ACOUSTIC EMISSION ANALYSIS APPLIED TO CONCRETE UNDER DIFFERENT LOADING CONDITIONS

ANWENDUNG DER SCHALLEMISSIONSANALYSE AUF BETON UNTER VERSCHIEDENEN LASTSZENARIEN

APPLICATION DE L'ANALYSE D'EMISSIONS ACOUSTIQUES SUR DU BETON SOUMIS A DIFFERENTES CHARGES

Bernd Weiler, Shilang Xu, Utz Mayer

SUMMARY

Acoustic emission is a nondestructive testing technique that is applied frequently to materials like metals or compounds. Due to the complicated structure of the material, its application to concrete is not yet well established. Over the last years, many acoustic emission tests on concrete were carried out at the FMPA. Concrete behaviour was studied on test specimens of various geometries under different loading conditions. The results presented in this report show the suitability, but also the limits of this method.

ZUSAMMENFASSUNG

Die Schallemissionsanalyse ist eine zerstörungsfreie Prüfmethode, die häufig an Materialien wie Metallen oder Verbundwerkstoffen Anwendung findet. Aufgrund der komplexen Struktur von Beton hat sich das Verfahren bei diesem Werkstoff noch nicht durchgesetzt. In den letzten Jahren wurden an der FMPA zahlreiche Schallemissions-Versuche an Beton durchgeführt. Sein Verhalten wurde an verschiedenen Probekörpergeometrien unter unterschiedlichen Lastszenarien untersucht. Die in diesem Bericht vorgestellten Ergebnisse zeigen die Eignung dieses Verfahrens, aber auch seine Grenzen.

RESUME

L'analyse des émissions acoustiques est une méthode non destructive souvent appliquée à des matériaux comme les métaux et les matériaux composites. A cause de la structure complexe du béton, cette méthode n'y est appliquée que très rarement. Au courant de ces dernières années, de nombreux essais d'émission acoustique sur du béton ont été réalisées à la FMPA. Le comportement du béton a été étudié sur des éprouvettes de différentes géométries soumises à différentes charges. Les résultats présentés dans ce rapport montrent les possibilités, mais également les limites de cette méthode.

KEYWORDS: acoustic emission, concrete, uniaxial tension, bending, compression

1. INTRODUCTION

When materials or structures are subjected to a load, a part of the deformation energy can be released as elastic waves. These acoustic emissions were first observed in metals ("crying of tin"), but it was soon discovered to be a general phenomenon. This led to a new non-destructive testing method, the so-called acoustic emission analysis. Although its results were often called into question, the method has developed with respect to instrumentation and evaluation, as well as with respect to its application to different research and test topics and different materials.

Over the years, the evaluation changed from simply counting the acoustic emission events, to the extraction of signal parameters like rise time or energy [ROGERS, TSCHELIESNIG, 1996]. Later, the use of several transducers enabled a localization of the event origin. A last step was made by the application of evaluation algorithms coming from geophysics. Thus, source parameters such as crack type, orientation and energy could be inverted. Examples for these advanced acoustic emission techniques can be found in [ONO (ED.), 1996]. A precondition for this progress was the improvement of the recording system, starting with an analogous oscilloscope and ending with a multi-channel high-frequency transient recorder with high processing and storing capability. Most important for that was the development in microelectronics and microcomputers. But also the contribution of transducer manufacturers concerning high sensitivity broadband accelerometers should not be neglected.

But not only evaluation and instrumentation made great progress, also the applicability of this technique was improved. At first, being limited to defect location in mechanically loaded metals, the method has conquered a field of applications on a wide range of materials. This starts with laboratory tests studying scientific questions on new materials and ends up with in-situ routine testing of structures, function monitoring, and quality assurance in industry. The materials range from metals and alloys to ceramics, plastics and compound materials such as metal matrix composites, fibre reinforced ceramics, glass-fibre-epoxy, laminates, and fibre reinforced plastics. A good survey on various applications can be found in journals like [NDT & E, 1997]. Quite new is the application of the acoustic emission analysis to concrete. Concrete differs from the above mentioned materials by its inhomogeneity, its high attenuation, and the large dimensions of the structures created with it. However, acoustic emission can successfully be used to answer a number of questions referring to the behaviour of concrete under load.

