Acoustic Emission for Monitoring Damage Accumulation in Reinforced Concrete Structures

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Keywords: Acoustic emission, reinforced concrete, source localization, fracture progress, magnitude-frequency distribution

Abstract

Acoustic emission (AE) analysis is a good tool for monitoring the formation of damage in a structure. A loading experiment with a reinforced concrete beam was carried out and the obtained AE data were analyzed in order to get information about the internal processes of deterioration. Events could be localized, and their estimated source coordinates coincide with the developing crack planes. The occurence in time and the magnitude distribution of AE signals contain information about the fracture processes. The signal rate for small events with a low maximum amplitude was compared with the occurence of signals with a high one. A qualitative interpretation of the magnitude-frequency distribution allowed to distinguish between early microcracking, crack formation and crack growing. Further work is necessary to derive reliable parameters for estimating the damage progress.

Introduction

Interesting aspects for structural engineering are the monitoring of damage development in critical parts of a structure. Compared to other active ultrasonic methods that assess mainly the structure itself or existing failures, the power of AE analysis is the possibility to directly observe the process of deterioration. With AE analysis spatial and temporal correlations are examined. One aspect of monitoring a stressed concrete structure is to localize AE sources and, in this way, to observe the region where damage takes place. On the other hand, investigation of the AE activity in terms of signal rate or event magnitude distribution could indicate the stage of damage progress. The aim is to obtain reliable relations that can be applied during the AE monitoring for condition assessment of the structural component. This way of data analysis could contribute to an early warning system that is able to detect precursors of a soon failure. In this paper experimental AE data of a load test on a reinforced concrete member are examined and some preliminary results are presented.

Experimental Setup

A reinforced concrete beam was loaded in a four-point bending test in the structural engineering laboratory at ETH Zurich. An amount of AE signals was gained mainly from opening and growth of several bending cracks. The test arrangement can be seen in fig. 1.

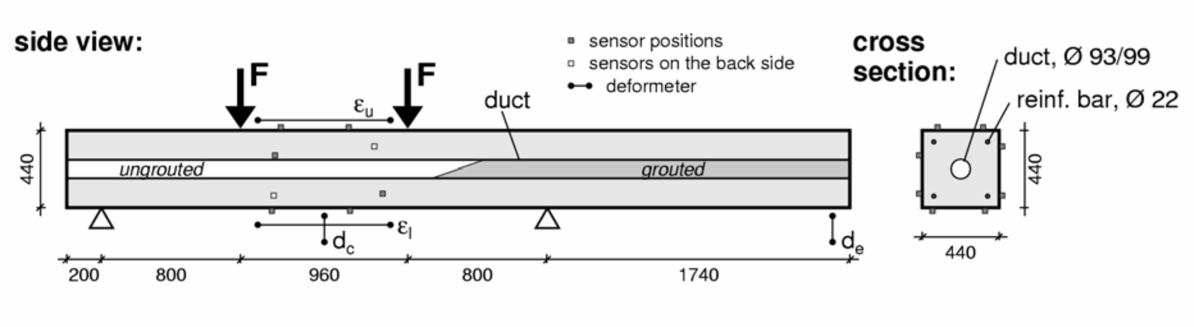


Fig. 1: Side view and cross section of the concrete beam showing the loading configuration and the positions of AE sensors and deformeters.

