ACOUSTIC EMISSION ANALYSIS OF SFRC BEAMS UNDER CYCLIC BENDING LOADS

SCHALLEMISSIONSANALYSE AN STAHLFASERBETON UNTER ZYKLISCHEN BIEGEVERSUCHEN

ANALYSE DES ÉMISSIONS ACOUSTIQUES DE BETONS RENFORCES PAR FIBRES D'ACIER SOUS FLEXION CYCLIQUE

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SUMMARY

To further understand the failure processes within steel fibre reinforced concrete members under cyclic load, a series of 3-point bending tests was performed on notched beams using quantitative acoustic emission (AE) measurements. AE measurements supplement the mechanical test data by providing a large quantity of information about the progress of damage in terms of time, location and cause. Quantitative analysis of acoustic signals consists of an accurate localization of the fracturing and under certain assumptions an inversion for the moment tensor can be performed to gain information about the total energy released and the orientation of the rupture plane. After decomposition of the moment tensor, the type of rupture process can be quantified and visualized using ostensive crack models like those for shear and opening. In this article some first results of the fatigue test series and the analysis of the AE-data are presented.

ZUSAMMENFASSUNG

Zur Untersuchung von Schädigungsprozessen innerhalb stahlfaserbewehrter Betonbauteile unter zyklischer Last wurde eine Reihe von 3-Punkt-Biegeversuchen durchgeführt und die auftretenden Schallereignisse aufgezeichnet. Neben den mechanischen Prüfdaten können so Informationen über den Zeitpunkt und den genauen Ort der fortlaufenden Schädigung gewonnen werden. Darüber hinaus kann unter bestimmten Voraussetzungen eine Inversion auf den Momententensor durchgeführt werden, welcher bruchmechanische Parameter, wie z. B. die Bruchenergie und die Orientierung der Bruchflächen enthält. Nach einer geeigneten Zerlegung des Tensors können die enthaltenen Bruchmoden quantifiziert und durch anschaulich Bruchmodelle, wie die des Öffnungs- oder des Scherbruches beschrieben werden. In diesem Artikel werden erste Ergebnisse der Ermüdungsversuche und der Schallemissionsanalyse vorgestellt.

RESUME

Afin d'analyser les processus de détérioration à l'intérieur d'éléments en béton armé de fibres d'acier sous chargement cyclique, nous avons réalisé une série d'essais de flexion 3 points et enregistré les émissions acoustiques. Ainsi nous avons pu gagner, outre les données mécaniques, des informations sur la nature, le moment et le lieu exacts des émissions acoustiques, et, par là, sur la progression de la rupture. Dans certaines conditions, le tenseur des moments peut être calculé par inversion. Celui-ci contient des informations sur l'énergie libérée et l'orientation de la surface de rupture. Après la décomposition du tenseur de moment, les modes de rupture peuvent être quantifiés et visualisés à l'aide de modèles simples, comme ceux pour le cisaillement et l'ouverture. Dans cet article les premiers résultats des essais de fatigue et de l'analyse des émissions acoustiques sont présentés.

KEYWORDS: fatigue test, steel fibre reinforced concrete, acoustic emission, moment tensor

INTRODUCTION

Steel fibre reinforced concrete (SFRC) has been in use since the late 60s, mainly as shotcrete for underground constructions and flooring. Some advantages of SFRC are a minimization of crack widths and permeability or an increased toughness. Although various basic works on the behaviour of SFRC members have been published [e.g. WEILER 2000], there remain open questions about the mechanical laws and processes that exist during failure. The interaction between steel fibre reinforcement and a cementitious matrix, as well as the characterization of failure of SFRC members, are mayor topics of the subproject A6 in the collaborative research centre SFB 381.