2. EVALUATION BASES

The precondition for a quantitative acoustic emission analysis is the registration of the whole signal waveforms. On-line, these data can be processed in terms of a qualitative analysis and, in case of a sufficient data quality, in terms of an additional fast localization of the events, which is the first step of a quantitative evaluation. Nowadays, these features are implemented in most of the commercial acoustic emission equipments. However, high-end research applications, often with a poor database, usually require self-developed off-line processing procedures.

Due to the inhomogeneity of concrete and the resulting bad quality of data, acoustic emission analysis on this material mainly has to be performed off-line. Even the localization of hypocenters becomes a difficult task and therefore is part of the postprocessing.

2.1 Source localization

As already stated, the evaluation of acoustic emission tests with respect to source location is nothing new. This problem was solved long before in geophysics. Even the exact algorithm used in this work was described early in this century [GEIGER, L., 1910]. Nevertheless, it seems useful at this point to deal with the basics in order to give an insight also for readers that are not familiar with this problem.

During the formation of a crack, a part of the energy is emitted as an elastic wave propagating spherically from the crack location and reaching the acoustic emission transducers at the specimen surface. The crucial point for the localization is the determination of the arrival times of the compressional waves at each transducer, the so-called ”picking” of these times. A data set with a good signal-to-noise ratio of an 8-channel acoustic emission recording on concrete under compressive load is displayed in fig. 1. In this example, the arrival times are clearly detectable and marked with an arrow.

For the present work, all the picking was done semi-manually. Due to the usually poor data quality and the different frequency contents of the signals, standard automatic pickers fail. Nevertheless, work on a automatic picker allowing manual control over the procedure is in progress at the FMPA.

