APPLICATION OF IMPACT-ECHO TECHNIQUES FOR CRACK DETECTION AND CRACK PARAMETER ESTIMATION IN CONCRETE

C. U. Grosse, H. W. Reinhardt, M. Krüger and R. Beutel

Institute of Construction Materials, University of Stuttgart, Pfaffenwaldring 4, D-70569 Stuttgart, Germany, http://www.iwb.uni-stuttgart.de

ABSTRACT

Existing instruments designed for measurements involving the Impact-Echo (IE) technique are usually of limited use in field tests when investigating large concrete structures like buildings or tunnels. In 2001 demand for such instruments increased significantly particularly in Germany, as German authorities made quality control tests of state road tunnel constructions mandatory. For this task, it is essential that the equipment used for Impact-Echo measurements along profiles uses the scanning technique and is easy to work.

A new concept for impact-echo testing systems is presented. The new device is small and easy to handle, robust and unproblematic regarding transportation. The system utilizes advanced impact generation, measurement, data acquisition, filtering, and visualization techniques. Regarding the software state-of-the-art requirements were implemented for both, scientific applications and field-tests. A new option is the flaw detection and estimation of crack parameters like crack width and depth out of the impact-echo signals. Some first results of in-situ measurements are shown.

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 characterisation. 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 [3] that single-point measurements are somehow more difficult to be interpreted compared to measurements using a scanning technique. 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 Köhler [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. The system has already the potential to be used in quality control of cementitious materials during setting and hardening, what was shown by Grosse et al. [9]. The described IE system is now used also in the frame of a collaborative project "Sustainable Bridges - Assessment for Future Traffic Demands and longer Lives" [10] funded by the European Commission in the sixth Framework Programme ("Sustainable development, global change & ecosystems"). Some first results of these experiments are shown.

2 IMPACT-ECHO BASICS

The Impact-Echo method uses transient stress waves generated on the surface of concrete or masonry structures by an elastic impact (Fig. 1). 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.

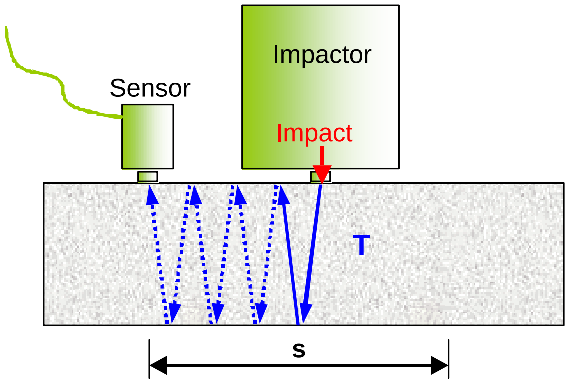

Fig. 1: Principle of impact-echo measurements to detect boundaries or voids.

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

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

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).

However, practical application of Impact-Echo measurement is often circuitous and time-consuming thus reducing its benefits. Therefore, modern Impact-Echo testing techniques require better operability of the test equipment for quickly gaining repeatable and reproducible results leading to cost-effective measurements.

3 IMPACT-ECHO MEASUREMENT SYSTEM

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 [8]. 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.

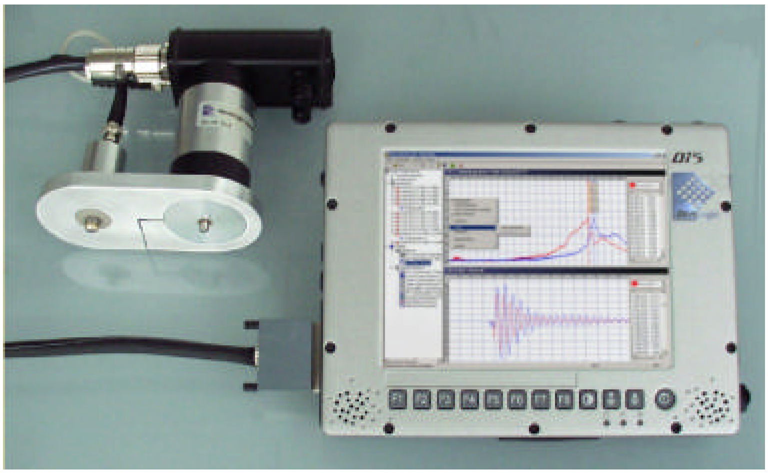

Fig. 2: DAI-1 impactor and sensor (left) together with the tablet-PC control unit (right).

