

**DETECTION OF CRACKS IN REINFORCED CONCRETE -
AN INTRODUCTION TO THE PROBLEM WITH SOME
MEASUREMENTS**

**DIE DETEKTION VON RISSEN IN STAHLBETON -
EINFÜHRUNG IN DIE PROBLEMATIK MIT EINIGEN
MESSBEISPIELEN**

**DETECTION DE FISSURES DANS DU BETON ARME -
UNE INTRODUCTION DANS LES PROBLEMS AVEC
EXEMPLES DE MESURE**

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SUMMARY

Reviewing the state of the art in non-destructive technique the detection of cracks in concrete structures is an unsolved problem. The use of "classical" ultrasonic testing methods offers not a sufficient solution. Acoustic Emission Technique (AET) as an integral testing method is known as a good possibility to detect cracks in metal down to very small dimensions nondestructively. To enable the use of AET for concrete, an efficient instrumentation for data acquisition and a comprehensive signal analysis are some of the preconditions.

A measuring device on the basis of a multi-channel transient-recorder was developed at the FMPA; it meets the requirements and can be operated in the field. During a laboratory test series the wave propagation of the p-, s- and surface-waves in specimen out of concrete or reinforced concrete were investigated. Under field conditions we conducted preliminary tests to detect cracks in catching basins (chemical industry). In addition our method could be applied to other problems in building construction, like the testing of bridges and dams.

ZUSAMMENFASSUNG

Die Detektion von Rissen in Betonstrukturen ist ein weitgehend ungelöstes Problem. Wie die Vergangenheit zeigte, bereitet die Lösung dieses Problems mit den klassischen Untersuchungsmethoden (vor allem Ultraschall-Durchstrahlungstechnik) aus wellenphysikalischen Gründen große Schwierigkeiten. Die Schallemissionsanalyse als integrales Meßverfahren bietet dagegen eine gute Möglichkeit, Risse bis hinab zu kleinsten Größenordnungen zerstörungsfrei zu messen. Dies setzt jedoch eine sehr leistungsfähige Apparatur und eine umfangreiche Analyse der Meßsignale voraus.

An der FMPA wurde eine feldtaugliche Apparatur entwickelt, die auf der Grundlage eines Mehrkanal-Transientenrekorders die Anforderungen an die Meßtechnik erfüllt. In einer Reihe von Laborversuchen an Probekörpern aus Beton und Stahlbeton wurde die Wellenausbreitung von P-, S- und Oberflächenwellen im Beton untersucht. Außerdem wurden erste Tests unter Praxisbedingungen bei der Detektion von Rissen in Auffangwannen der chemischen Industrie durchgeführt. Weitere Anwendungsgebiete für dieses Meßverfahren sind die Untersuchung von Brückenbauwerken und Staumauern aus Beton.

RÉSUMÉ

La détection de fissures dans les constructions en béton constitue toujours un problème non résolu. Comme montre le passé la solution de ce problème à l'aide de méthodes classiques d'essai à ultra-son pose des difficultés. L'analyse à émission acoustique en tant que méthode de mesure intégrale offre une bonne possibilité de détecter des fissures même les plus petite sans détruire. Ceci demande pourtant un équipement effectif et une analyse globale des signaux de mesure.

FMPA a développé un équipement pour essais in situ qui à la base d'un multi-channel-transient-recorder correspond aux demandes de la technique de mesure. Dans une série d'essai en laboratoire sur des éprouvettes en béton et béton armé les phénomènes physiques de la propagation d'ondes P-, S- et ondes surface ont été investigés. En outre on a réalisé les premiers essais sous conditions pratiques pour la détection de fissures dans des bassins récepteurs de l'industrie chimique. Cete méthode de mesure peut être appliquée à d'autres domaines d'application comme p.ex. l'investigation de ponts et barrages en béton.

KEYWORDS: reinforced concrete; crack detection; acoustic emission technique; wave propagation.

1. INTRODUCTION

Today the non-destructive testing in civil engineering is usually done with methods, which do not have the same evidence compared to those in medical diagnostic or testing of metals. This statement is valid in particular for concrete structures and makes

oblique the operation at a frequency of 20 kHz to 200 kHz, due to the very heterogeneous composition of the material (cement, aggregates and in the most cases reinforcement). The corresponding wavelength is in the range of 2 to 20 cm and therefore direct ultrasonic techniques are not able to detect defects (e.g. flaws) with smaller dimensions.

Acoustic emission analysis offers in contrast a better possibility, because the cracks "produce" quasi their own signal and emit a wide range of frequencies including the required wavelength. On the other hand the high attenuation (10-20 dB/m) limits the detection range of the signals drastically. Some assumptions - by static calculations for instance - about the most critical areas are required to limit the number of detectors which are necessary for the experiment. Due to the inhomogeneities and the relatively long distance between source and receivers a comprehensive signal analysis and the development of a multi-channel instrumentation is necessary.