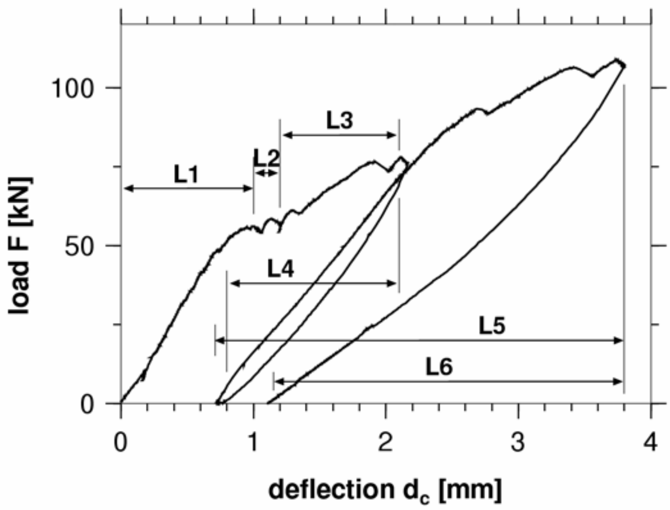
The beam had a length of 4.50 m and a cross section of 0.44 x 0.44 m. The maximum grain size of the aggregates was 16 mm. It was reinforced with four 22 mm steel bars. The tendon in the center (steel, interior/exterior diameter 93/99 mm) was not prestressed and had no supporting effect. It was ungrouted in that part of the beam that was stressed in that first experiment. The other part was grouted and will be examined in a second test. This design was chosen in order to study also the effect of reinforcement bars and an ungrouted or grouted tendon on the ultrasonic wave propagation. There is evidence that these components as well as the aggregates lead to a strong scattering of the waves [1].

Recording System

AE signals were recorded by an eight-channel Vallen AMSY-4 measurement system. The piezoelectric transducers of type KSB 250 have a broadband characteristic between 50 and 250 kHz. They are adequate for a detailed inspection of a selected volume, but their sensitivity is not sufficient for a spacious monitoring of the structure. For each signal exceeding the threshold value of 38.1 dB, AE parameters like arrival time, rise time or maximum amplitude are stored. Additionally, transient waveforms of signals with amplitude grater than 50 dB are recorded for later more detailed analysis. The sampling rate was set to 5 MHz. The sensors were attached to the concrete surface by a hot-melt adhesive. They covered the volume between the loading points where the bending cracks were expected to appear. A greater distance between sensors was not choosen in order to record an event preferably at all eight channels. This is necessary for a good hypocenter localization. With increasing travel distance the signal disappears in the noise due to the high attenuation of ultrasonic waves in concrete.

Loading

The load was applied using four hydraulic jacks, two jacks with load *F*/2 at each loading point, respectively. The pressure was controlled with a manual oil pump. Very little noise was generated by that kind of loading equipment. During the loading, the deflection in the middle between the loading points d_c and at the free end of the beam d_e was measured as well as the strain on the upper side ε_u and on the lower side ε_l. The load itself was measured by load cells and by the pressure at the oil pump. The procedure of loading is shown in a load-deflection-curve in fig. 2. After the first loading up to *F*=76 kN the beam was completely unloaded, and a deformation remained. The second loading was stopped at *F*=108 kN, when shear cracks outside the monitored volume had grown. It was not intended to reach the failure of the beam.



	loading phase	load F [kN]
cycle 1	L1	0-55
	L2	55-57
	L3	57-76
	L4	76-0
cyc.2	L5	0-108
	L6	108-0

Fig. 2: Load-deflection diagram showing the two load cycles of the test and the schedule of loading phases L1-L6.

Source Localization

An approved technique for quantitative data analysis is the localization of the AE sources. Thereby, the sources are assumed as point-like in time and space. The medium is approximated to have homogeneous wave propagation properties. The distribution of the hypocenters gives valuable information to identify the regions where the damage is progressing. This is especially important if the location is inside the structure, where no direct observation from the surface is possible. The time of an AE event can easily be found with an accuracy of about 1 ms as the time of the first threshold crossing, which is stored in the AE parameters. The transient recordings had to be repicked, because mostly the first threshold crossing did not agree with the first onset in the data within an acceptable deviation. For picking and localizing of the events the software *POLAR*^{AE} [2] was used. The linearized algorithm uses the differences in the arrival times between the sensors to estimate the source coordinates. Uncertainties in the localization results arise from errors in the mean wave speed c_P and the sensor positions, or bad data quality and arrival-time reading precision.