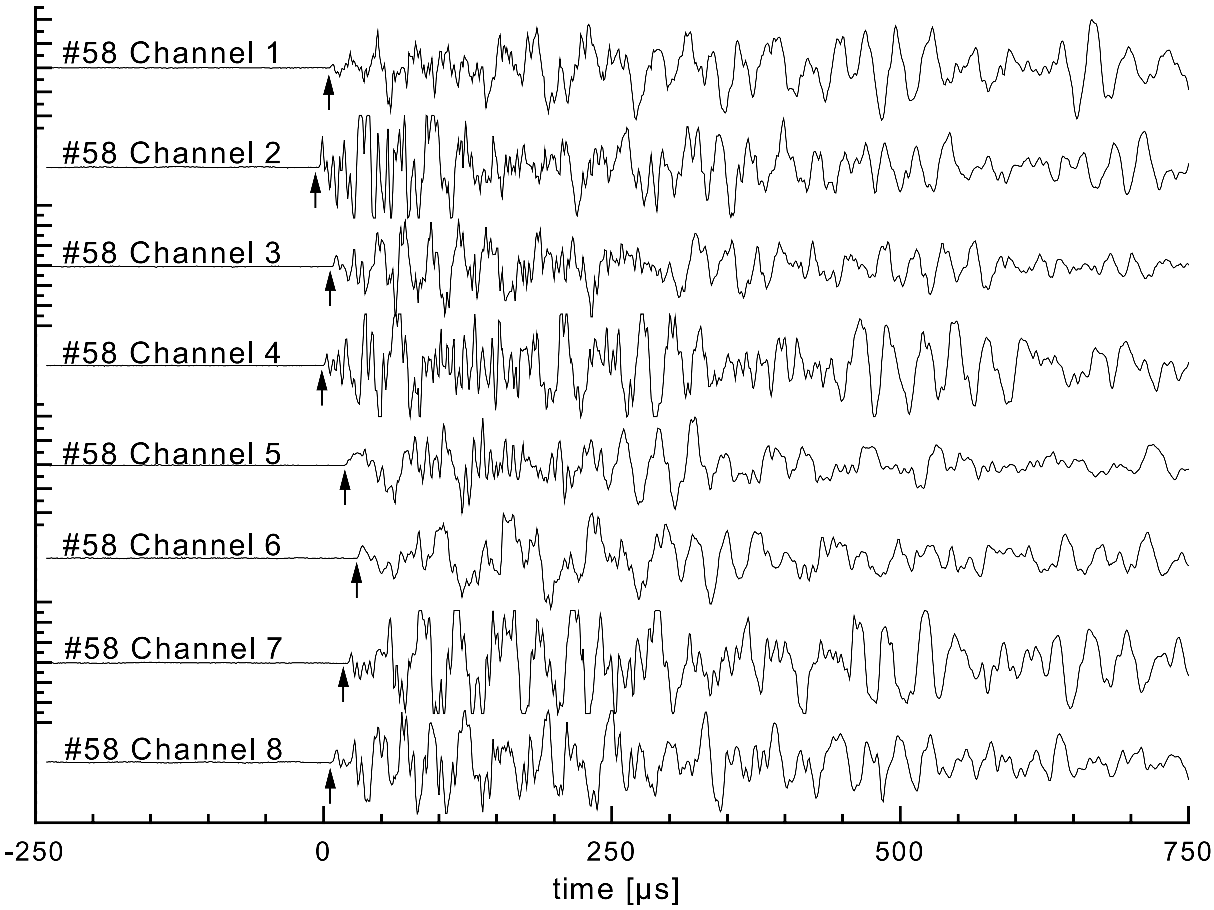

Fig. 1: *8-channel acoustic emission recording on concrete; the arrival times are marked with an arrow.*

The arrival times being picked, the next step is the calculation of the event locations. Since there are 4 unknown parameters of the event (three location coordinates and the origin time), for a 3-dimensional localization at least 4 transducers with identifiable arrival times are required. If there are more transducers available, the resulting equation system is overdetermined and has to be solved by an iteration.

With respect to the transducer with the first arrival t_0, the other arrival times t_i can be used as relative arrival times Δt_{0i}. They are related to the distances d_i between each transducer location and the event location by the compressional wave velocity v_P as follows:

$$\Delta t_{0i} = \frac{d_i - d_0}{v_P}$$

where

$$d_i = \sqrt{(x_i - x_e)^2 + (y_i - y_e)^2 + (z_i - z_e)^2}$$

As the event coordinates (x_e, y_e, z_e,) are unknown, any algorithm has to start with estimated values, for example the centre of the specimen. When the sum of all error squares of the relative arrival times for all transducers

$$F(x_e, y_e, z_e) = \sum_{i=2 \ldots k} \left(\frac{d_i - d_0}{v_P} - \Delta t_{0i} \right)^2$$

becomes minimal, the best calculation for the event locations is reached. This calculations are usually performed using a least square algorithm.

2.2 Localization accuracy

A value for the accuracy of the localization is given in the remaining error of each event coordinate after the iteration. Usually, errors of below 5 mm are achieved for the following tests with the above mentioned algorithm. More information about the picking quality gives the residuum of calculated and manually picked arrival time, which should reach below 1 µs. Of course, this value is directly connected to the maximum sampling rate of 1 MHz of the experimental equipment. But also other test conditions play an important role for the accuracy besides the iteration accuracy: The wave velocity used for the calculations, the symmetry of the transducer arrangement, the covering of the herd sphere, the homogeneity of concrete, the coupling of the transducers, and so on. Additional tests with simulated emissions on a test cube indicated, that a reasonable value for the localization accuracy under the present test conditions and with the present specimen dimensions is about 10 mm. This has to be considered for the interpretation of the test results.

3. EXPERIMENTAL

The acoustic emission measuring equipment used for the following tests is based on a 12-channel transient recorder with sampling rates of up to 10 MHz. Its vertical resolution is 12 bit, and the triggers of the channels can be linked logically. A highly linear preamplifier was used to condition the signals coming from up to 12 sensors with significant sensitivity over a broad frequency range. Usually, a high pass filter was applied to suppress environmental and machine noise; the trigger condition was a very high slewrate. All is described in more detail in [GROSSE, 1996].

4. TESTS, RESULTS AND DISCUSSION

4.1 Three-point bending tests on fibre-reinforced beams

The first of the test series, which is still in progress, is part of a collaborative research project aiming on the “characterization of the damage progress in fibre reinforced materials by means of nondestructive testing“. Fibre reinforced concrete is an advanced material with a brittle concrete matrix, and, in the present case, a ductile steel fibre reinforcement. Due to the complexity of the material, there are not many techniques capable of detecting voids and cracks. Acoustic emission finally is the only method to monitor the progress of damage, since the signals are produced by the damage itself. As a realistic loading condition, three-point bending tests were chosen, providing a compression zone as well as a tension zone in the middle of the specimen. Such a localized damage zone is also very advantageous for the acoustic emission measurements. The specimens were notched concrete beams 0.15 m x 0.15 m x 0.7 m with different percentages of Dramix ZC 60/.80 steel fibres. They were tested in a Schenck 100 kN testing machine at constant rail speed.