An interesting field of operation is given in the environmental protection. The storage of hazardous fluids in the chemical industry is usually done by big containers out of metal or plastic. There is an actual need of a secondary shield against leaking, what is normally done by catching basins out of reinforced concrete. In case of leaking of the primary containment the can should be impermeable for at least 72 hours (for more details please refer to the article by Aufrecht & Reinhardt in this volume). If the can is cracked, this requirement is not met. - Locating flaws at the bottom side of a concrete structure is not only a problem in environmental protection. This method would be also very helpful in construction engineering; for instance in the maintenance of bridges or dams, where fatigue cracks are a common problem.

2. PHYSICAL BACKGROUND

There was a lot of effort spent in the past to detect cracks in reinforced concrete. Most authors [1,2] used direct measurement techniques like ultrasound to record the

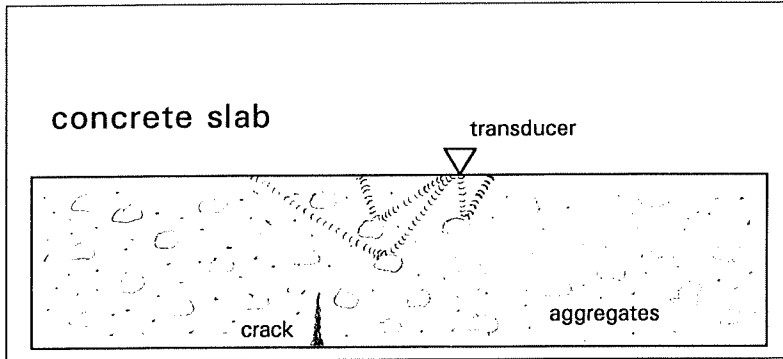


Fig. 1: Scattering of spherical waves at discontinuities (aggregates) in concrete. The waves are scattered before they reaches the crack.

dimensions of the cracks in a structure. But in contrast to measurements in steel, for example, it is only possible to detect inhomogeneities of several centimeters in concrete. The reason for this is the very heterogeneous and porous consistency of the material.

The main components of concrete are cement and aggregates; usually in the dimensions up to 16 or even 32 mm. In civil engineering steel bars are very often used to reinforce concrete. Together with the porosity of concrete (about 18% air bubbles) all those components, which have the same dimension as the aggregates, cause a high scattering and attenuation of any waves. On the other hand it is no solution to choose lower frequencies (what means higher wavelengths). If you want to detect a crack of some square centimeters and a width of only a few millimeters you should use a source, emitting waves with a wavelegh of about the same dimension.

Fig. 1 represents an example: if the aggregates are in the dimension of about 12 mm (about half an inch) and you use ultrasonic waves with an frequency of 1 MHz (standard in metal industry) the wave in concrete (with a P-velocity of about 4 km/s) will have a wavelength of only a few millimeters (a tenth of an inch). Depending on the

impedance contrast and the reflectivity of the inhomogeneities, the waves will be scattered before they reach the crack. In order to minimize the effect of scattering you have to choose frequencies in the kilohertz range. The ultrasound measuring techniques developed by Carino et al [1] as well as the one by Hillger [2] have not been able to detect defects of bigger size than the used wavelength, i.e. cracks of about 2-4 cm.

The consequence was in the past that methods were used, which were unable to detect defects smaller than a few centimeters, res. which were partly destructive or only in the position to detect surface cracks by visible methods. This and some other reasons (accessability, flexibility, effectiveness) forced us to investigate the possibility of using acoustic emission technology to detect cracks in concrete.

3. ACOUSTIC EMISSION

The AE method is used for the last 20 years in non-destructive testing. It relies on the detection of elastic waves generated by sudden deformation in stressed materials. Other NDT techniques (such as radiography, ultrasonics, eddy current) detect geometric discontinuities by beaming some form of energy into the structure under test. Acoustic emission is different: it detects microscopic movement and not geometric discontinuities. The growing defect makes its own signal, which travels as a spherical wave to the detecting sensors. Therefore it is not necessary to scan the hole structure, with this integral method you only need a couple of sensors to detect the defects.

