ACOUSTIC EMISSION MEASUREMENTS DURING A TENSILE FATIGUE TEST IN REINFORCED CONCRETE

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Abstract:

In a research project funded by the German Federal Ministry of Education and Research (BMBF) acoustic emission (AE) measurements were carried out during a tensile fatigue test on a plate-shaped reinforced concrete specimen to investigate the fatigue behaviour of an embedded steel anchor with a clothoid-shaped form in reinforced concrete. The results of AE measurements show that the AE activity begins immediately after starting dynamic loading. Due to the limited location accuracy, the located AE events are not identified on fracture planes, but are cloud-like distributed in zones of the high stresses on the left and right edges of the steel anchor. During the test 9,132 AE events could be located using the longitudinal (L wave) and transverse (T wave) wave onsets. The locations of the AE events let suggest that microcracks occur due to the form-closed connection between the concrete and the steel anchor under fatigue stress.

1 Introduction

Today, many constructions activities deal with repair of existing buildings and it will gain in importance in the future. In order to decide on the necessity the type and scope of a redevelopment measure, the knowledge about the conditions of the existing building is required. The current mapping of reinforced concrete structures extends to the visual inspection about damage of the structure surface without technical aids. This appraisal of the structure is necessary but not always sufficient. Damage inside the building remains hidden and can only be discovered with a delay.

The use of non-destructive testing methods can provide information on processes inside the structure. Acoustic emission (AE) testing is a non-destructive testing method, which is used to detect material damage. Due to the damage of structures like concrete components elastic waves emit during fracturing of materials under load. The AE signals are detected by AE sensors, which are mounted on the surface of the component, allowing the state of the material and the cause of the deformation to be traced.

The investigation of AE in reinforced concrete started very early. Rüsch (1959) examined in first tests on concrete pressure prisms (100 mm · 150 mm) the strength, the deformation behaviour and the AE activity under short-term and continuous load and under cyclic load [1]. He traces out that the so-called "Kaiser effect" on concrete is not valid. The "Kaiser effect" is defined as the absence of AE at stress level below the previously applied maximal stress [2]. In the 1960s and 1970s this was followed by many further investigations using AE analysis to detect crack formation in concrete. A good overview of literature provides the bibliography made by Drouillard (1986) [3]. Manthei (2016) gives an overview about the application of the AE in concrete in the last decades [4]. Further important works about AE in concrete are
published by Schechinger (2005), Shiotani et al. (2006) and Grosse & Ohtsu (2008) [5-7]. Pull-out tests of concrete reinforcing bars were examined by Finck (2005) with AE analysis. The focus of the study was the material behaviour of concrete under static load until failure [8].

At the THM (Germany), Koob et al. (2015) are developing an innovative hybrid framework with low material input in an ongoing research project [9]. The hybrid framework will serve as a supporting structure for the construction of wind turbines. Due to the rotation of the rotor blades, the building materials are exposed to high dynamic loads, whereby the fatigue limit of the used materials can be achieved. In this intention anchored concrete dowels are examined under dynamic tensile stress. The specimen is inspected for stress, marginal forces, cracking and fatigue behaviour. The damage to the transition zone between concrete and reinforcing bars is preceded by the formation of microcracks in the concrete matrix. AE is based on the appearance that elastic waves are emitted during deformation or cracking in a material. These elastic waves can be detected with sensitive AE sensors. The aim of the AE measurements is to directly measure microcracking and to locate the AE events. With the location of the cracks the progress of damage during dynamic loading is analysed. Changes in the velocity of the elastic waves are measured using transmission measurements with ultrasonic signals. These can also indicate cracking.

2 Testing programme

2.1 Description of the experimental specimen

With the help of pull-out experiments, a concrete dowel anchorage should be checked under dynamic conditions. Koob and Minnert (2018) investigated the pull-out resistance, the slip development and the failure mechanism of the dowel anchorage [10]. In the plate-shaped specimen of reinforced concrete with the dimension 146 cm · 45 cm · 16 cm a 61 cm long and 26 cm wide steel anchor with a thickness of 20 mm were embedded into the specimen. Figure 1 shows a front view (left) and a side view (right) of the specimen with the location of the embedded steel anchor with a clothoid-shaped form and the reinforcing bars. The arrows indicate the direction of the tensile load.

