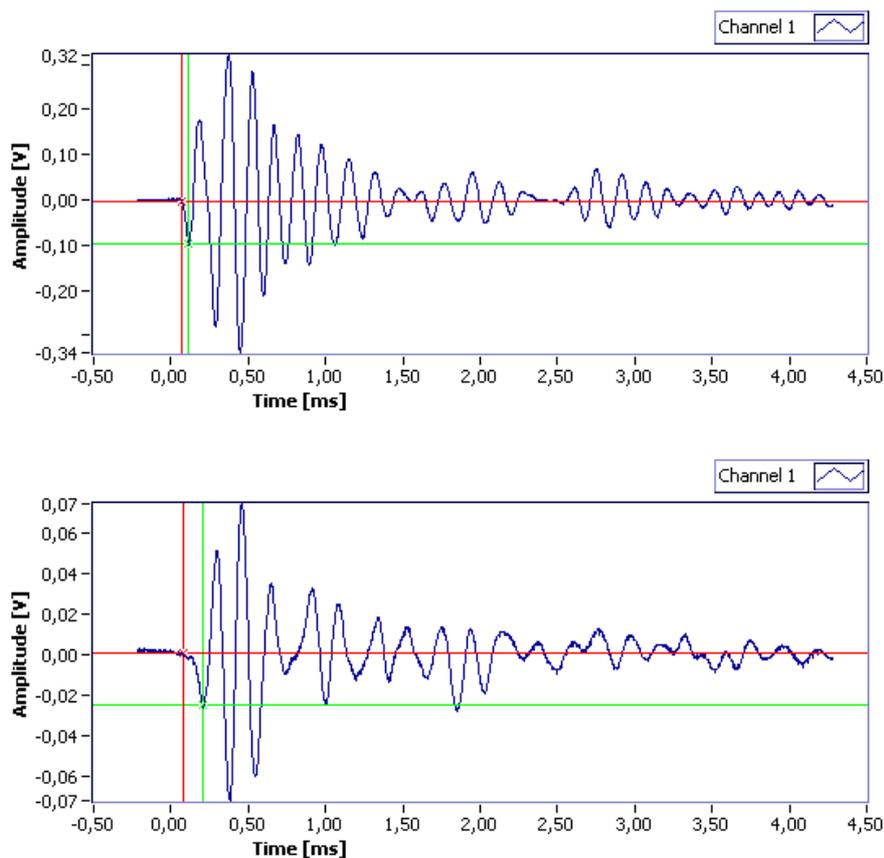


Figure 5. Measured signals obtained across a crack at a crack width of  $<0.1\text{mm}$  (upper curve) and at a crack width of approximately  $0.7\text{mm}$  (lower curve).

An example of a recorded signal measured across a crack is given in Figure 5. It can be seen that the maximum signal amplitude and the onset time of the signal depends on the crack width and thus also crack depth.

Figure 6 shows the cumulated energy of two measured signals. The blue curve represents the cumulated energy of a measurement across an undisturbed surface and the red curve represents the cumulated energy of a measurement obtained across a crack. It can be clearly seen that the cumulated energy of the measured wave decreases with an increasing crack depth. However, the cumulated energy of the signal gives also a good hint for the quality of the concrete. For a characterization of a crack the partial derivative of the cumulated energy of the first part of the curves could be taken (see the slope in the area of interest in Figure 6). If the partial derivative is positive no crack is existent (descending slope in Fig. 10). If on the other hand the partial derivative becomes negative a crack is existent and if the partial derivative becomes more negative this implicates larger crack depth (ascending slope in Fig.10).

