VIII International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-8
J.G.M. Van Mier, G. Ruiz, C. Andrade, R.C. Yu and X.X. Zhang (Eds)

MONITORING OF FATIGUE CRACK GROWTH IN CONCRETE-CONCRETE INTERFACES USING ACOUSTIC EMISSION

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Key words: Fatigue, Concrete Interfaces, Acoustic Emission

Abstract: The fatigue crack growth in various concrete-concrete interface specimens are monitored using Acoustic Emission (AE) technique. Beam specimens of different sizes having a jointed interface between two different mixes (strengths) of concrete are prepared and tested under three-point bending (TPB) in a closed loop servo-controlled testing machine under fatigue loading. The fatigue load is programmed as variable amplitude loading with step-wise increase in the maximum load, with constant minimum load. The fatigue crack growth is continuously monitored using six AE-sensors mounted on the specimen. The results of load, displacement, CMOD, number of cycles, AE-events and AE-energy are simultaneously stored in a computer during the testing.

The CMOD compliances at different cycles are measured from the load-CMOD curves and the equivalent fatigue crack lengths are determined using the compliance calibration curve obtained from finite element analysis. The fatigue crack growth curve is plotted using the results of crack lengths and the number of cycles. It is observed that the rate of increase of acoustic emission events and energy are same as that of fatigue crack growth suggesting the existence of a relationship between the number of AE-events and the length of fatigue crack. It is observed that the number of AE-events and amount of AE-energy are the measure of cracking and damage that has occurred inside the structure and can be monitored on-line during the fatigue loading, which is very difficult to observe or to measure by any other techniques. It is observed that as the difference between the compressive strength of concrete mix on either side of interface increases, the number of AE events, AE counts and amount of AE energy decreases which indicates the increase in the brittle behaviour of interfaces. It is concluded that AE technique can be very useful for monitoring the fatigue crack growth in concrete structures.

1 INTRODUCTION

AE in simple terms is defined as a transient elastic wave generated as an outcome of material deformation. This stress wave propagates through the solid due to the energy released during the deformation process. The acoustic emission technique offers the possibility of capturing the damage process with regard to the time and position of its occurrence [1]. The amount of acoustic energy released depends primarily on the size and the speed of the local deformation process [2].

No work has been reported in the literature on the use of AE technique for monitoring the fatigue crack growth in concrete interfaces. In this paper, AE technique is used to monitor the fatigue crack growth at concrete-concrete interfaces. The relationship between crack length and number of AE events under fatigue loading is studied.

2 EXPERIMENTAL PROGRAM

Three different sizes of geometrically similar notched interface beams (S/b) of 2.5, notch to depth (a_0/b) of 0.2 and notch width of 2 mm are used in this study. The details of the geometry and its nomenclature are shown in Table 1.

Table – 1 *Designation of the beams*

Beam size	Depth d(mm)	Span S(mm)	Length L(mm)	Thickness b (mm)	Notch a_0 (mm)
Small	76	190	241	50	15.2
Med	152	380	431	50	30.4
Large	304	760	810	50	60.8

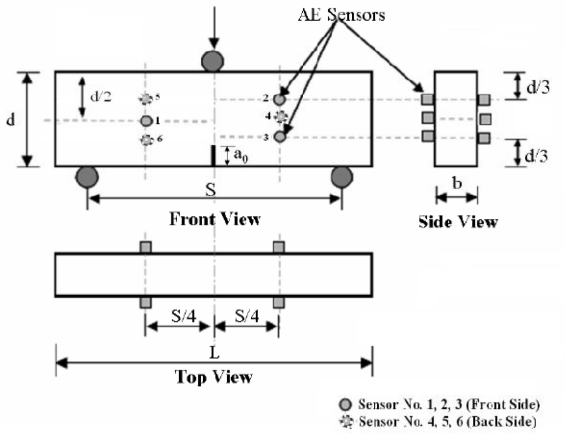


Figure – 1 *Specimen geometry and AE-sensor location*

The details of the geometry and location AE Sensors are shown in Figure – 1. The interface is made rough and the surface is cleaned by water jet and the interface is kept exposed for 48 hours. A notch is introduced at the interface during the casting process itself by inserting a wooden strip of 2 mm thickness and is removed after 2 hours. On the third day, the second-half of the beam is casted by mixes A, B, C and D as shown in Table – 2.