In a fatigue test series with steel fibre reinforced concrete (SFRC) beams under cyclic 3-point bending load we studied the behaviour of ongoing failure. Thereby, the investigation of acoustic emissions under changing conditions (e. g. load, amplitude and frequency) was the main focus, not an accurate statistical investigation of the members. The external, i. e. visible, fatigue is given by mechanical test data containing the deflection in dependence on load and the number of load cycles. Additionally, acoustic emission analysis yields information about the internal processes of failure, which correspond to the emission of seismic energy due to cracking. Each single crack (event) is localized and for a selection of events moment tensors are evaluated. A suitable decomposition of this tensor [JOST & HERMANN 1989] yields parameters such as the energy released during rupture, the orientation and the size of the rupture plane and a combination of ostensive fracture modes. From these parameters the stress regime in the member and the mechanics of failure can be derived.

SETUP OF THE FATIGUE TEST SERIES

For the test series beams with dimensions 15 cm X 15 cm X 70 cm with a 1.5 Vol.% reinforcement of Dramix® RC 80/60 BN steel fibres (length: 60 mm, diameter: 0.75 mm) were used. On the bottom surface in the middle of the beam a notch with a depth of approximately 3.3 cm caused a well-defined start of a crack. The transmission of force by the servo hydraulic 100 kN test frame was realized using three steel cylinders. The two fixed lower supports had a distance of 60 cm and the upper support at the centre was free to rotate around the longitudinal axis of the beam to avoid torsional stress. Figure 1 shows details of the test setup, with the AE sensors attached to the specimen.

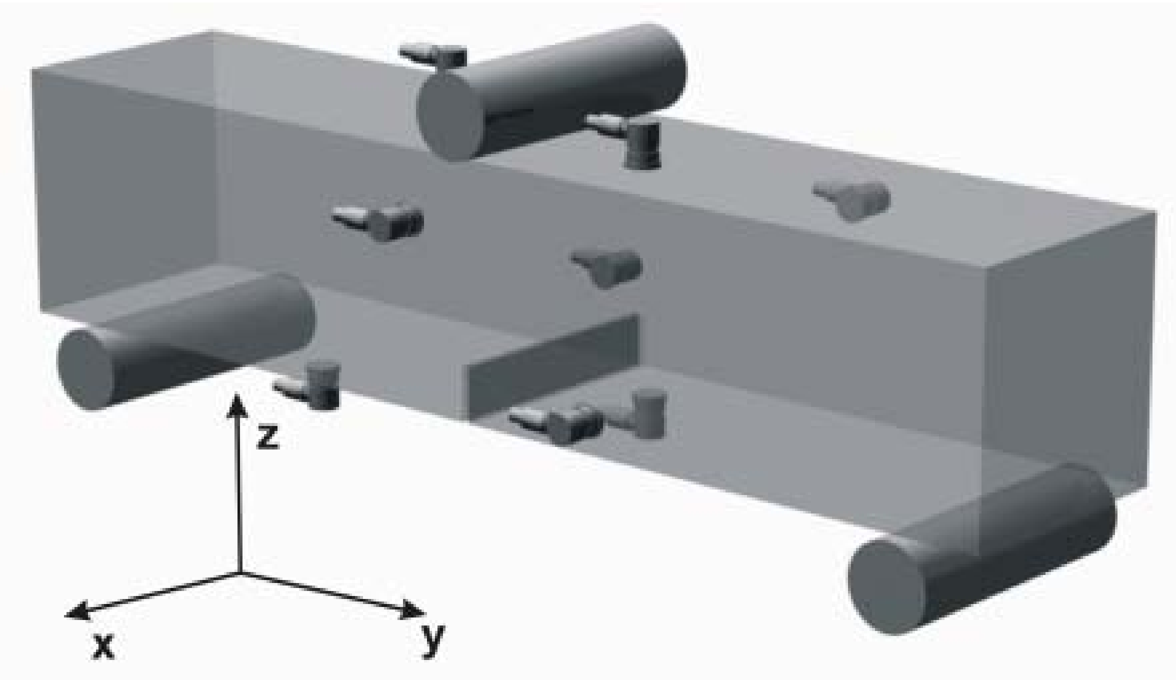

Figure 1: Sketch of a notched SFRC beam under a cyclic 3-point bending load. AE sensors are mounted around the area of damage.