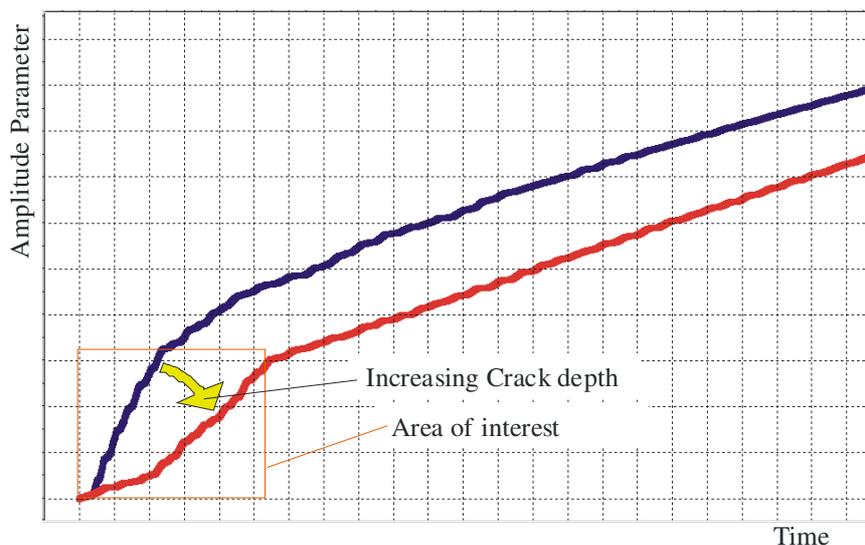


Figure 6. Cumulated energy (amplitude) calculated for the first 5000 samples of received signals obtained across cracks (lower curve) and across undisturbed surfaces (upper curve).

An interesting aspect is that the new developed Impact-Echo measurement technique as shown above provides different values simultaneously, which could be used for the characterization of the observed structure. The value which is normally used for the detection of flaws is the resonance frequency in the spectrum. However, with the new developed measurement system it is possible to use the Impact-Echo technique to receive additional values e.g. onset time for the wave speed determination and the time of flight technique and in addition

the cumulated energy for a more precise characterization of the inspected structure. Horizontal and vertical cracks and flaws as well as the concrete quality could now be characterized in one single measurement.

## LABORATORY TESTS

To prove the theories of crack detection and crack characterization it was needed to make some preliminary tests with a well known test set-up. Therefore, a test specimen was produced, in which some cracks could be initiated by inserting splints with a hammer (see Figure 7). This allows producing realistic cracks with different crack width and crack depth.



Figure 7. Test specimen for laboratory tests (Cracks initiated by splines)