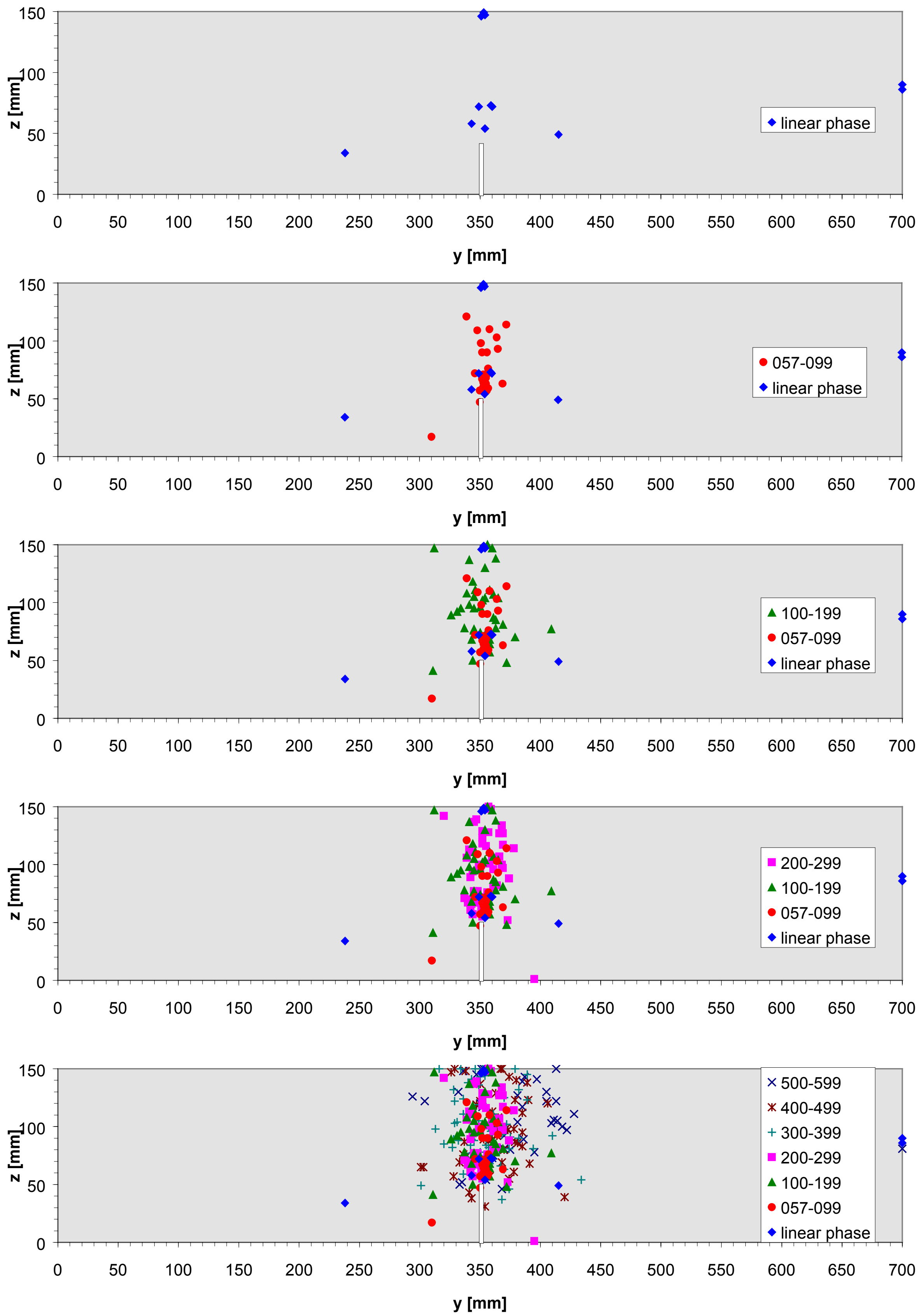

Fig. 2: *Sequence of acoustic emission event locations of a 3-point bending test on a steel fibre reinforced concrete beam with 1.0 % fibres at different stages of the test.*

