Fatigue Monitoring of High Strength Concrete Using Acoustic Emission and Ultrasonic Techniques

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ABSTRACT

In this work we present the results of a measurement campaign performed on high strength concrete, to investigate fatigue behavior under cyclic loading in terms of a Structural Health Monitoring (SHM) system. The specimens, small concrete cylinders, were equipped with acoustic emission (AE) and ultrasonic (US) sensors which recorded signals from the onset of beginning fatigue processes in the material until complete damage of the specimen. The parameters monitored have been the acoustic emission activity and the ultrasonic signals time-of-flight respectively travel velocity. The results are in accordance to tests on different concrete material and demonstrate the capability of the proposed methods to trace the fatigue process of concrete. As roundup, results obtained with similar sensing technologies on a large scale structure are presented.

INTRODUCTION

These days concrete is a widely-used material for building. Engineered concrete structures are increasingly exposed to dynamic loads due to architectural, economic and constructional demands. A better knowledge of the fatigue state of concrete structures is of great interest for their designer, operator and maintainer since it can lead to realistic remaining life estimations and give valuable input for an infrastructure life-cycle management.

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Structural Health Monitoring (SHM) as a damage detection strategy seems a good choice to approach this problem. Things are complicated though by the very complex material behavior of concrete, which basically results from its highly heterogeneous microstructure.

The goal of this work is to demonstrate on laboratory level a Structural Health Monitoring system for fatigue endangered concrete structures, as e.g. wind energy plants (on- and offshore) based on ultrasonic (US) and acoustic emission (AE) sensor techniques. The measurement system consisted of two US-Sensors (a sender-receiver pair), one AE-Sensors, as well as data acquisition and signal actuation hardware and own developed measurement and evaluation software.

For the test campaign specimens of high strength concrete, the same as used in the field have been produced at the concrete laboratory of the Züblin AG, Stuttgart. The sensory equipped specimens were put into a test apparatus capable of applying cyclic loading at the Institute for Structural Engineering of the University of Natural Resources and Life Sciences, Vienna.

EXPERIMENTAL SETUP

The specimens were cylinders in size 6 x 18cm, made of the high strength concrete C80/95, with a maximum grain size of 16mm. The sensors used for the experiments were *S24 HB 0.1-0.3* from Karl Deutsch for US measurements and *VS75-V* Sensor from Vallen for the acoustic emission.

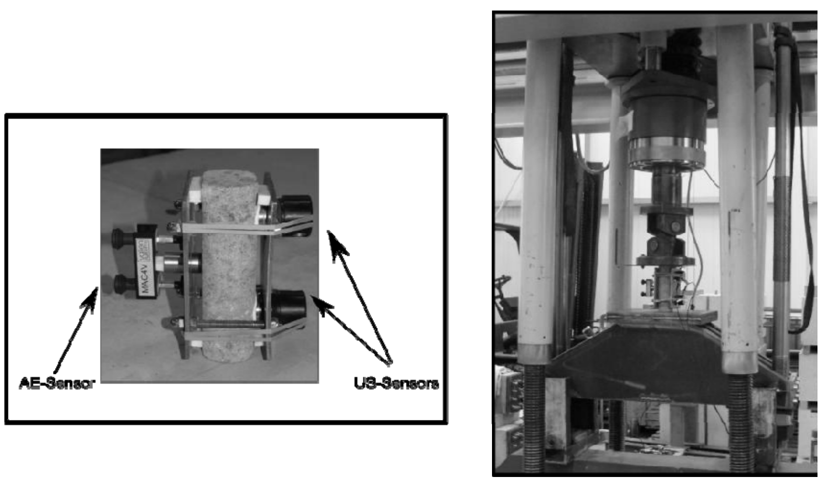


Figure 1. a)Concrete cylinder with mounted sensors, b)cyclic loading apparatus with inserted specimen.

Small parts of the cylinders have been cut off to achieve a planar surface for applying the sensors. ***Figure 1*** shows the specimen with mounted sensors (a) and placed in the apparatus used for applying the cyclic loading (b). The distance between the US-Sensors was 10cm. On the opposite side of the cylinder, exactly in the middle, the AE sensor has been mounted.

The actuation and data acquisition units were realized using the actuation board ARB1410 from Physical Acoustics and an 8 channel CompuScope card from Gage

On the software side a Labview program was implemented that combined both (AE and US) tasks in a single application. The actuation signals for US measurements were 3 times sinusoids with frequency 100 kHz and amplitude +/-150V, confined by a sine window. The AE sensor had to be pre-amplified and was connected via a de-coupler box, acting as power supply, to the digital scope card.
The characteristics of the loading cycle were: frequency 3Hz, maximum force 200kN, mean force 110kN and amplitude 95kN.
This load level is 70% of the mean compression strength of the used concrete material.