In contrast to this cost saving and simplifying benefits there are some problems related to AE. To produce a stress field big enough for a stimulation of AE signals can be very difficult. Defects emit because they are associated with stress concentrations. Stress is also the agent that causes structural failure. So AE is intimately related to failure. Storage tanks and the surrounding structure (like catching basins) can be AE tested during routine filling with product. The stress field is excellently matched to the

service stress, so that defects growing in service will get just the right kind of stimulation. Very often the Kaiser effect is a handicap for this procedure. It states that structures will emit only when they are loaded above any previous maximum. This idea is based on the model, that on its first loading the material will undergo some plastic/permanent deformation; but afterwards the structure will behave elastically, not giving any more emission, until the load is taken higher. It was early shown that the Kaiser effect holds true very often, but not universally. Especially in concrete, deformation and emission can take place below previous maxima, if the period between two loadings is long enough. The testing of reinforced beams by Kapphan and Slowik [4] as well as examinations of plain concrete beams by Nielsen and Griffin [5] res. Hola et al. [6] showed that the Kaiser effect is only of temporary nature for concrete. This correlates with our experiences (see below). It seems that within a matter of hours concrete subjected to loading within its elastic limit recovers, and acoustical energy may again be released by reloading. Some characteristics - problems and benefits - of AE testing compared to other techniques are summarized in Table 1.

Tab.1: Comparison of some characteristics of the discussed testing methods; after Pollock [3].

Acoustic Emission	Most other techniques
requires stress	do not require stress
tests whole structure at once	scan local regions in sequence
detects active movement of defects	detect geometric forms of defects
is not immediately repeatable	are immediately repeatable
requires access only at sensors	require access to all regions
main problems: noise related;	main problems: geometry related

4. INSTRUMENTATION

Since the testing of a concrete structure is not immediately (or not at all) repeatable, the set-up for data acquisition is very important. Especially two problems caused difficulties in the past: for materials like concrete, where damping of the waves is very high, sensor spacing must be closer (than for metal i.e.) and source location is less economical; A/D-conversion and storing of the digital data to a disk must be very fast. With modern electronic we build up a measurement device, which is able to detect and record 80% of all AE signals at an emission rate of one hit per second. The most important characteristics of the equipment are the number of channels (which can record at the same time), the A/D-converting device (usually a transient-recorder) and the mass storage facility. The single components are described in the following chapters, where you can refer to Fig. 2 and 3.

4.1. Number of channels

From the start we concentrated our efforts to a precise location technique, because this is one of the best methods to discriminate between noise and acoustic emissions from a crack. In the past it was not possible or necessary to locate the recorded events. Reliability of a structure was estimated from the emission rate. For the most applications this gave only a qualitative impression of the material under test. Other authors [7] were restricted to a zonal (or linear) location of failures. As explained earlier the localization of AE sources in such a highly damping material like concrete is neither very easy nor economical. If a three dimensional localization is required, at least four sensors must have recorded the event in a good quality (arrival times). So we decided to configure our equipment with eight channels and the option to install additional channels (up to 32) later. In our opinion this ensures a good compromise between the size of the area which can be investigated and the amount of data which must be processed.

Fig. 2: Impression of the recording equipment developed at the FMFA. It contains the 8 channel transient-recorder (1), the preamplifiers (2), the notebook computer with a dock-in station (3) and an external monitor (4) and the Bernoulli-Box (5).

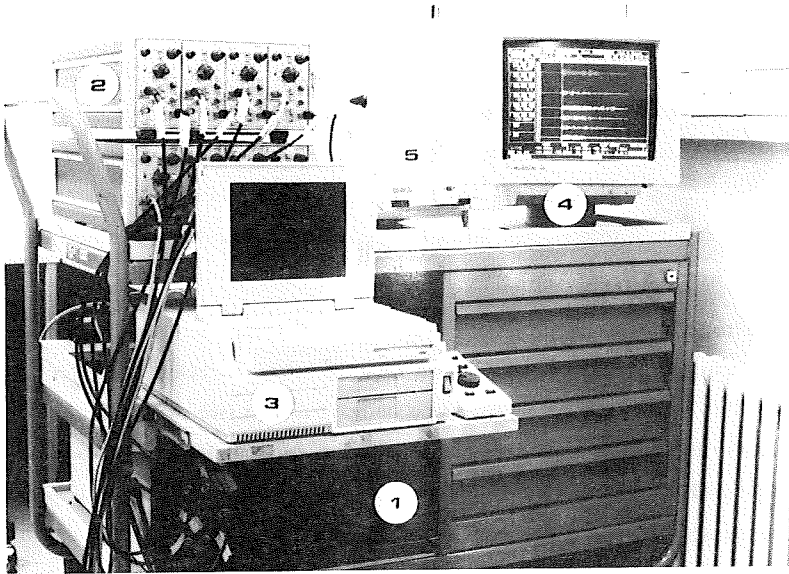
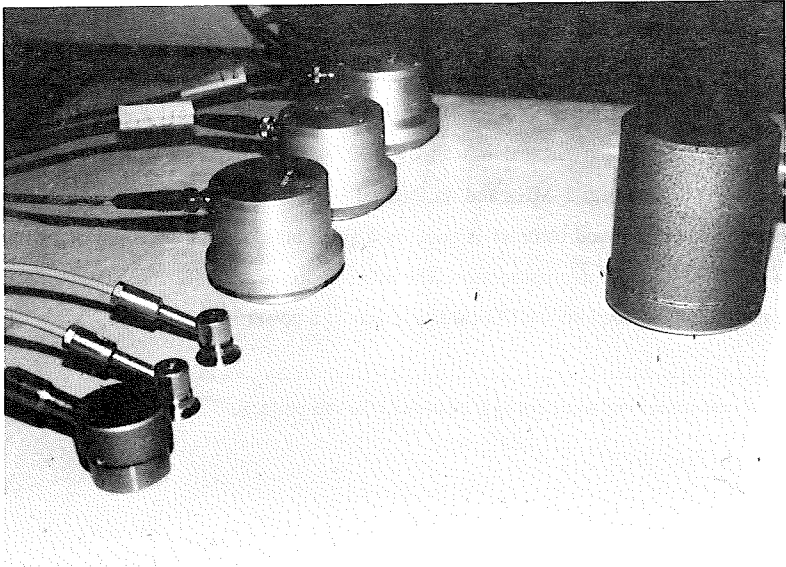