Piston displacement, load and crack opening were recorded over time. The acoustic emissions were recorded by an 8-channel transient recorder with a sample rate of 2.5 MHz per channel and an amplitude resolution of 12 Bit. Eight piezo-electric accelerometers were evenly distributed on the surfaces of the beam.

First, the range of the failure load was evaluated in two static bending tests. Although, a large variation of this value has to be expected due to a change in the distribution of fibres and the composition of concrete in the beam, this value provides an estimate of the load profile for the dynamic tests. During the dynamic tests, load, amplitude and frequency were adapted to the progress of damage and the AE activity.

PRESENTATION OF THE RESULTS

In the following section the results of one test run are presented. A load of 7.5 kN was applied statically before the load cycles began. In the second plot in figure 2 the different phases with changing load, amplitude and frequency during the fatigue test are labelled and coded by blue (dark grey) and green (light grey) respectively to be identified in the load over crack opening (displacement) plot and the crack opening over time or cycles plot. The frequency of the sinusoidal load cycles was 1 Hz from phase G. From that point the number of load cycles equals time in seconds plus 5000. On the bottom a histogram of the acoustic emission activity can be correlated with the ongoing failure in the beam.

With each increase of the maximum load the crack opening, as well as the AE activity, increases rapidly but a relaxation is visible with the continuation of the test. The extending areas of the hysteretic ellipses in the load over crack opening plots are another indicator for the damage progress.