AE recordings were combined to events. Criterion for a localization was that at least six of the eight sensors recorded a clear onset of the P-wave in the signal. Finally, only a small part of all AE signals could be used for localization. Fig. 3 shows the results for L2. 25 events could be localized with a standard error less than 50 mm. Most of them lie in the range of the two cracks growing up from the lower side. Some events are close to a reinforcement bar or the duct. This indicates that the AE events had their origin in crack growing and deterioration of bond between concrete and steel.

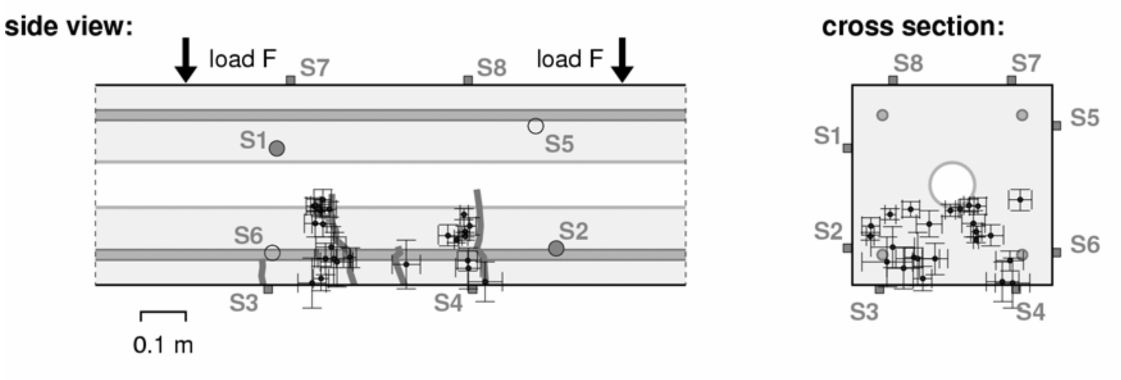


Fig. 3: Localized source positions of AE events recorded during loading phase L2. The error bars indicate the standard deviation in each direction. Also the sensor positions S1-S8 and the crack pattern that was visible on the surface is plotted.

It has to be studied how the localization accuracy depends on the sensor network configuration, the reinforcement components, and existing structural damage. Especially the air filled duct is expected to have a significant effect due to its circumference. Also, with increasing deterioration open cracks represent barriers for direct wave propagation.

Monitoring the Fracturing Process

The cracking load was calculated to 39.5 kN, considering the own weight of the beam. During the loading, several bending cracks appeared on the surface when the load approached the cracking load and then the stresses exceeded the tensile strength of the concrete. The cracks developed on the lower side of the beam with a crack distance of about 0.3 m and grew in upper direction.

A fracture process is a complex activity that takes place at multiple scales. In the nucleation stage microcracking occurs. The microcracks increase in density and grow together. The outcome of this is a macrocrack which results in the final rupture. AE signals are directly related to the fracture process. Therefore, their distribution is investigated to derive information about damage formation. The signal rate as well as the frequency of the event magnitudes are examined under the following aspects: Is differentiation possible between microcracking, macrocracking and crack growing, and is crack formation or crack growing announced. A prediction of potential failure would be possible.

Fig. 4b) shows the AE activity on all channels together during load phases L1, L2 and L3. One curve is the rate of signals with a maximum amplitude A_{max} in the intervall 43-45 dB, the other curve for signals with A_{max} between 59 and 61 dB, as indicated in the plot. Significant peaks in the signal rates correspond to macroscopic crack opening that coincides with an increase of the measured strain ε_l. At the same time, the pressure at the jacks is decreasing. A_{max} is taken as approximation for the event magnitude. Events with a large magnitude (A_{max} resp.) occur less often than events with a smaller magnitude. In seismology this is also observed for earthquake rupture processes. It can be described with a power law, known as Gutenberg-Richter magnitude-frequency relationship [3]:

$$\log N = A - bm$$

where N is the number of earthquakes with a magnitude greater than *m*, and *A* and *b* are determined from observations. In a *b*-value analysis, this value is calculated from the negative slope of the lin-log data distribution. For earthquake registrations from selected regions it is found, that the *b*-value decreases prior to strong earthquakes. This relationship for the magnitude-frequency distribution is also valid for AE recordings. So far, not many investigations exist for AE data. For AE monitoring of rock failures, Lei et al. [4] could identify phases of early microcracking, microcracking interaction and initiation of the final rupture. Prior to dynamic failure they observed a decrease of the *b*-value due to nonlinear crack growth. For a concrete load test, Colombo et al. used the *b*-value as an estimate for the development of the fracture process. They also could distinguish between micro- and macrocracking.

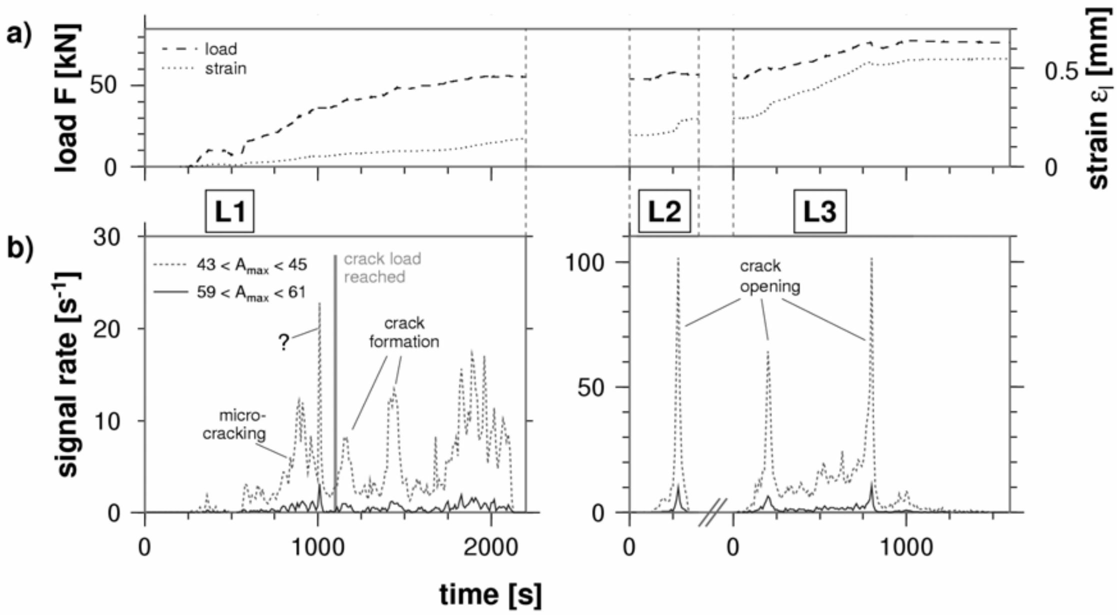


Fig. 4: *Loading history, strain on the lower side and rate of all recorded AE signals with A_{max} in the interval 43-45 dB and A_{max} between 59 and 61 dB, respectively.*

In this paper, high and low magnitude frequency are compared qualitatively. During L1, crack formation took place. The signal rates were at a moderate level, except one sharp peak, whose origin is unknown so far. Most activity is noticed at a lower amplitude level, distributed over broad time intervalls. The measured deformation of the beam and the load show small fluctuations that indicate the appearance of early damage. In contrast, L2 and L3 express another AE characteristic. There are single, remarkable peaks with a sudden exceeding high increase in the number of signals at all energy niveaus for a short period of time. A comparison with the strain data el shows significant rise of deformation at the same time. This means that cracking had reached a state of macroscopic crack opening. Crack growth proceeds in a highly nonlinear process expressing that characteristic. Increasing stresses provoke that the damage is also accumulating. An indicator for this is the ground level of activity, that increases with progressing load in L3. As a first interpretation, the signal rates for the two ranges of A_{max} were related to different phases of the cracking process. Early microcracking had a lower signal amplitude and occured soon after the beginning of loading. Crack formation took place with significant increase in signal rates during a certain time intervall. Sudden very high signal rates were related to crack growing.