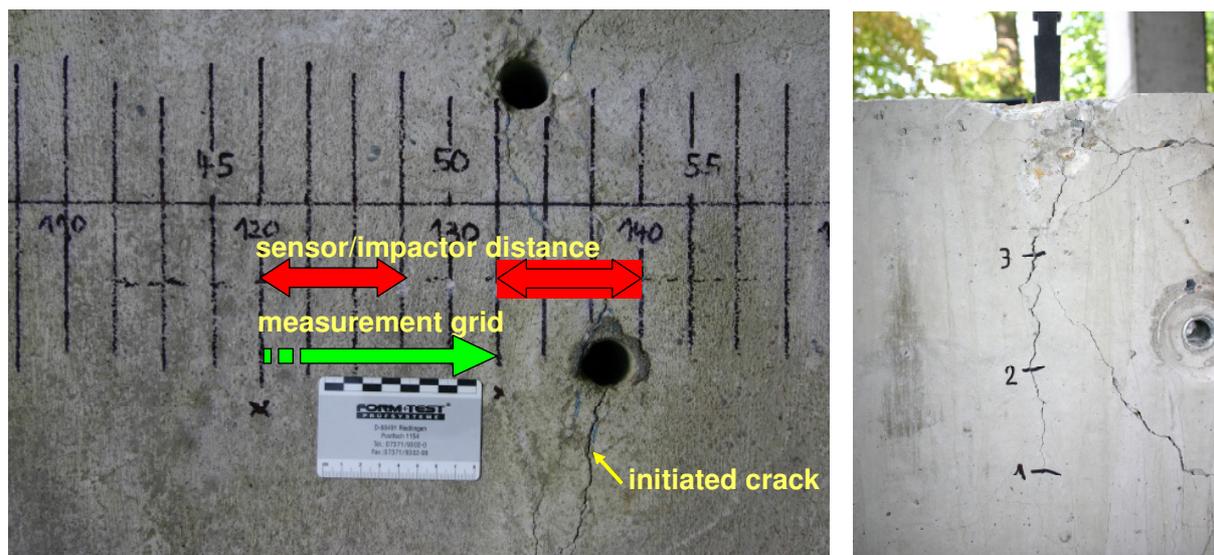


Figure 8. Test grid (top view) and initiated crack (side view)

First test were made with different crack width of approximately 0.1, 0.2, 0.4 and 0.7 mm. The crack width was controlled by inserting the splints differ-

ently. A measurement grid of 25mm was used (Figure 8) which is less than the distance of 75mm between the sensor and the impactor. The measurement unit was relocated 6 times starting at 120cm (see Figure 8, left sketch). The first five measurements are without a crack and the sixth measurement was across the initiated crack.

Figure 9 shows the test results of the measured signals in the time domain for different crack width in a B-Scan that could be generated by the software automatically. The results show that the peak energy of a time signal travelling across a crack (measurement No. 6) is delayed and of lower amplitude as well as the overall energy is significantly lower (for details see also Figure 5) compared to a wave travelling along an undisturbed surface, because a part of the impact energy is reflected at the crack surface (see Figure 4). With regard to different crack openings induced by the splines one could also observe a decrease of signal energy with increasing crack width that corresponds to the theory. This is also shown in Figure 10, in which the maximum signal amplitude is plotted against crack width.