Table 2 Details of Mix proportions

Mix Desg.	**Cement (kg/m^3)**	**Mix Proportion C:FA:CA:w/c**	**Comp. Strength MPa**
A	385.19	1:1.86:2.61:0.54	34
B	495.24	1:1.22:2.03:0.42	45
C	547.37	1:1.01:1.83:0.38	54
D	650.00	1:0.69:1.54:0.32	66

This creates an interface between the two mixes of concrete at mid-span. On the fourth day, the specimens are demoulded and kept in water for curing. While handling the specimens, great care is taken to prevent any falling or impact on the specimen. The designation of the beams with and without the interface is given in Table 3.

Table 3 *Details of Mix proportions*

Specimen Desg	Description
AI	No Interface, Intact beam: mix A
AA	Interface between mixes A & A
AB	Interface between mixes A & B
AC	Interface between mixes A & C
AD	Interface between mixes A & D

For each size, three identical specimens are cast. Intact beams (AI) without any interface are also cast to compare its behavior with the beams having an interface.

On day one, first-half of the beam is casted with mix A. On day two, the specimens are tested in a closed loop servo-controlled testing machine having a capacity of 500 kN. A specially calibrated 50 kN load cell is used for measuring the load. The load-point displacement is measured using a Linear Variable Displacement Transducer (LVDT). The Crack Mouth Opening Displacement (CMOD) is measured using a clip gage. All the fatigue tests are performed in load control with sinusoidal wave form and 1 Hz frequency. The fatigue loading is applied in such a way that the maximum load increased by 0.5 kN after every 500 cycles as shown in Figure 2.

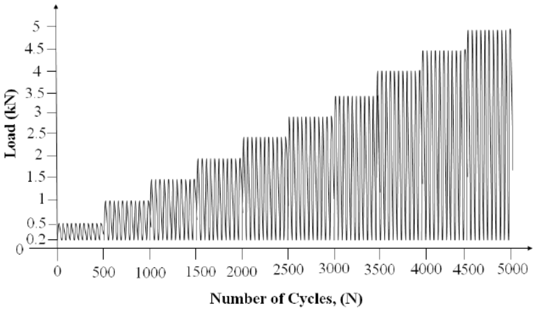


Figure – 2 *Typical pattern of fatigue loading*

The minimum load of 0.2 kN is kept for all the cycles to measure the unloading compliance and also to have some contact between loading device and the specimen for avoiding any impact loading during application of the fatigue load. The results of load, displacement, CMOD and time are simultaneously acquired through a data acquisition system. The details of instrumentation used for acquisition of AE data is shown in Figure 3. In order to obtain a three-dimensional location of AE-events, six AE-sensors are mounted on the specimen as shown in Figures 3.

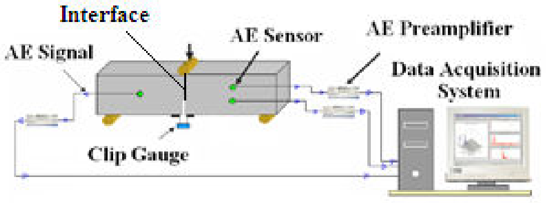
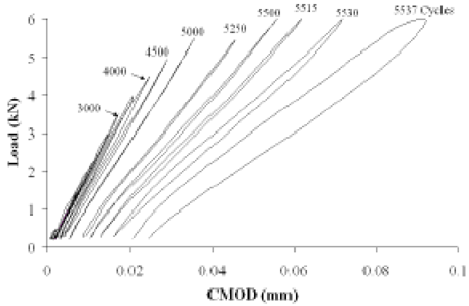


Figure – 3 *Details of AE acquisition system*

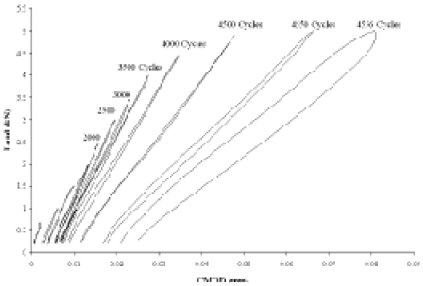
The AE signals are amplified with a gain of 40 dB in a (PAC) pre-amplifier. An AE win for SAMOS E2.0 (Sensor based Acoustic Multichannel Operating System), developed by Physical Acoustics Corporation (PAC)-USA has been used as AE data acquisition. A threshold of 45 dB, which is normally used for concrete is adopted.