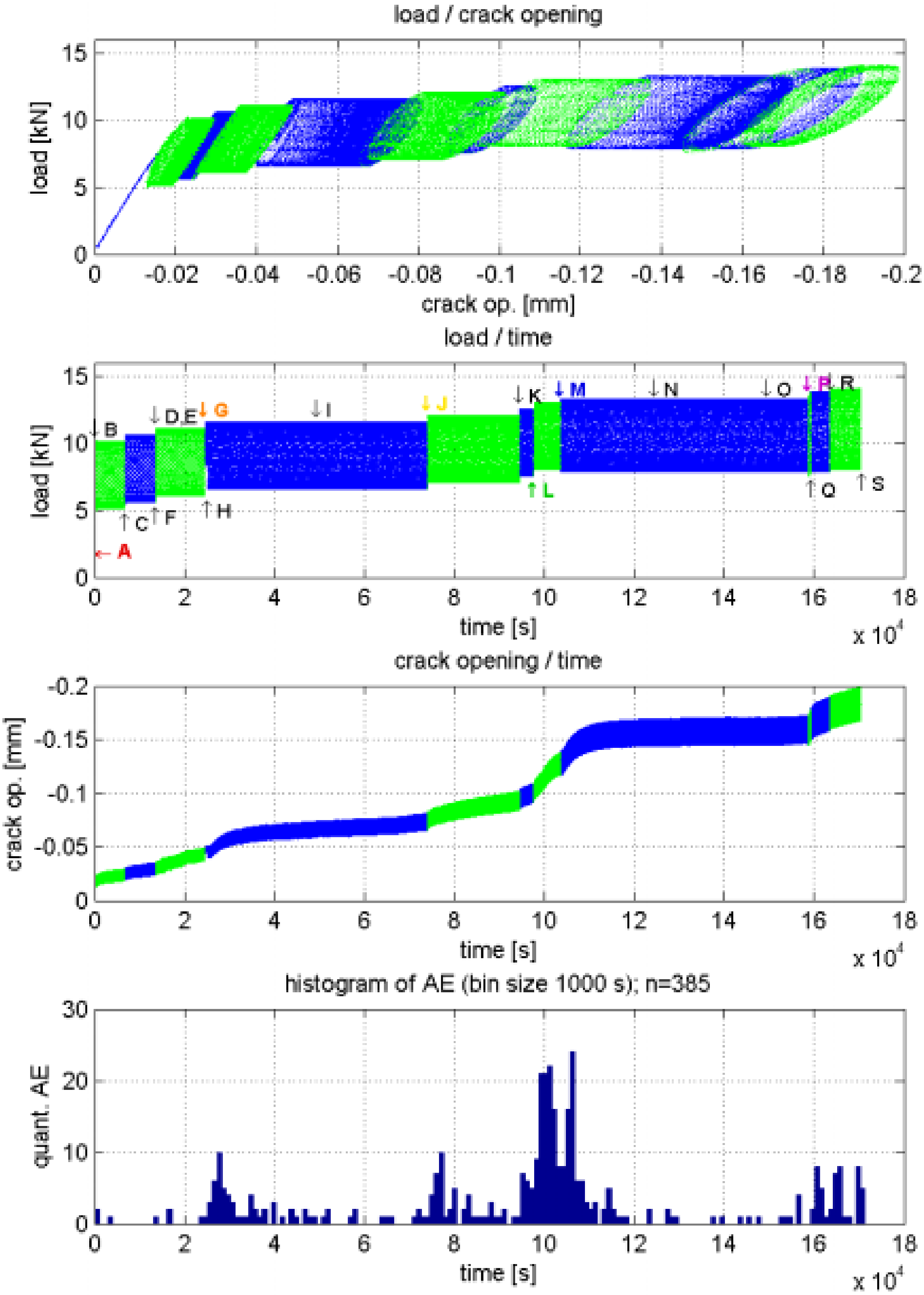

Figure 2: Mechanical test data of one fatigue test. From top: load deflection curve, load over time profile, crack opening over time and the AE activity.

During the test a total of 385 acoustic emissions were recorded from which 377 could be localized. The data quality was very good regarding noise due to the cyclic bending and the accuracy of the localization lies in a range of about 1 cm.

Figure 3 shows the located events from three prospectives: from above, a front view and a side view. The markers representing the sources of the acoustic emissions are given in the legend, corresponding to the test periods starting with the according labels (see also figure 2, 2nd plot). This illustrates the temporal growth of the damaged zone.