Fig. 3: The different sensors used during the experiments (the triaxial sensor is not shown) and the 20 KHz transducer.



4.2. Transient-Recorder (TR)

A typical AE system has a number of channels, measures the triggered signals on each channel and extracts a set of parameters describing these signals. The parameters (like arrival time, amplitude, rise time, duration, etc.) are stored to disk, while the original data will not be recorded. This procedure is recommended at tests of the most materials (metal, composites), because of their high emission rate: the number of AE events per second which are detected by the receivers exceeds the capabilities of the A/D-converter and the recording unit. Besides very often it is of more interest to get a high percentage of reduced data than a low percentage of data with the whole information.

It is a reasonable assumption, that the emission rate during the testing of concrete structures under working stress is - apart from the noise - far below one hit per second. This was checked during some tests on real buildings (see chap. 5.1). An AE-recording instrument must be configured in such a way, that it is possible to convert fast signals from at least 8 channels with a resolution of 12 bit and store them to a mass storage device. Because of Shannon's Theorem (aliasing effect) the sampling rate should not be less than one megahertz (what corresponds to ten times the maximum signal frequencies [8]).

To get a maximum of power and flexibility, we chose an eight-channel transient-recorder in form of a front-end instrument for the heart of our measuring device. The recorder is a simple mainframe of up to 16 channels; an extension of up to 32 channels is optional. Each channel has an own 12 bit-A/D-converter with a maximum sampling rate of up to 1 MHz and an internal storage facility of 256 KWords¹. The control of the front-end recorder is done by a small but powerful notebook PC based on an INTEL 386SX microprocessor. The interface to the recorder consists of a dock-station, which contains the I/O-cards and acts as a power supply.

¹ A time consuming multiplexing is inadequate for this problem.

4.3. Storing of data

According to our tests the maximum length of the signals is between 2 and 4 milliseconds. Every data point represents one word (16 bit) in digital units, so that a signal can have between two and four KByte at a sampling frequency of 1 MHz. An event, recorded at eight channels, will then produce 32 KByte in maximum. It is easy to calculate that a continuous registration of 15 minutes is equivalent to 28 MByte; respectively, that in the same time 900 events (assuming an emission rate of 1 event per second) can be recorded. During our experiments it was shown that not more than 10% of the events are of interest (AE signals). With an intelligent trigger algorithm it should be possible to reduce the number of recorded events and to extend the period of observation.

For the storage of the data we are using Bernoulli technique: a transportable subsystem with removable disks of a capacity of 44 MByte connected over an ordinary parallel interface to the dock-in station. The main data processing can be done with the host computer. This system offers a maximum of flexibility and a high transfer rate.

5. MEASUREMENTS IN CONCRETE

Reviewing the last chapter the conclusion must be drawn, that the selection of the equipment and the set-up for the test is one of the most important things; with a well designed apparatus, the recording of acoustic emissions in concrete should be very effective in principle. Our intention was therefore to test first the possibility of crack recording at a concrete structure in the field. This was done at a catching basin out of reinforced concrete during routine loading. With the experience that we've got during this test series, we combined the equipment and built up a measuring device, which met our requirements. With this newly developed device we are conducting now an extensive test series in our laboratory to get more experience in measurements of ultrasonic waves in concrete.