In a sequence, figure 2 shows the damage accumulation in one of these specimens. In the initial phase with a linear load-deformation behaviour of the specimen, only a few events in the notched area can be found, indicating the beginning of damage in this area. The other events at the top and at the end of the specimen result from the pressing of the rail at the beginning of the test, and from a source transducer fixed at the end of the beam for ultrasonic through-transmission measurements. After the linear phase, the acoustic emission activity spreads conically away from the notch tip (line 2 of fig. 2), but the damage zone still is rather narrow. With increasing test time and the activation of the fibres as crack-bridging elements, the zone becomes wider (line 3 and 4 of fig. 2). It reaches its maximum extension after passing the load maximum (last line of fig. 2), when the randomly distributed fibres get hooked with each other.

Apart from this evolution of damage observed during a single test, tests on beams with different percentages of steel fibres reveal other interesting effects (see fig. 3). First, more events than in the previous test are recorded during the linear phase. Second, the movement of the active damage zone up and away from the notch is much more clear than at higher fibre percentages. Finally, the damage remains much more concentrated in the middle of the beam. All these statements seem convincing, as they meet the experience.

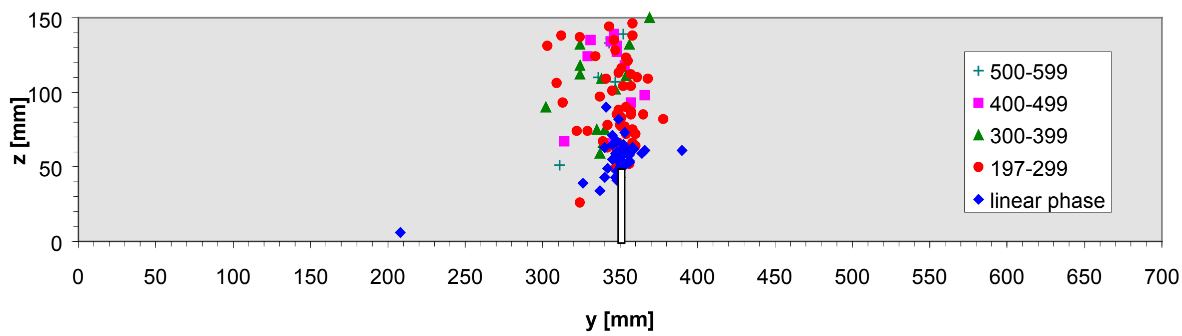

Fig. 3: *Complete acoustic emission event locations of a 3-point bending test on steel fibre reinforced concrete with a low content of fibres (0.5 %).*

Further tests on beams reinforced different types of fibres concerning fibre dimensions and fibre geometry are still in progress.

4.2 Axial tension tests on reinforced concrete columns

Another series of tests was performed within the framework of a research project on the plastic deformation capacity of reinforced and prestressed concrete structures in the ultimate limit state [ELIGEHAUSEN, MAYER, 1997]. One of the main factors of the deformation capacity is the contribution of concrete (tension stiffening) between the cracks after yielding of the reinforcement. This interaction of the embedded reinforcement with the concrete is essential for a reliable and realistic model that should serve as materials law for nonlinear calculations of structures under the above mentioned conditions. The model should be developed basing on tests of specimens loaded in axial tension with different degrees of reinforcement and different concrete strengths. Some tests were accompanied by acoustic emission measurements.

Below, the results of a test on a specimen of 2.50 m of length with a cross-section of 0.3 m x 0.3 m are presented. The concrete was a B 25, reinforced with 8 bars of 12 mm diameter and 8/25 cm stirrups (reinforcement ratio 1.0 %). The specimen was tested deformation-controlled in a 5 MN AMSLER test machine. It reached yield and failure strengths of 511 kN and 555 kN, respectively. Two acoustic emission transducers were mounted on each side of the specimen 10 cm or 15 cm above and below the middle plane, at 7 cm from the edges. By chance, the first visible crack occurred in this middle plane. As the transducers were arranged around this plane, this meant optimal conditions for the acoustic emission measurements. Nevertheless, the data quality was fairly poor. The dimensions of the specimen were rather large, hence the attenuation strong and the acoustic emission equipment not optimized for such conditions. Resonant transducers, for instance, would have increased considerably the sensitivity of the measurements. Another negative aspect was the immense noise produced by the huge testing machine.