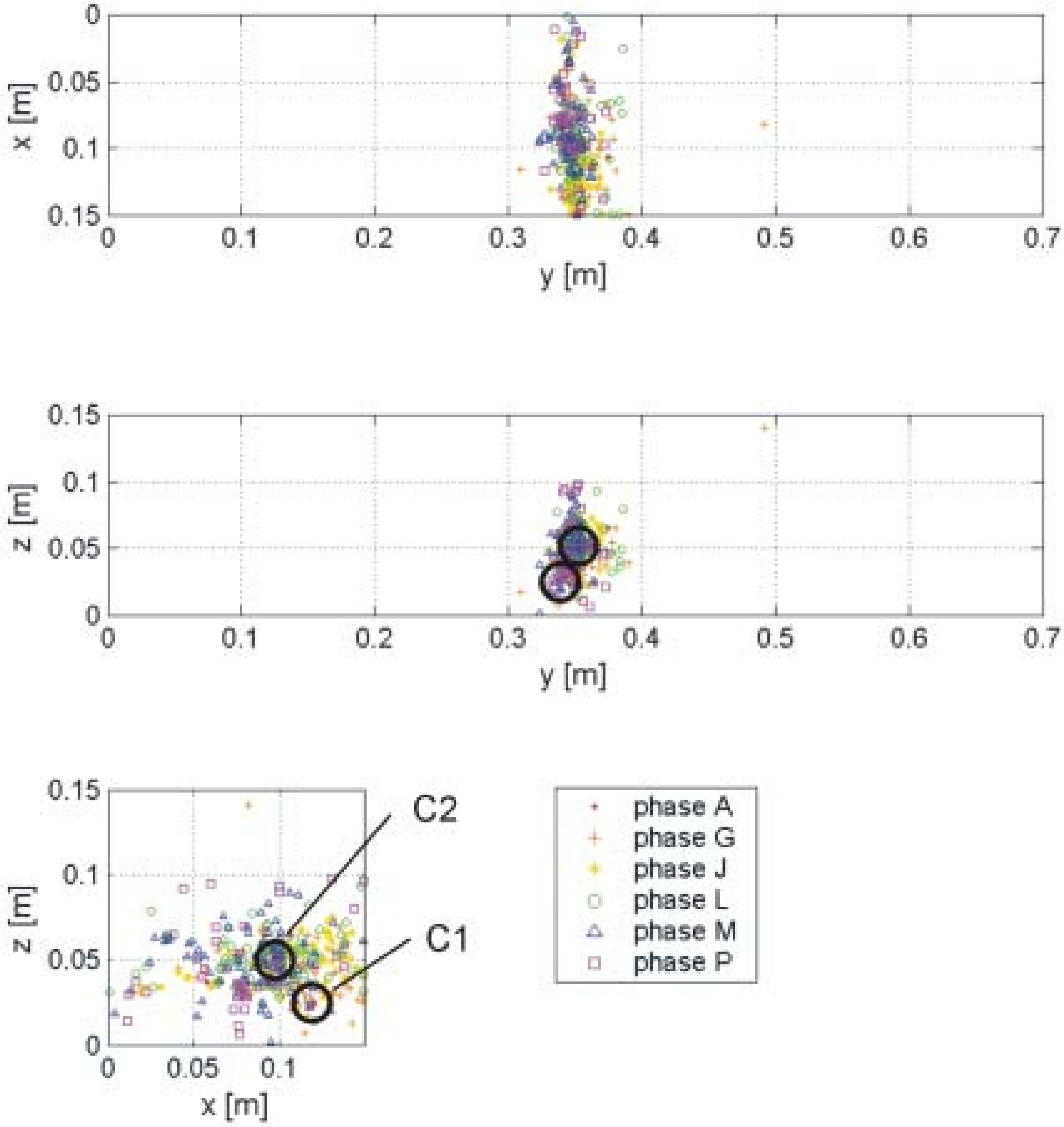

Figure 3: Projection of the localization of acoustic emissions. The different markers correspond to various test periods, as indicated in the legend.

Nearly all acoustic emissions lie in the central region of the specimen in the vicinity of the main crack. Due to the steel fibres, some smearing of the damage zone takes place. The early events come from the lower half of the specimen since the crack starts in the edge of the notch due to tension. Then steel fibres are activated and accommodate load as they are pulled out. The crack grows towards the top of the specimen under a relative constant spatial AE activity from the complete region under fatigue. The width of the damage zone in y-direction is more or less in the range of the fibre length (i. e. 60 mm). This suggests that always the short end of the fibre is being pulled out, as expected.

THE INVERSION OF MOMENT TENSORS

To gather more information about the mechanical reasons of failure, we calculate moment tensors with a relative moment tensor inversion (RMTI) technique developed by DAHM 1993. The application and some theory of this method on acoustic emission data has been described previously [e. g. FINCK 2002, FINCK 2001, GROSSE 1999]. An advantage of the RMTI is the elimination of the Green's functions [AKI & RICHARDS 1980] of the medium by an inversion for a cluster of events. Two circles in figure 3 indicate the orientation of two clusters of 16 events each which were inverted for their moment tensors. C1 is a cluster from very early events in the tension zone, events in C2 originate from an advanced stage of the test.