5.1. Testing of a concrete can

A number of scientists carried out experiments with concrete specimen by using AE-technique in the laboratory. Due to technical difficulties not the same attention was paid to measurements of AE in buildings. To our knowledge no investigations were carried out in the field. Therefore a number of questions must have been answered, before the development of a new apparatus was justified:

- is the noise level too high to record AE's?
- does the Kaiser effect allow to apply AE techniques in general?
- how big is the attenuation in reinforced concrete structures and how many sensors are necessary to test the important parts of the structure?
- do the AE waves follow geophysical principles?
- emission rate - how many events per second (including noise and AE)?

Of course the problem of stressing the structure is always a serious problem too. At the end of march 1991 we have got the permission to conduct a test series at a big chemical factory. We selected a ten years old catching basin of a dimension of 11 to 25 m out of reinforced concrete (no gaps). Fig. 4 gives an impression of the can, which contains one 250 m³ tank filled with Butyraldehyd². As a matter of routine the tank is filled up to a level of 1/2 to 2/3 of the maximum. During our tests 23 tons have been pumped into the tank up to a maximum level of about 170 tons (90% loaded). We used this opportunity not only to test the method but also to test the equipment. For the duration of the experiment we had at our disposal a set of various sensors (broad-band and resonant), different preamplifiers, various transient recorders, a digital oscilloscope and a magnetic tape recorder. The piezoelectric sensors have been placed in the vicinity ($\Delta = 1$ m, see Fig. 4a) of the tank, where cracks are expected due to statical calculations. They were mounted with ordinary gypsum. About 200 events have been recorded during and immediately after the filling of the tank - the trigger level was put to 10-40 mV ("OR"-trigger).

² The other two tanks are planned but not yet finished.

Fig. 4: Catching basin out of reinforced concrete in the dimension of 11 x 25 m.
 Only the tank to the right is finished; it contains up to 250 m³ Butyraldehyd.

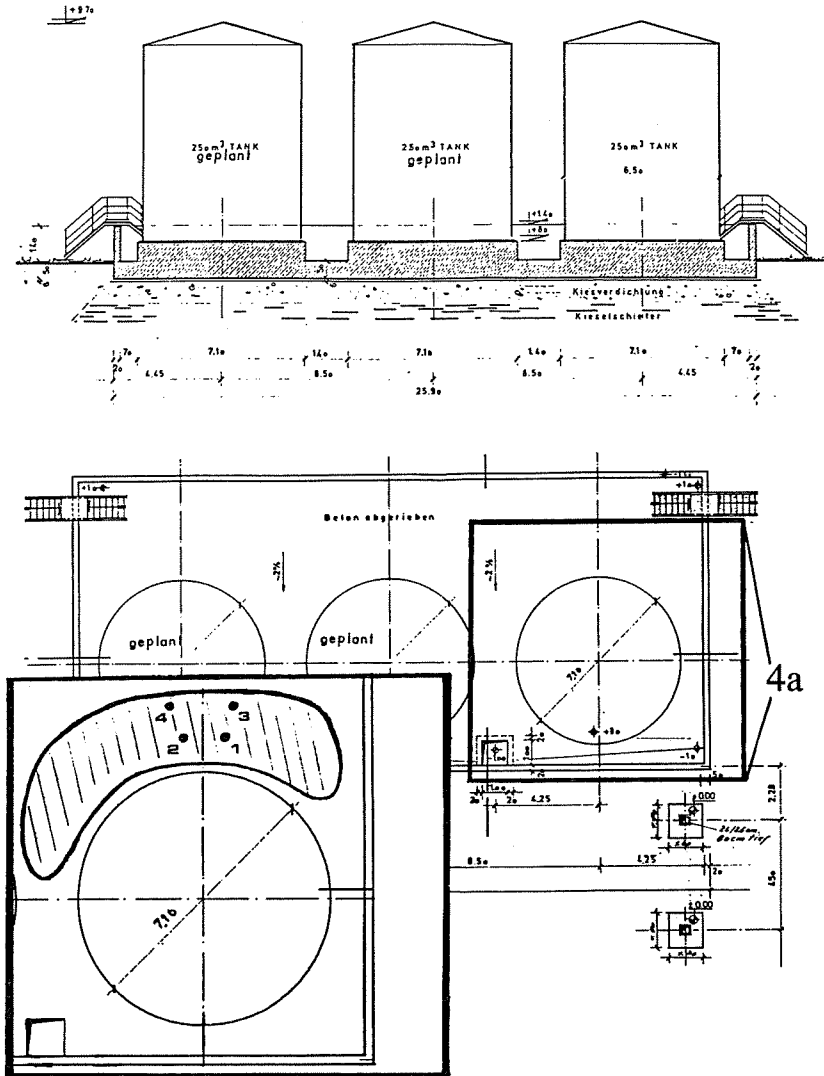


Fig. 4a: Location of the sensors. The area with the highest degree of probability for cracks is dashed.