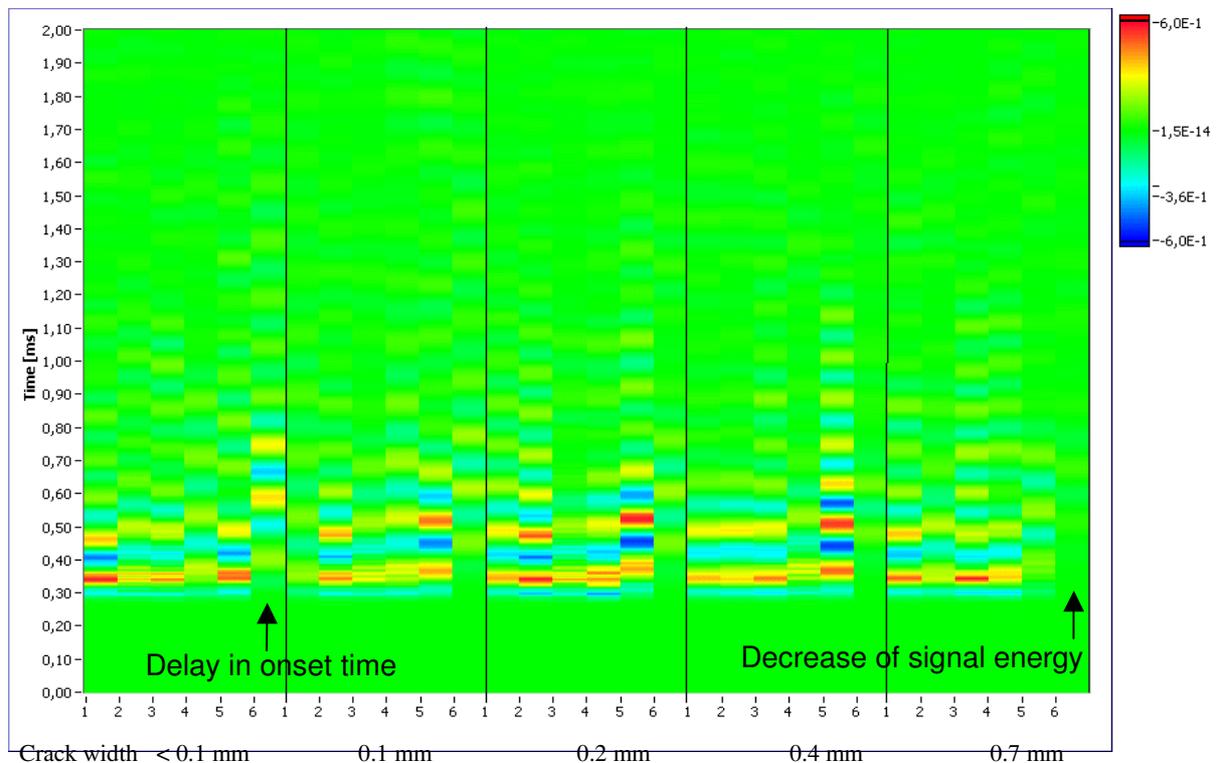


Figure 9. Test results from measurements at different crack width (B-scan of signals).

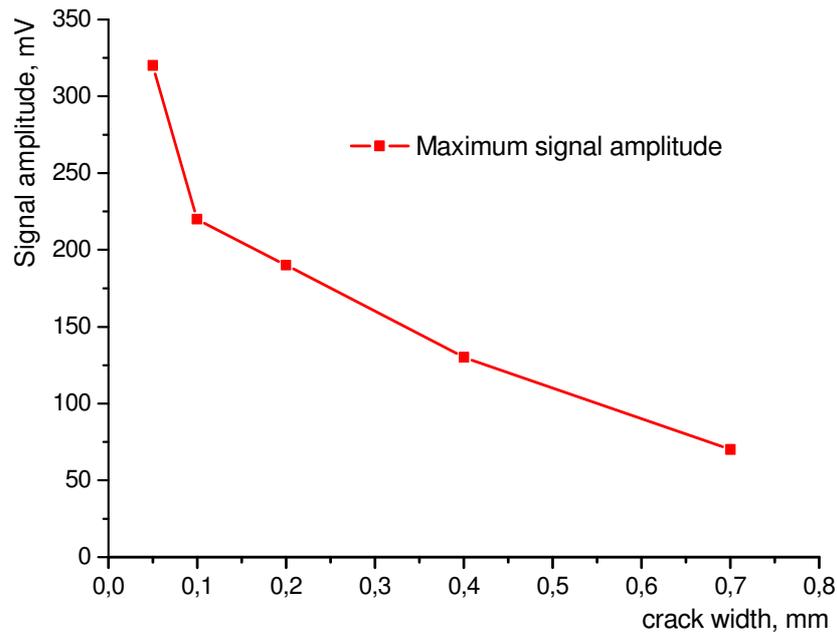


Figure 10. Maximum signal amplitude obtained across a crack at different crack opening.

A combination of the described methods can be used for automatic crack detection and in future for a determination of other crack parameters like crack depth and width. However, the signal amplitude and the signal energy could be used as criteria only if an internal horizontal interface or external boundary exists at the inspected structural part. As a conclusion it could be shown that the test method permits the detection of vertical cracks in general as well as crack depth.

## OUTLOOK AND FUTURE WORK

Regarding the civil engineering industry an increasing demand for quality control of structures can be observed. Advanced Impact-Echo testing techniques that are easy to use for fast, repeatable and reproducible measurements can be used to improve the existing techniques or to replace visible inspections detecting voids or cracks. The benefits are already obvious to be the one-sided access and the easiness to conduct measurements saving time and money and bring the inspection on a more reliable and objective level.

It was shown that the IE technique has the potential to detect precisely large voids, honeycombs and inhomogeneities as well as the thickness of concrete structures. The new developed device reduces the time necessary for each measurement by a factor of ten. Some new methods are described concerning the detection of cracks. First promising results were shown using the cumulative

energy of the transmitted signal as a crack discriminator. Essential is that the new system provides a more reliable impact generation.