3 RESULTS OF MECHANICAL TESTING

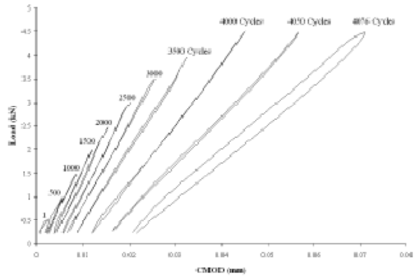
The data on load, CMOD and mid-span vertical displacement acquired during the tests is analysed. Figure 4 shows the typical load versus CMOD curves corresponding to certain selected number of cycles for Intact (AI) and interfaces AA, AB, AC and AD specimens. From these curves, the CMOD-compliance is measured as the slope of the unloading curve. The measured value of the initial compliance (at 1st cycle) is calibrated using finite element (FE) analysis using the commercial package Atena [3]. The FE analysis is performed for different notch to depth (a_0/d) ratios and the respective compliances are computed. A typical compliance calibration curve for small specimen obtained using FE analysis for different interfaces is shown in Figure 5. Using the measured compliances at different cycles, the corresponding effective crack lengths are estimated using the compliance calibration curve for that specimen.



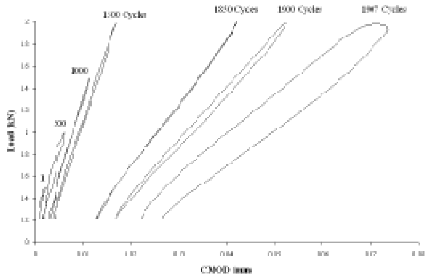
(a) AI



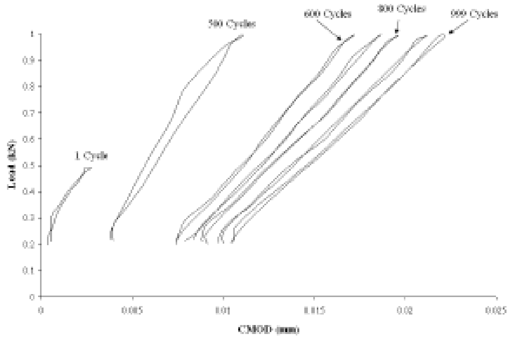
(b) AA



(c) AB



(d) AC



(e) AD

Figure – 4 *Load versus CMOD plot (selected cycles) for small, medium and large specimens with different Interfaces*

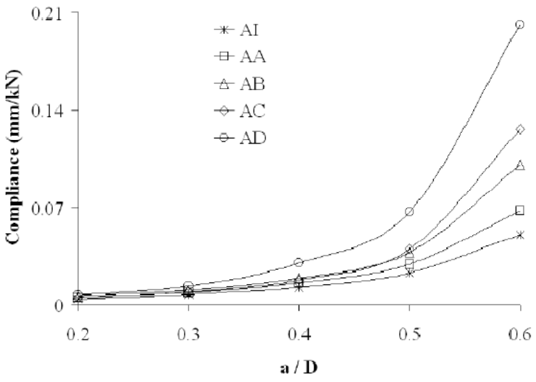


Figure – 5 *Typical compliance calibration curve obtained from FE analysis*

5 RESULTS ACOUSTIC EMISSION (AE) TESTING

The AE events locations at fatigue failure for medium specimen are shown in Figure 6. The number of AE events occurring for different specimens are indicated in these figures. It is clear from the figures that as the difference between the compressive strength on either side of the interface increases, the number of AE-events decreases thereby demonstrating the increase in brittle behavior. The greatest advantage of the AE-technique is online the monitoring and this advantage is exploited for the on-line monitoring of fatigue crack growth. To measure or observe the fatigue crack propagation in concrete-concrete interface specimen is very difficult, because the crack will not be visible unless it has become critical and when it becomes critical, in fraction of seconds the specimen will fail completely. With application of acoustic emission the number of AE-events, number of AE-counts, number of AE-hits and AE-energy can represent the amount of cracking and damage that is undergoing during the fatigue loading. Figure 7 shows the plot of cumulative number of AE events versus number of cycles for all the specimens. It is observed that in first two stages (i.e. stage I of crack initiation, and stage II of stable crack propagation) the rate of increase of number of AE events is constant and as soon as the fatigue crack becomes critical, (i.e. stage III of unstable crack propagation), the number of AE events increases very rapidly until final failure. This aspect of AE-events can be very important tool to monitor the fatigue crack growth in civil engineering structures, as change in AE events is the representative of amount of damage occurred in the structure due to the fatigue load. It is very important to know the amount of energy required for fatigue crack propagation and failure. The AE energy can be very useful to estimate this because, the amount of energy required for crack propagation is proportional to the amount of AE energy emitted. In case of the present fatigue experiments, it is observed that there is rapid increase in AE energy when the fatigue crack growth enters in the region-III (unstable fatigue crack propagation). The cumulative AE energy emitted during fatigue loading is plotted with the number of cycles as shown in Figure 8, for small, medium and large specimens.