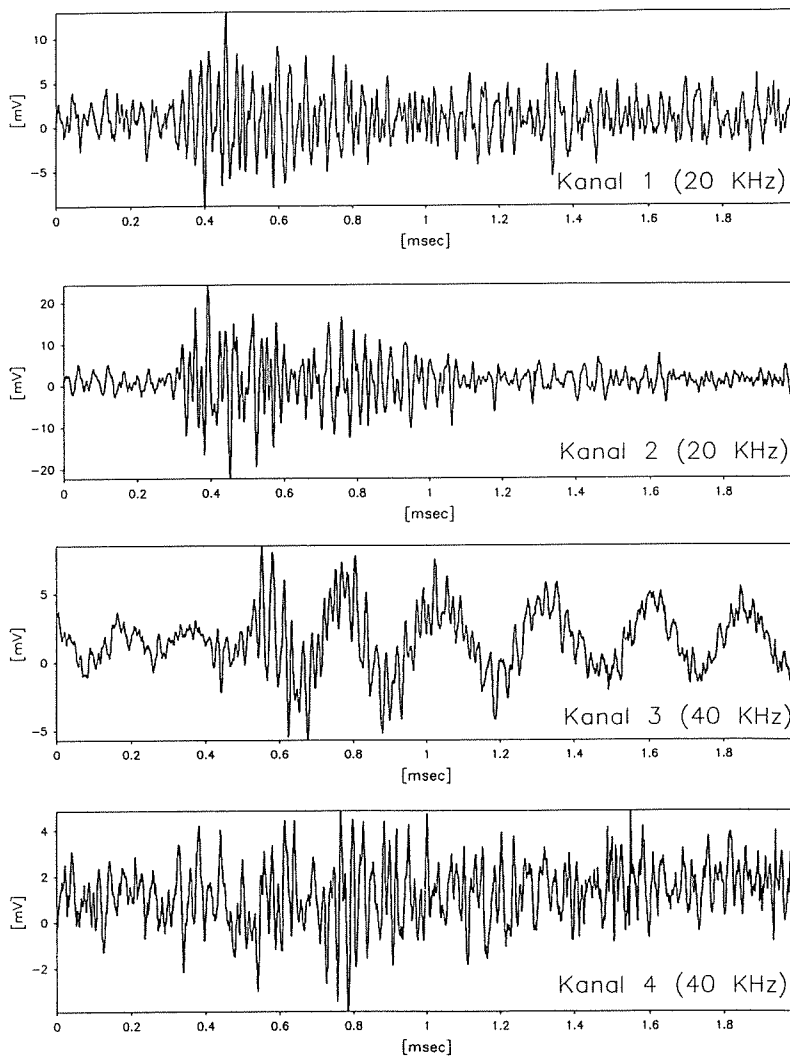
An event rate of about one per second was recorded i.a. during some blasts of wind. I suppose that the wind caused a change of the stress-field, which produced an increase of AE activity. Almost 20 events were processable and showed a coincidence, i.e. that a signal was recorded at all sensors. An example of such a recording is represented in Fig. 5. To enable a better compatibility the traces of only four similar sensors of the resonant type (channel 1+2: 20 KHz; channel 3+4: 40 KHz) are shown. Obviously the noise level is very different at the sensors. One reason may be that the coupling was probably not perfect; it is also possible that the different position to the pump (which filled the tank) had a various influence. However, the problem of noise is a serious problem especially in event discrimination and source location. The waves are following geophysical principles, i.e. that all common methods of improving the signal to noise ratio can be applied. The simplest (but nevertheless a very effective) method is the band filtering of a time series. The filtering relies on the experience that a signal can have a better S/N-ratio at a certain frequency range. An example is shown in Fig. 6, which represents the same signals as Fig. 5. The first graph (a) shows the Fast Hardley Transformation (FHT³) of the complete channel-1-signal (c); diagram (b) figures the applied bandpass-filter. We compose the filters with a butterworth lowpass and a highpass; both of the tenth order and cascaded. We are also using forward-backward filter techniques to avoid phase reversals [8]. The following diagrams (c) - (f) represent the filtered signals - an improved S/N-ratio is the result. To apply more sophisticated techniques like beamforming or azimuth velocity analysis [9] the number of recording channels must be increased. Our newly developed apparatus will have at least eight channels so that those techniques can be applied in future. The S/N-ratio shown in Figure 6 is not as good as it will allow the discrimination of the single wavetyps and their arrival times (what is a presupposition for localization techniques). Another way is the reduction of noise, generated during the experiment.

³ Nonlinearities were not yet observed.

⁴ The Fast Hardley Transformation is equivalent to a Fast Fourier Transformation (FFT) but faster.