Basic parameter of the ultrasonic measurement is time-of-flight (TOF) from the signal generated at the actuation sensor to the receiver. The TOF is extracted online from the signals. This is realized by the implementation of an algorithm that detects the first peak of the receiving signal (***Figure 2***). In succession the wave velocity in the concrete can be calculated from the TOF. Evolving micro cracks due to the cyclic loading will alter the TOF and allow to establish a correlation to the structures fatigue state.

The AE measurement was running continuously and only stopped at defined periodic intervals for US measurements to take place. It is important for these measurements to not interfere with each other. During each of these breaks several numbers of US-measurements were made.

The measurement software does an analysis of the raw recorded signals of the AE-Sensor and extracts AE-hit parameters such as: maximum amplitude, counts, energy, rise time and duration, which are then stored to disk. The individual hits are then collected to generate a resulting hit rate (hits per time unit), cumulative hits and cumulative energy content of hits over the time period of the load test. Since the very huge amount of data that is produced during the continuously running AE measurement (sample rate 2.5 MS/s), transient (raw) signals have been recorded only in distinguished intervals (e.g. every 1000 load cycles).

RESULTS

Ultrasonic measurements

The typical development of the US-velocity over the lifetime of the concrete cylinder is exemplified for one specimen in ***Figure 3***. The three phases of concrete fatigue as described e.g. in [1] can easily be identified.

> *Phase I*: sharp decline, nonlinear increase of cracks due to initial applied loading and release of energy from inherent intrinsic stresses in the structure
> *Phase II*: gradual decrease, gradual increase of damage has linear effect on US velocity (starting at 10-20% of lifetime)
> *Phase III*: sharp decline rise of total deformation, disproportional formation of micro cracks and merging of existing cracks, collapse of the structure (start at approx. 80% of lifetime)

The US-signals TOF respectively its velocity is highly sensitive to micro cracks in the concrete structure. These cracks accumulate while the cyclic load campaign is progressing and so the velocity becomes a measure for the integral condition of the concrete that is crossed by the signal on its way from sender to receiver. For the several US measurements that have been made during a break of the AE there is a cyclic variation in TOF and the deduced wave velocity. This is because the TOF is depending on the current stress level in the still ongoing cyclic loading. At the maximum pressure point of the load cycle cracks are compressed and less visible for the US-signal, while at the point of least compression the micro cracks are farthest open and hence pose a bigger obstacle for the US wave. In ***Figure 3*** this is represented by the minimum- and maximum denoted curves.

This could be an evidence for a mechanism similar to crack breathing in steel structures as described e.g. in [3].

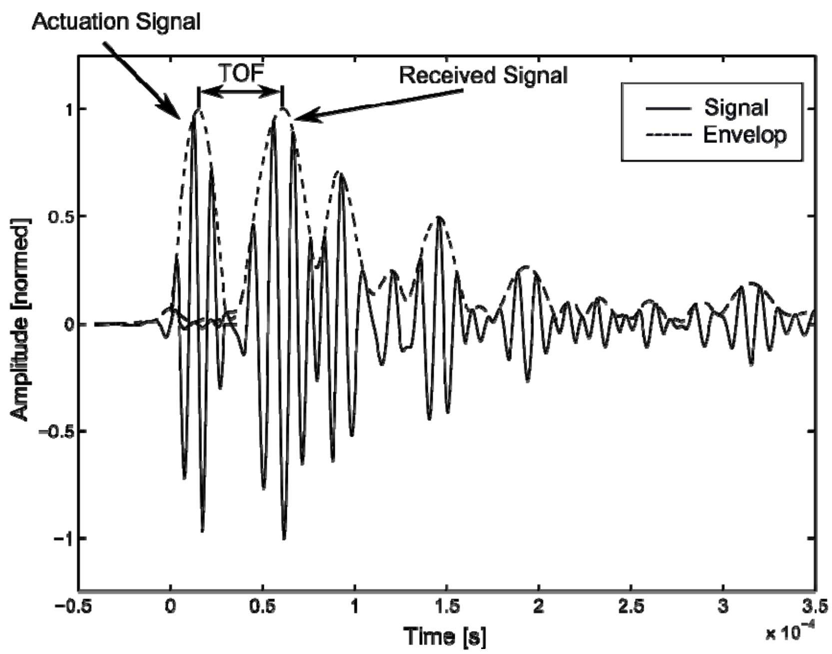


Figure 2. Typical US-Signal with superimposed actuation signal.

Acoustic Emission

AE hits are elastic waves that occur due to formation of new damage or as a result of friction noise between already existing damages. Under load there is usually a high AE activity and a large amount of hits are generated. A good representation of the AE activity is the hitrate (hits per time unit) and the cumulative number of hits occurring over time.