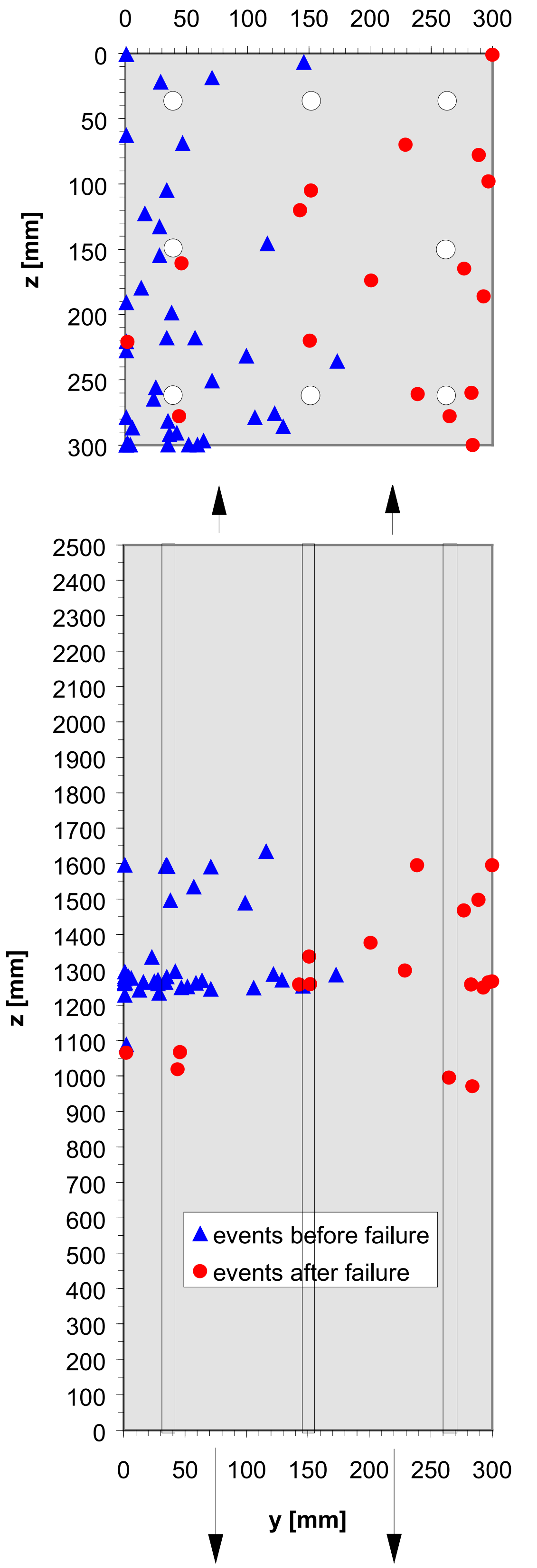

Fig. 4: *Acoustic emission event locations on a reinforced (O)concrete specimen under axial tension*

Altogether, 242 signals were recorded. A quarter of them were either noise or machine vibrations. In the end, 60 could undoubtedly be localized as acoustic emissions.

The event locations exhibit a concentration in the middle plane on the left hand side of the specimen, especially before matrix failure (triangles). This corresponds with the first visible crack in this area. Later (spheres), also in planes above and below acoustic emissions are recorded. Experience shows that cracks occur preferentially at the positions of the stirrups, which is confirmed by these event locations and also by visible inspection. Although later cracks appeared at larger distances from the specimen's middle plane, namely at the positions of other stirrups, no acoustic emissions from these areas were detected. This seems to be an effect of long distances and high attenuation.

Finally, a detailed analysis of the locations leads one to suppose that the crack initiation takes place inside the specimen around the reinforcing bars. This could also be derived from the shape of the stress trajectories.

4.3 Compressional tests on plain concrete specimens

A third test series was carried out on double notched plates under compressional load. This setup was chosen in order to create mode II cracks. Since mode I crack propagation is considered to be the most important reason for failure in engineering structures, this phenomenon is well understood. As a sum of all the investigations, standard methods for the determination of values such as fracture toughness or fracture energy for a wide range of materials were developed.