Fig. 1: Front view (left) and side view (right) of the specimen of reinforced concrete with position of the embedded steel anchor with a clothoid-shaped form and the vertical and horizontal reinforcing bars. The arrows indicate the direction of the tensile load.
The entire specimen mounted on a solid steel plate for attachment to the lower punch of the testing machine. To initiate the tensile force of the testing machine the concrete dowel protruded about 41 cm out of the specimen. In the concreted part of the concrete dowel recesses are cut out in clothoid-shape (Fig. 1). By encasing in concrete, the concrete hardens in the recesses and it forms a positive anchoring of the dowel in the concrete. In order to increase the bearing strength, additional reinforcing bars are laid through the recesses.

2.2 Experimental setup for AE measurement

In a previous research project, broadband AE sensors with a measurement frequency of up to 200 kHz were developed for the detection of microcracks especially for concrete. For the three-dimensional location of the AE sources, 16 of these AE sensors were attached to the surface of the plate-shaped specimen. The bottom of the sample was inaccessible because the steel plate for attaching the specimen was fixed of the testing machine. The arrangement of the AE sensors can be seen in Figure 2 (left).

![Figure 2: Left: Perspective view of the contour of the specimen with the position of the AE sensors (red dots) and ultrasonic transmitters (yellow dots). Right: Installation situation of the specimen with the AE sensors and preamplifiers (blue boxes) and displacement sensors in vertical and axial direction.](image)

Six AE sensors (red dots) were placed on the front side and back side, two sensors were placed on the top and one sensor on the left and right side of the sample. With the additional ultrasonic transmitters (yellow dots) ultrasonic measurements could be made in longitudinally and transversely direction at three points of the specimen. The sensors were mounted to the test specimen with screws. The couplant between the sensors and the surface of the specimen was a high-strength vacuum grease to improve the acoustic conductivity. A 16-channel system was used for AE and transmission measurement (manufacturer: GMuG). The measuring system digitized the signals in a very high frequency with a sampling frequency of 10 MHz and an amplitude resolution of 16 bit. The signals were pre-amplified by 40 dB (factor 100) and bandpass filtered. The lower and upper cut-off frequency of the bandpass was set to 20 kHz and 200 kHz, respectively. The transmission measurements were repeated at the beginning of the test and during stopping phase of the testing machine to measure the wave velocities used for AE location. During a single transmission measurement eight signals of different shape were transmitted serially through the specimen to the receiver. There were used a wide band signal (step function) with rise time of 1 µs and seven signals with centre frequencies between 20 and 200 kHz. In order to improve the signal quality up to 256 stacking (i.e. repetitions with summation) were performed for each
measurement. A servo-hydraulic testing machine was used for the test, which was designed for tensile and compressive forces of up to 2,000 kN and dynamic load up to ±1,600 kN.

2.3 Experimental procedure

The load of the specimen was applied in three phases. After a static preload phase of 80 kN, the dynamic testing of the specimen was force-controlled carried out. Figure 3 shows the time course of the tensile load (black continues line) and the vertical displacement of the testing machine (red continues line). The cyclic load history at 8 Hz is shown in the inlet in the upper left corner of Figure 3. During a periodic load cycle the applied load oscillates with ± 36 kN with a mean tensile force of 44 kN. Thus, the upper and lower tensile force is 80 kN and 8 kN, respectively. A total of 10 stress cycles were performed with 10,000 cycles each. After 100,000 load cycles, a residual carrying capacity of about 161 kN was measured. Furthermore, it can be seen that during the dynamic load the displacement of the testing machine remains nearly constant at approximately 1 mm. At the ultimate load, the displacement is about 3.0 mm and increases up to 30 mm until failure.

![Fig. 3: Load (black continues line) and displacement behavior (red continues line) versus time. Upper left: Reduced representation of the dynamic tensile load with oscillation frequency of 8 Hz with a mean tensile force of 44 kN.](image)

3 Results of AE measurement

The main part of the evaluation was the three-dimensional location of the AE sources for the analysis of the spatial distribution of the cracks in the specimen. For this purpose, an automatic location programme was used. The location method uses clear discernible onsets of L and T waves. A location is valid if the location error is below 5 cm and more than five L- and T-waves onsets are used for location. The location error is calculated using the travel-time residuals of the L and T waves. We assume that the real location error is two times greater. An event was rejected when these conditions are not fulfilled.