Fig. 5: Example of a recording during the AE experiment at a catching basin.

EMPA



It should be mentioned, that the discovering of the noise sources is generally a very difficult and time consuming problem. These very first measurements should only have proven the method in principle. Under the assumption that the measured events are produced by cracks in the catching basin, the test showed, that the noise level is not too high to record AE signals in a field structure and that the Kaiser effect is of limited value for concrete.

Some other tests have been conducted during this experiment to determine the wave velocities in concrete, the attenuation, the noise spectrum and the eigen-frequencies of the can. The results were verified by measurements at a specimen in the laboratory and are summarized in the next chapter. Also a lot of experiments were set up to compare the equipment at our disposal. These experiences led to the configuration of our measuring device described in chapter 4.

5.2 Laboratory tests

After the development of the measuring device we started to conduct an extensive test series, which is not completely finished until now, in our laboratory. We have concreted a number of specimens with different size and consistency to study the wave propagation in plain and reinforced concrete. Fig. 7 shows a first impression of the results. We fixed seven sensors of various type (20 KHz, 40 KHz, broadband, s-wave, tri-axial) at the upper side of a reinforced concrete slab (dimensions: 30x80x150 cm) as can be seen in Fig. 3. An ultrasound pulse generator (20 KHz) was attached at the lower side, so that the signal had to travel through the concrete. The signals are not filtered, but the amplification was varied according to the source/receiver distance and the different sensitivities of the sensors.

The seismograms are drawn proportional to the original spacing (20 cm) of the sensors. It is very good to see how the different waves are running apart. At the first few sensors ($\Delta = 30$ cm) it is not possible to discriminate between spherical- and surface

Fig. 6: Filtered seismograms of the same event shown in Fig. 5. Diagram (b) figures the bandpass-filter, which is composed of a lowpass and a highpass filter.

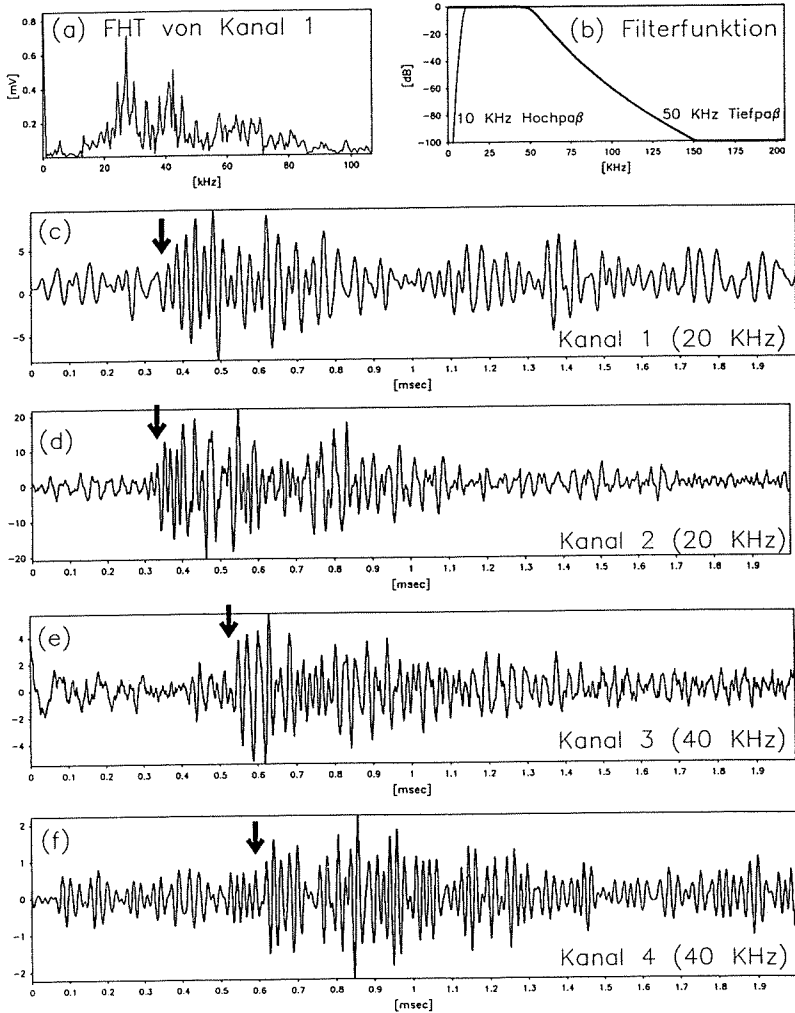
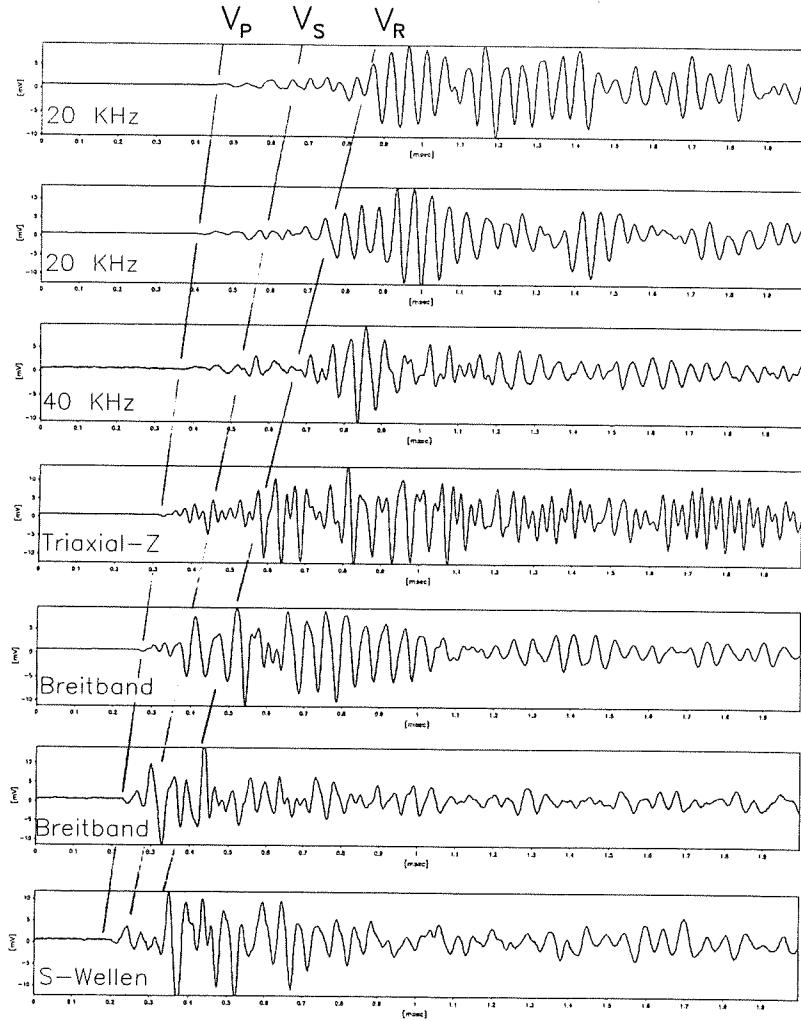