Compared to that, investigations on mode II (shear) fracture have been neglected for many years. Nevertheless, mixed mode patterns as well as shear fracture often appears, especially in complex structures under complex loading states. To observe pure mode II cracks in concrete, the following tests were carried out. The acoustic emission technique is capable not only to define the crack location, but also to determine the crack mode and its orientation [WEIHE ET AL., 1997]. Yet, the present results are confined to the evaluation with respect to the localization only.

As can be seen in figure 5, the specimen had a length of 0.4 m, a cross-section of 0.2 m x 0.1 m, and two 20 mm deep notches in the middle of the long sides. This type of specimen was proposed earlier by one of the authors [XU, REINHARDT, GAPPOEV, 1996]. One half of the specimen was loaded uniformly in compression. In order to reduce machine noise to a minimum, a self-designed testing machine with a hand-driven hydraulic cylinder of 1000 kN capacity was used. Eight acoustic emission transducers were fixed on the specimen to cover all sides. At 500 kN of load, enough acoustic emission signals and some visible cracks were obtained, so the test was stopped.

More than 500 signals, as expected with very low amplitudes, but of a good quality, were recorded. Most of them could be identified as acoustic emissions, and 65 % clearly could be localized.

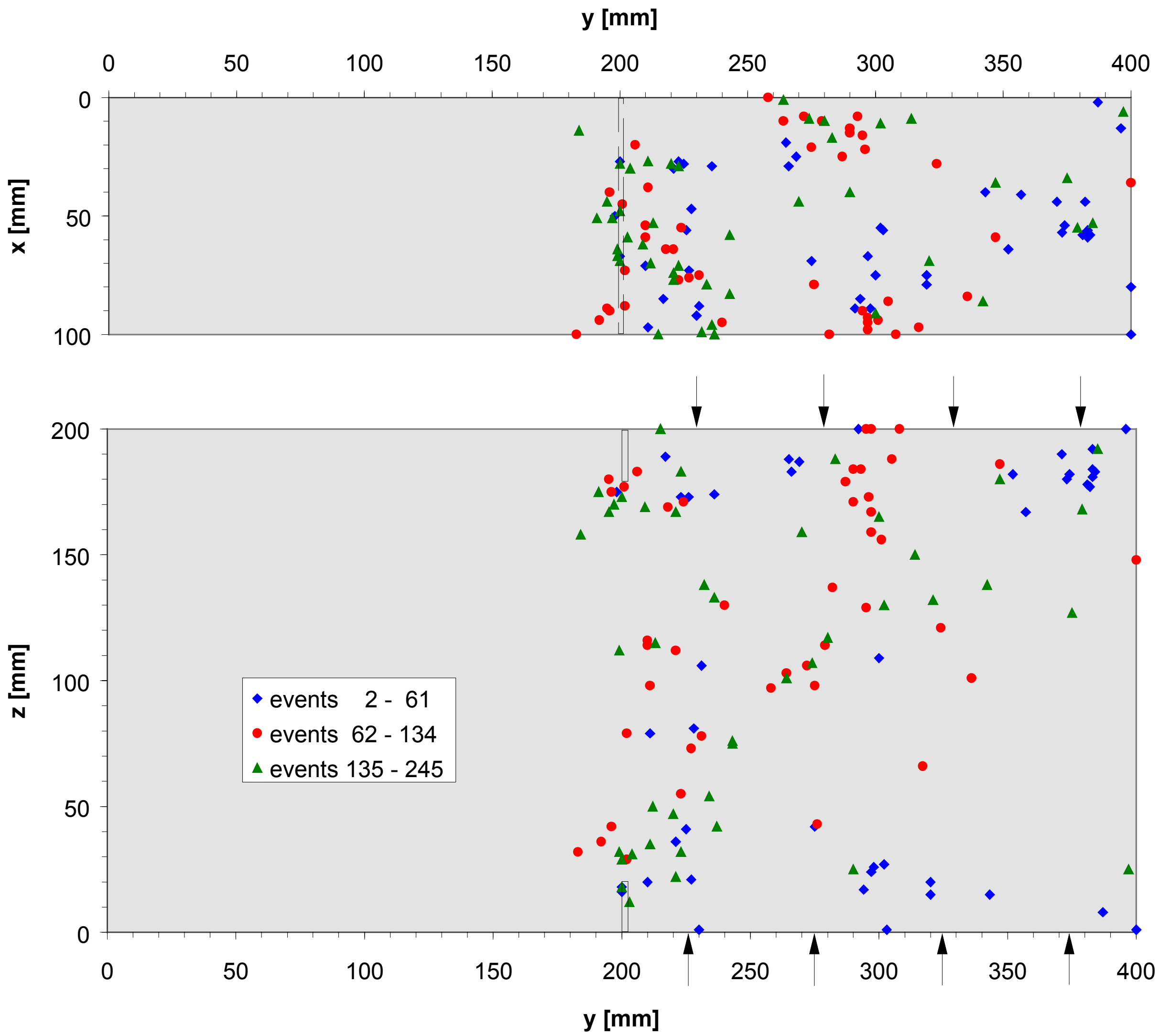

Fig. 5: *Event locations of a compression test on a notched specimen of plain concrete*

First, most of the event locations are concentrated in the compression zone (diamonds in fig. 5). These cracks later became visible as macrocracks parallel to the load direction (z-coordinate). Cracks at the tips of the notches already occur at the end of this phase. At later times, this area becomes predominant for the acoustic emission activity (spheres and triangles), whereas several emissions from the upper compression zone indicate the formation of macro cracks in this area. Further evaluation with the moment tensor inversion will reveal, whether the events at the notch tips are pure mode II cracks or not, and how they can be distinguished from the other cracks of the compression zone.

5. CONCLUSIONS

In all the applications of the acoustic emission analysis to concrete that are presented here, very encouraging results were obtained. In spite of the difficulties due to the complex material, the adaptation of equipment and evaluation techniques was rather good.