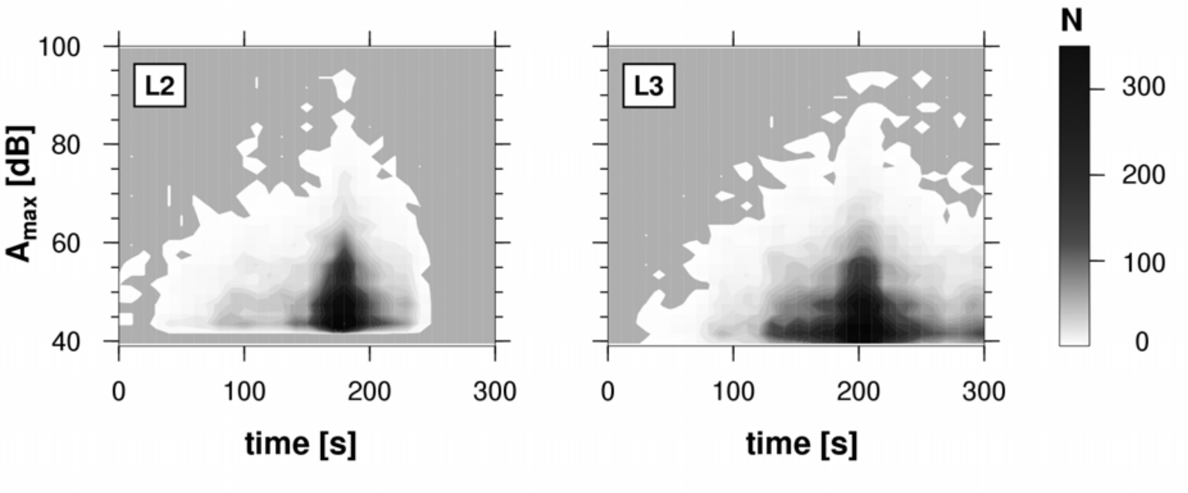


Fig. 5: Magnitude-frequency distribution for L2 and the beginning of L3. The color scale indicates the number of signals N in the specified intervals. The time axis refer to the beginning of the plot window..

For L2 and the beginning of L3, the distribution of the parameter A_{max} is shown again in fig. 5. The color scale indicates the number of signals *N* for intervals of ΔA=2 dB and Δt=10 seconds. The sources belonging to the events of L2 were localized on two cracks, respectively, as shown in fig. 3. Both cracks were active at the same time. Crack growing shows distinct patterns with very high signal rates for all amplitude levels.

A more detailed conclusion is expected from adding the information of the localization results. This interpretation was not yet based on a quantitative analysis. So far, *b*-value calculations did not result in clear trends due to large fluctations. It is intended to derive parameters that could help to classify the damage progression.

Outlook

An outlook is given on work that will be done in the near future to improve the analysis methods for monitoring of fracturing. The given interpretations had to be proofed on the basis of the localization results, whether single peaks in the AE activity can be assigned to certain clusters or crack planes. Also the second load cycle will be examined in that manner. For possible applications it is necessary to have reliable parameters, that allow conclusions about the processes of deterioration that are taking place within the specimen. Further investigations will show if such a parameter could be the *b*-value or a similar derived value.

Another important point is to determine the localization accuracy. Comparison with a load test of the grouted part of the beam shall show the effect of a void in the ungrouted tendon on the localization results.

Acknowledgements

This research was funded by the Swiss National Science Foundation SNF.

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