For that purpose a test system has been developed (Fig. 2). On the hardware side, it 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 ruggedized 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 [11, 12] is now obsolete.

4 APPLICATIONS

4.1 Applications for bridge testing detecting voids

On a steel reinforced concrete road bridge (96 m length) in Stuttgart the capabilities of the IE technique and in particular the new hard- and software were tested to detect voids (Fig. 3).

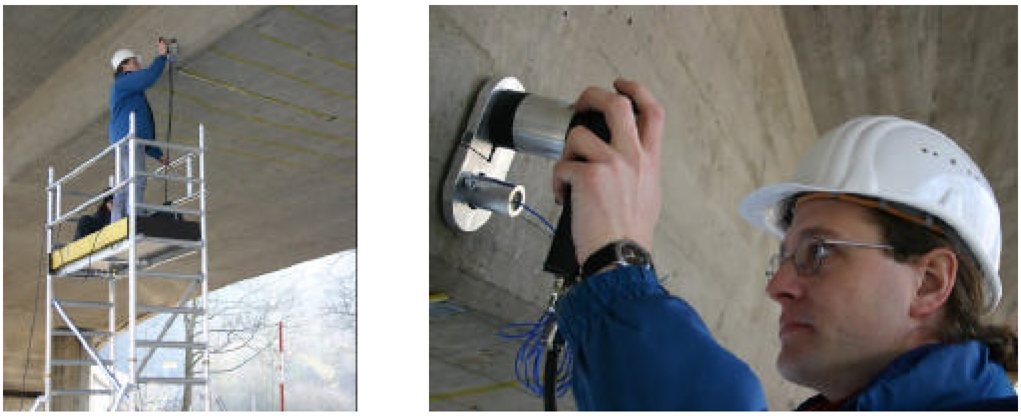

Fig. 3: Void detection using the DAI-1 impact-echo system at a concrete bridge.

As visible in Fig. 3 IE-measurements were done along profiles across the bridge. In frequency domain the data can be arrange as so-called impactechograms (Fig. 4). Due to the construction (dated from the early seventies) there are large voids (tubes) present in the middle of the bridge. Fig. 4 shows a part of the cross-section next to the pylons – grouted ducts for pre-stressed cables are not shown in the diagram. In the impact-echogram the bottom of the tubes is clearly seen. Using the previously measured v_p of 4162 m/s the distance between the tube bottom and the lower side of the bridge is determined to

(2) $$d = \frac{4162\,m/s}{2 \cdot 15kHz} = 14\,cm$$

According to the blueprints this distance was prospected to be 15 cm. The bridge is not needed anymore and will be disassembled soon. Some more measurements will be conducted before. During the demolition the correct depth will be checked.

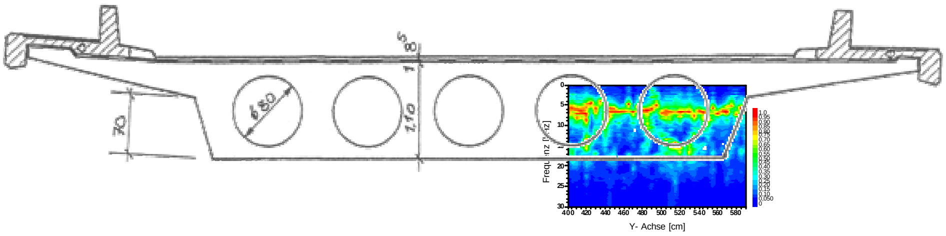

Fig. 4: Results of void detection along a scanning line in a concrete bridge (see Fig. 3).

4.2 Applications for crack detection

The principle of crack detection using the described test system is similar to time of flight techniques [13]. A signal emitted by the impactor will be detected after a certain travel time and with a certain amplitude or energy, respectively. If a surface crack with a tip depth *d'* is present between emitter and sensor, a time delay Δt occurs in the signal with the following relation to the original travel time t:

(3) $$\Delta t = (t_1 + t_2) - t$$

Δt 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.