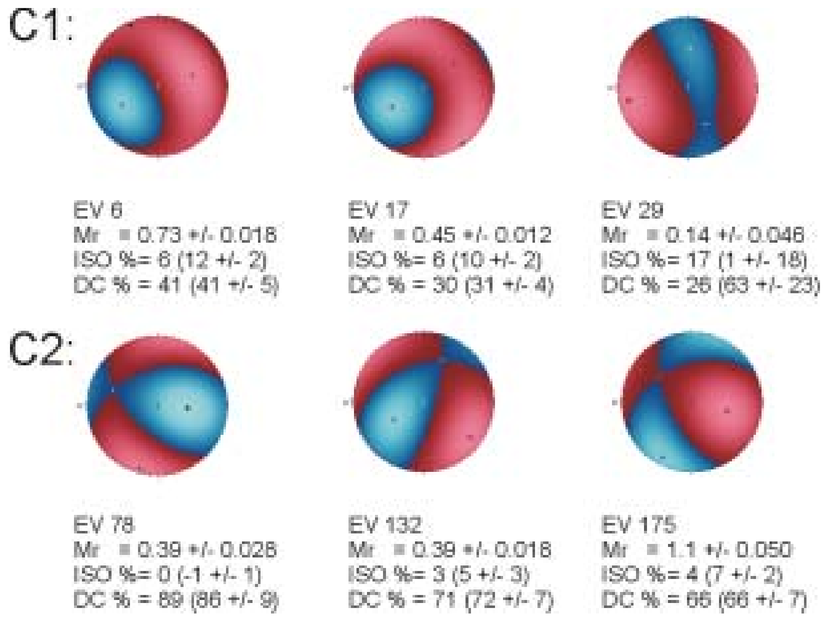

Figure 4: Radiation patterns of seismic energy and results from the moment tensor inversion for selected events from cluster C1 an C2 (see figure 3). M_r is the relative seismic moment, ISO is the isotropic component of the event and DC is the double-couple portion of the deviatoric component.

A combination of two different crack modes is expected for the performed test. First, the opening of the main crack should radiate energy similar to event EV 29 in cluster C1. An opening mainly perpendicular to the vertical crack-surface with particle motion outwards parallel to the y-axis and a significant remaining isotropic component. This conforms to mode 1. Second, a great number of events should correspond to the pull-out of steel fibres. Mainly a double couple mechanism for shear failure is expected in this case, with a small isotropic component only (conforming mode 2 or 3).

A selection of the results is shown in figure 4. The first row contains results for cluster C1, the second for C2. Under the top view projection of the radiation patterns of seismic energy the relative seismic moment M_r, the isotropic component ISO and the double-couple portion DC of the deviatoric component are given with errors. The best results from a boot strap analysis [EFRON & TIBSHIRANI, 1986] can be found in the brackets. The majority of the moment tensors consist of a very small positive isotropic component. For event EV 29 the errors are very high, so the results must be doubted, though the radiation pattern fits to first expectations. For the other events in C1 the DC component is rather small. The deviatoric components of these events can not be explained by one pure shear crack. Other deviatoric phenomena seem to take place. But the early events in C1 vary from the results for C2. The events occurred at an advanced stage of the test, where the fibre-pull out seems to be the major reason for acoustic activity. Here, the DC component is large.

The results have a great stability for a changing composition of the investigated clusters. In earlier investigations the results for single events were dependent on the composure of the cluster, meaning that the existence or non-existence of other events had an influence on the results. Also the errors are small.

CONCLUSIONS

We successfully obtained high quality acoustic emission data from cyclic bending tests of steel fibre reinforced concrete beams. The majority of these events could be localized and an inversion for the moment tensor of a selection of events was performed. Stable results from the moment tensor inversion can partially be correlated with the expected mechanisms of failure – an opening of the crack (mode 1) and mainly the pull-out of fibres (mode 2 or 3). Acoustic emission analysis helps understanding complex mechanisms of failure even over a large period of time.

The decomposition of the moment tensor into crack modes known from geological investigations seem not to be suitable for experimental data from the laboratory. A decomposition taking crack modes from engineering models in to account, is needed. This subject will be of intensive interest in future

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