An important factor for the quality of the measurements turned out to be the positioning of the transducers with respect to the expected event locations. Even if the events are well surrounded by the transducers, asymmetries their arrangement can lead to errors in the localization. For events far away from the area with the transducers, the errors become grave, and for very large specimens events at large distances are almost undetectable. Another important factor is the choice of a suitable trigger condition to suppress machine noise an specimen vibrations.

Still, acoustic emission analysis on concrete are far away from a routine application, but it has proved to be a valuable tool for laboratory tests and scientific investigations. The progressive automation of the method will increase considerably its applicability and acceptance.

ACKNOWLEDGEMENTS

The authors appreciate the assistance of their technicians Mr. Guenther Schmidt and Mr. Eugen Lindenmaier. Parts of this work were funded by the Deutsche Forschungsgemeinschaft (DFG) in part A6 of the special research program SFB 381 "Charakterisierung des Schädigungsverlaufes in Faserverbundwerkstoffen mittels zerstörungsfreier Prüfung" and in the DFG research project EL 72/8-1 “Mitwirkung des Betons zwischen den Rissen ...“

REFERENCES

ELIGEHAUSEN, R.; MAYER, U. (1997): *Parameterstudie zur Mitwirkung des Betons unter Kurzzeitbelastung (Parametric study on the contribution of concrete between cracks under short-term loading)*. Research report, Institut für Werkstoffe im Bauwesen, Universität Stuttgart

GEIGER, L. (1910): *Herdbestimmung bei Erdbeben aus den Ankunftszeiten,* Nachr. v. d. Königl. Ges. d. Wissensch. zu Göttingen, Vol. 4, 331-349

GROSSE, C. U. (1996): *Quantitative zerstörungsfreie Prüfung von Baustoffen mittels Schallemissionsanalyse und Ultraschall.* Doctoral Thesis, University of Stuttgart (1996).

NDT & E (1997) Nondestructive Testing and Evaluation International, Vol. 30, issue 2

ONO, K., (ED.) (1996): *Materials research with advanced acoustic emission techniques ...,* Journal of Acoustic Emission, Vo. 14, No. 3-4

ROGERS, L., TSCHELIESNIG, P., (EDTS.) (1996*): Proceedings of the 22nd european conference on acoustic emission testing,* Robert Gordon University Aberdeen, Scotland

WEIHE, S., GROSSE, C., OHMENHÄUSER, F., KRÖPLIN, B., REINHARDT, H. (1997): *Characterization of damage and failure during the pull-out of a reinforcement bar by acoustic emission and numerical simulation,* 1st Int. Conf. Damage and failure of interfaces, Vienna, Austria

XU, S., REINHARDT, H. W., GAPPOEV, M. (1996): *Mode II fracture testing method for highly orthotropic materials like wood,* International Journal of Fracture, No. 75, 185 - 214