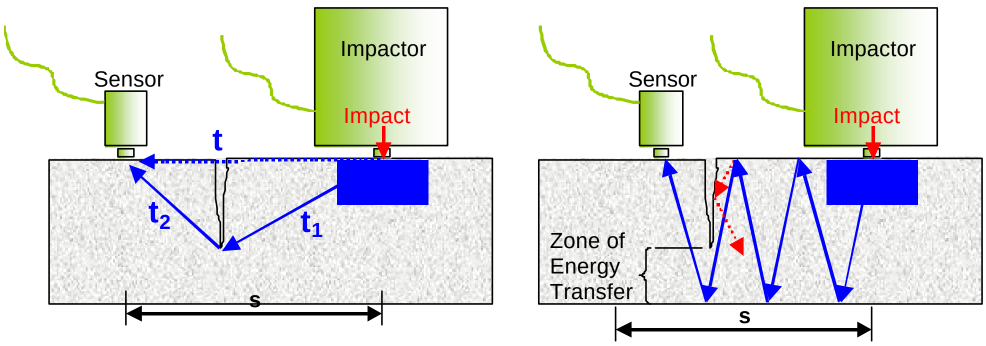

Fig. 5: Principle of IE measurements for crack detection.

Therefore, it is more 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 DAI-1 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 energy of a time signal travelling across a crack is delayed and the overall energy is significantly lower (Fig. 6) compared to a wave travelling along an undisturbed surface, because a part of the impact energy is reflected at the crack surface (Fig. 5, right). This can be used for automatic crack detections and in future for a determination of other crack parameters like crack depth and width.

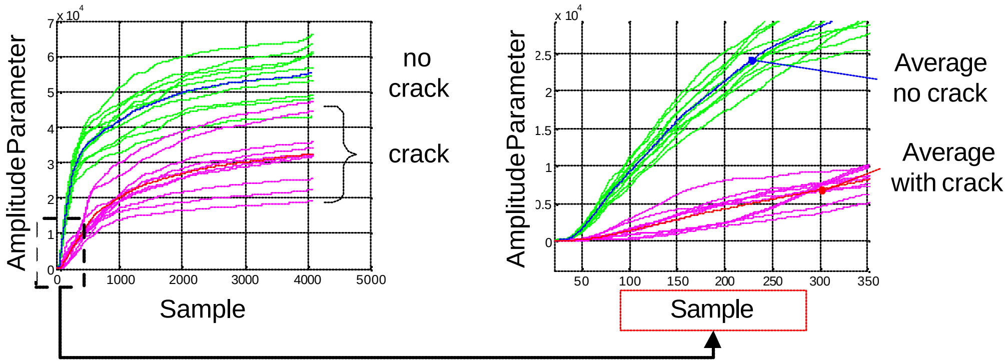

Fig. 6: Cumulated energy (amplitude) calculated for the first 5000 samples (left) of received signals obtained across cracks (lower curves) and across undisturbed surfaces (upper curves); right: detail (by courtesy of *develogic GmbH*, Gerlingen, Germany).

4 OUTLOOK

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 inhomogenieties as well as the thickness of concrete structures. A new device reduces the time necessary for each measurement by a factor of ten. Some applications 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 will be evaluated during tests to be performed in several collaborative research projects. These tests will give more details about the reproducibility and reliability of this method.

5 ACKNOWLEDGEMENTS

A part of the presented work and developments were supported by the Deutsche Forschungsgemeinschaft (DFG) via grant FOR384 and by the European Community in the frame of the project “Sustainable Bridges”. The help of the develogic company and especially Dr. F. Berning and Dipl.-Ing. M. Motz is appreciated. The authors are also grateful for the help of G. Bahr and M. Schmidt.

6 REFERENCES

[1] Carino, NJ., 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 (FMPA). 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] http://www.sustainablebridges.net

[11] Grosse, C. U.: 'Quantitative zerstörungsfreie Prüfung von Baustoffen mittels Schallemissionsanalyse und Ultraschall'. Ph.D. thesis, University of Stuttgart, 168 pp, 1996.

[12] Sansalone, M. J., Streett, W. B.: Impact-Echo. Bullbrier Press, Ithaca, 336 pp., 1997.

[13] 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.