Fig. 7: US-pulse (20 KHz) recorded by seven sensors fixed at the upper side of a concrete slab.



waves. At the last sensors ($\Delta = 1.50$ m) the compression waves, the shear waves and the surface waves are clearly to separate. In all seismograms the surface waves are represented by the waves with the highest amplitudes. The arrival times of the waves are indicated with dotted lines.

With the known distance between the sensors it is possible to calculate the wave velocities. We have found the following values:

- v_P : 3800 - 4200 m/s (P-wave velocity)
- v_S : 1900 - 2300 m/s (S-wave velocity)
- v_R : 1700 - 2000 m/s (calculated surface-wave velocity; $0.9 \cdot v_S$)

The variation of the measurements depends on the influence of the reinforcement. An error can occur also at the stations with resonant piezoelectric sensors, which are very sensitive but therefore not well damped. A single delta-pulse will be transformed to a broaden signal and the arrival times are less exact to pick.

After a calibration (mounting) of the sensors also the attenuation was calculated. We've found a damping rate, which is dependend on the consistency of the concrete (reinforcement) and had a value between 10 and 20 dB/m. - A lot of measurements have been conducted with different sources and sensor settings. According to our experiences the best results can be achieved by using sensors with a resonant frequency of 20 KHz. The problems with the attenuation and reflections of the waves are still under investigation and the results of the whole experiments will be reported later.

6. CONCLUSIONS

It was showed that the acoustic emission technology offers a valuable tool in the detection of cracks in reinforced concrete. But especially the problem of source location needs still a lot of investigation. We have built up a very powerful and sophisticated

⁵ The phase and group velocity of the surface waves are frequency dependent.

apparatus with the aim to enhance the data basis for the signal analysis. We will now extend our software to improve the signal to noise ratio and to discriminate the different waves in the seismograms. This will be the fundament for source location and classification.

We are planning to write a beamforming program under the use of the delay and sum method. It depends on the quality of the seismograms whether a momentum analysis (fault plane solution) can be applied or not. The most important aim will be the creation of an automatic localization algorithm. Parallel we will continue with our laboratory tests and conduct some experiments in the field at catching basins, bridges and other buildings.

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