These newly developed methods including a new software front end IEDA 2.0 will be evaluated and calibrated during further tests. The tests will give more details about the reproducibility and reliability of this method. After that the next actions are the development, evaluation and implementation of proper algorithms for semiautomatic or automatic crack detection into software.

## 2 REFERENCES

- [1] Carino, N.J., Sansalone, M., and Hsu, N.N.: A Point Source - Point Receiver Technique for Flaw Detection in Concrete", *Journal of the American Concrete Institute*, Vol. 83, No. 2, pp. 199-208, 1986.
- [2] RI-ZFP-TU: Richtlinie für die Anwendung der zerstörungsfreien Prüfung von Tunnelinnenschalen, Bundesanstalt für Straßenwesen, Reg.-Nr. 05.72, Verkehrsblatt-Dok. Nr. S 1050 - Vers. 03/01, 2001.
- [3] Colla, C.; Schneider, G.; Wöstmann, J.; Wiggenhauser, H.: Automated Impact-Echo: 2- and 3-D imaging of concrete elements. *NDT.net*, Vol. 4, No. 5, 1999.
- [4] Weiler, B.: State assessment of sandstone by ultrasonic measurements. *Otto-Graf-Journal*, Vol. 6, pp. 188-199, 1995.
- [5] Grosse, C. U.; Weiler, B.: Analyse von Vielfachreflexionen nach mechanischer Pulsanregung - Impakt-Echo-Verfahren (FMPE). In: "Erprobung und Bewertung zerstörungsfreier Prüfverfahren für Betonbrücken", Abschlussbericht FE-Nr.:9.94241 F1 der Bundesanstalt für Materialprüfung BAM, H. B18, Berlin, pp. 116-123, 1997.
- [6] Kretschmar, F., Köhler, B., Hentges, G.: Analyse von Vielfachreflexionen nach mechanischer Pulsanregung - Impakt-Echo-Verfahren (EADQ). In: "Erprobung und Bewertung zerstörungsfreier Prüfverfahren für Betonbrücken", Abschlussbericht FE-Nr.:9.94241 F1 der Bundesanstalt für Materialprüfung BAM, H. B18, Berlin, pp. 104-115, 1997.
- [7] Lausch, R.; Wiggenhauser, H.; Schubert, F.: Geometrieeffekte und Hüllrohrortung bei der Impaktecho-Prüfung von Betonbauteilen – Experimentelle und modelltheoretische Ergebnisse. *Proc. DGZfP Annual meeting*, Weimar, BB80-CD, *NDT.net*, Vol. 7, No. 11, 2002.

- [8] Motz, M., Krüger, M., Grosse, C. U., Haller, P., Beutel, R.: Impact-Echo: New Developments Regarding Hardware and Software. Intern. Symp. Non-Destructive Testing in Civil Engineering (NDT-CE), Proceedings BB 85-CD, Berlin, 2003.
- [9] Grosse, C. U., Reinhardt, H. W., Beutel, R.: Impact-Echo Measurement on Fresh and Hardening Concrete. In: Concrete Science and Engineering (Ed. K. Kovler, et al.), RILEM PRO 36, RILEM Publ. S.A.R.L., pp 95-104, 2004.
- [10] Grosse, C. U.: 'Quantitative zerstörungsfreie Prüfung von Baustoffen mittels Schallemissionsanalyse und Ultraschall'. Ph.D. thesis, University of Stuttgart, 168 pp, 1996.
- [11] Sansalone, M. J.; Streett, W. B.: Impact-Echo. Bullbrier Press, Ithaca, 336 pp., 1997.
- [12] Sansalone, M. J., Lin, J.-M., Streett, W. B.: Determining the depth of surface-opening cracks using impact-generated stress waves and time-of-flight techniques. ACI Mat. J. Vol. 95, 168-177, 1998.
- [13] Bahr, G., Krüger, M.: IEDA V2.0 – User Manual, Smartmote&IWB, Stuttgart, 2005.