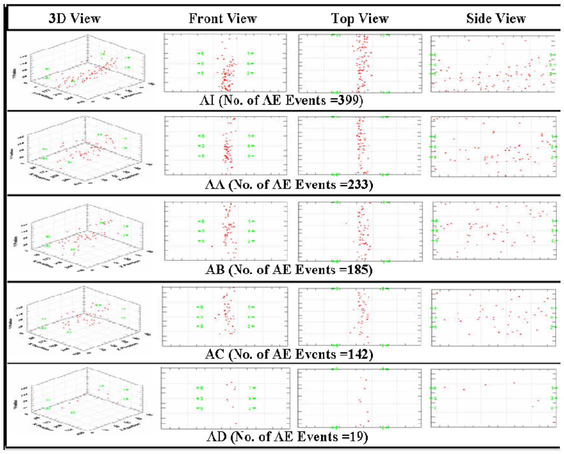


Figure – 6 *AE Event locations for medium specimens at failure*

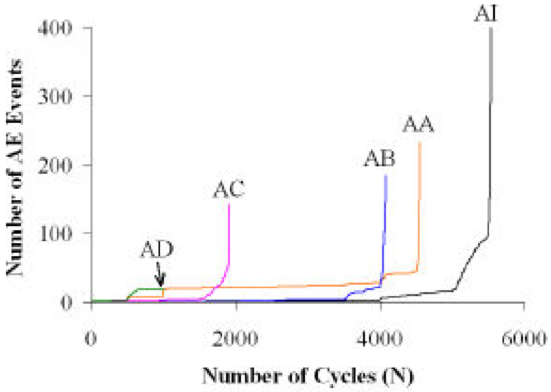


Figure – 7 *AE Event v/s Number of cycles at failure*

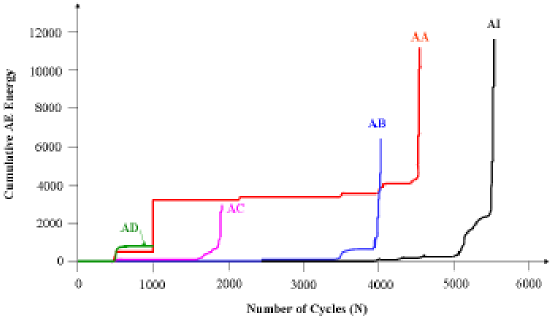


Figure – 8 *Cumulative AE Energy v/s Number of cycles at failure*

The comparison of number of cycles to failure, number of AE events, Number of AE counts and amount of AE energy released as shown in Table – 4, for medium specimens. It is seen that the for intact specimen, number of AE events and AE counts as well as the amount of AE energy released are very high for intact specimen and it decreases as the difference between the compressive strength on either side of the interface increases, thereby demonstrating the increase in brittleness.

Table – 4 *AE Testing Data*

Spec. Desg.	No. of Cycles	No. of AE Events	No. of AE Counts	AE Energy (PAC Units)
AI	5550	399	12000	1.34E+07
AA	4563	233	11000	3.08E+06
AB	4091	185	5800	2.35E+06
AC	1922	142	3000	1.19E+06
AD	1019	19	1000	6.60E+05

6 CONCLUSIONS

The fatigue crack growth for concrete-concrete interface specimens is studied using Acoustic Emission (AE) technique. Beam specimens of different sizes having a jointed interface between two different mixes (strengths) of concrete are prepared and tested under three-point bending (TPB) in a closed loop servo-controlled testing machine under fatigue loading. It is observed that the rate of increase of acoustic emission events and energy are same as that of fatigue crack growth which suggests the existence of a relationship between the number of AE-events and the length of fatigue crack. It is seen that the AE-events and AE-energy are the measure of cracking and damage that has occurred inside the structure and can be monitored on-line during the fatigue loading, which is very difficult to observe or to measure by any other techniques. It is observed that as the difference between the compressive strength of concrete mix on either side of interface increases, the number of AE events, AE counts and amount of AE energy decreases which indicates the increase in the brittle behaviour of interfaces. When a fatigue crack becomes critical, the number of AE events increases very rapidly until final failure. This aspect of AE-events can be very important tool to monitor the fatigue crack growth in civil engineering structures, as change in AE events is the representative of amount of damage occurred in the structure due to the fatigue load.

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