The waveforms for an event with 16 channels are shown in Figure 4. At the end of the signal trace the maximum of the amplitude is given in volts. The automatically determined L- and T-waves onsets used for location are marked above the signal by a vertical line. Dashed lines
below the signals mark the calculated arrival times of the L and T waves. The considered event was located using 10 and 2 L-waves and T-waves onsets, respectively. The measured L-wave velocity is 3.6 mm/μs and T-wave velocity is 2.1 mm/μs, which were used for location. The occurrence origin of the considered event is approximately in the middle of the front of the sample with coordinates \( x = 61.1 \text{ cm}, y = 2.8 \text{ cm}, \) and \( z = 24.6 \text{ cm}. \) The calculated location error is about 2.7 cm. The good agreement between the measured and calculated onsets leads to the expectation that the real location error is in the range of the calculated error.

**Fig. 4:** Event originating from the middle of the front of specimen. The picked and calculated first (L wave) and second (T wave) arrivals are marked by vertical ticks above and below the signal traces, respectively.

Figure 5 shows the cumulated AE events versus time (red continues line) together with the tensile force of the testing machine (black continues line).

**Fig. 5:** Temporal course of cumulative number of localisations (red continues curve) and tensile force (black continues curve) during the test.
The AE activity starts immediately with the dynamic load and increases steadily during the test. At approximately 12:30 the number of AE events decreases slightly, which is certainly due to the fact that the damage to the sample has increased and open gaping cracks hinder the propagation of AE signals. However, a slight increase of the number of the AE events can be seen at the end of the test, when reaching the residual load capacity. Figure 6 shows all located events in a lateral view in projection onto the x-z-coordinate plane.

Fig. 6: Location of the 9,132 AE events in lateral view on the x-z coordinate plane.

A total of 9,132 events could be located over the test period of approximately 7 hours. Figure 6 shows that the events are preferentially distributed in some accumulations of event at the edge of the embedded concrete dowel. It is noticeable that about 6,700 events are distributed in two accumulations on the left edge (ovals in Fig. 6).

Figure 7 displays an enlarged part of the specimen together with the contour of the concrete dowel. This figure illustrates that the above-mentioned accumulations of events are clustered in zones, where the clothoid-shaped recesses of the concrete dowel influence the stress state.

Fig. 7: Position of the located events in a projection onto the x-z-plane together with the contour of the concrete dowel in an enlarged view.

For further verification of the AE results, the located AE events were compared with the result of a non-linear finite-element calculation of the anchorage in the concrete. The remaining tensile strength of the concrete after the dynamic load is shown in Figure 8. The tensile strength is displayed in projection onto a vertical cross section in the middle of the concrete dowel anchorage in a perspective view. In this figure the red colour is indicating
areas of undisturbed concrete, whereas in the blue collared areas the bearing capacity of the concrete are significantly decreased. That means in this zones the concrete structure is damaged and no tensile force can be transmitted. In comparison with the results of the AE measurements the main part of the AE events occurred in the high damage, where the bearing capacity is very low (blue areas in Fig. 8). According to the results of the AE location, the damaged zone continues below the clothoid recess, approximately to the lower end of the concrete dowel.

Fig. 8: Non-linear finite-element calculations of the tensile strength in projection onto a vertical cross section in the middle of the concrete dowel anchorage in a perspective view.

4 Conclusions

This work demonstrates, that AE is a non-destructive method for localisation of fracture processes in loaded concrete structures. During the execution of a cyclic pull-out test, the crack formation in the reinforced concrete specimen could be detected by AE measurement. The main task of this work was the location of cracks within the specimen. Because of the limited location accuracy of the AE sources, there is no direct proof that cracking indicated by AE occurs on planer microscopic cracks. The AE activity starts early in the loading immediately after beginning of the dynamic load. In the later stages of the test microcracking occurred in the vicinity of the concrete dowel. In these highly damaged zones, the ultimate failure occurs. In our experiment it was not possible to follow this development by AE source location because microscopic open tensile cracks lead to a high attenuation of wave propagation.

The aim of further investigations is to optimise the evaluation procedure and thus extend the AE analysis to the application for existing structures with high dynamic loads such as bridges or wind turbines.
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References