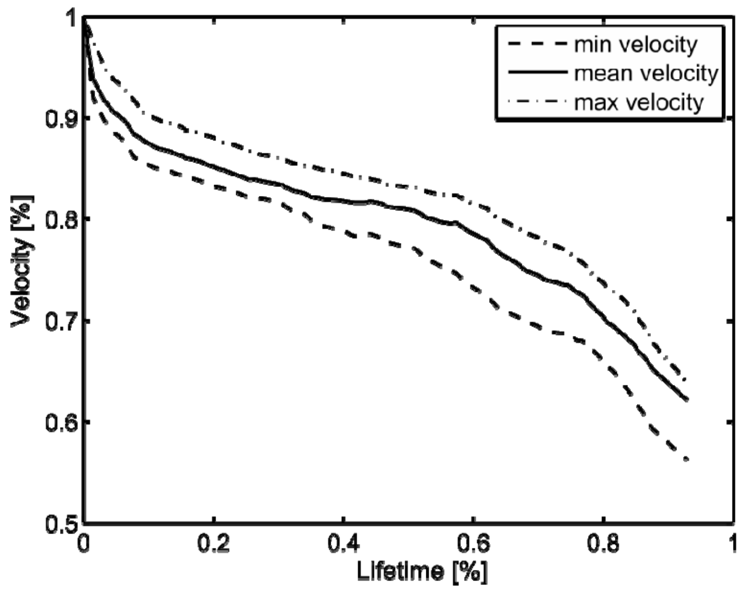


Figure 3. US-velocity development over specimens lifetime.

In ***Figure 4*** these representations are shown for a specimen's lifetime under cyclic loading. At the end of the test the hitrate is characterized by a sharp rise in the number of AE-Hits. The plot of cumulated hits and the cumulated energy of the hits show the interesting feature that the slope of the cumulative hit energies surpasses the hit numbers at the end of the test. This indicates that the same number of hits carry larger amounts of energy. The rise in the energy content of the hits could be a useful feature to detect the onset of severe damage formation in the structure, as described in phase III above.

At periodic intervals (every 1000 cycles) the AE-raw were recorded. These signals were subject to a fast Fourier transformation (FFT) to reveal their frequency content. In ***Figure 5*** the results of the FFTs are shown. At the end of the specimen's lifetime certain peaks in the frequency spectra begin to appear (one at around 75 kHz and a clearly lower but still significant one at 212 kHz). Whether this feature can be a useful measure for the material's fatigue state has to be investigated in future research.

The results (both US and AE) are consistent with recently published experiments [2]. In the referred work a concrete material of lesser strength has been used.

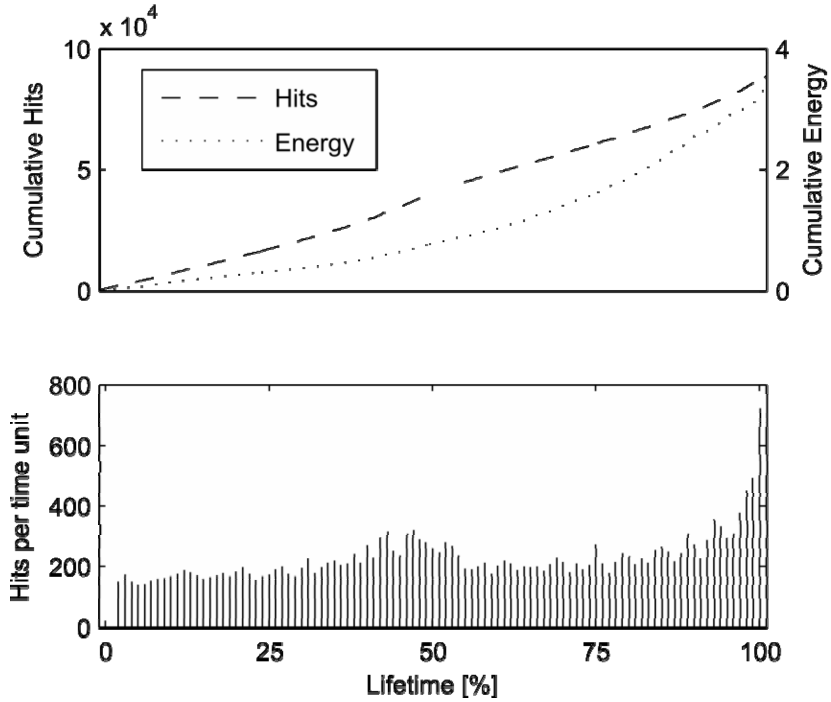


Figure 4. Hitrate, cumulative hits and cumulative energy over the specimens lifetime.

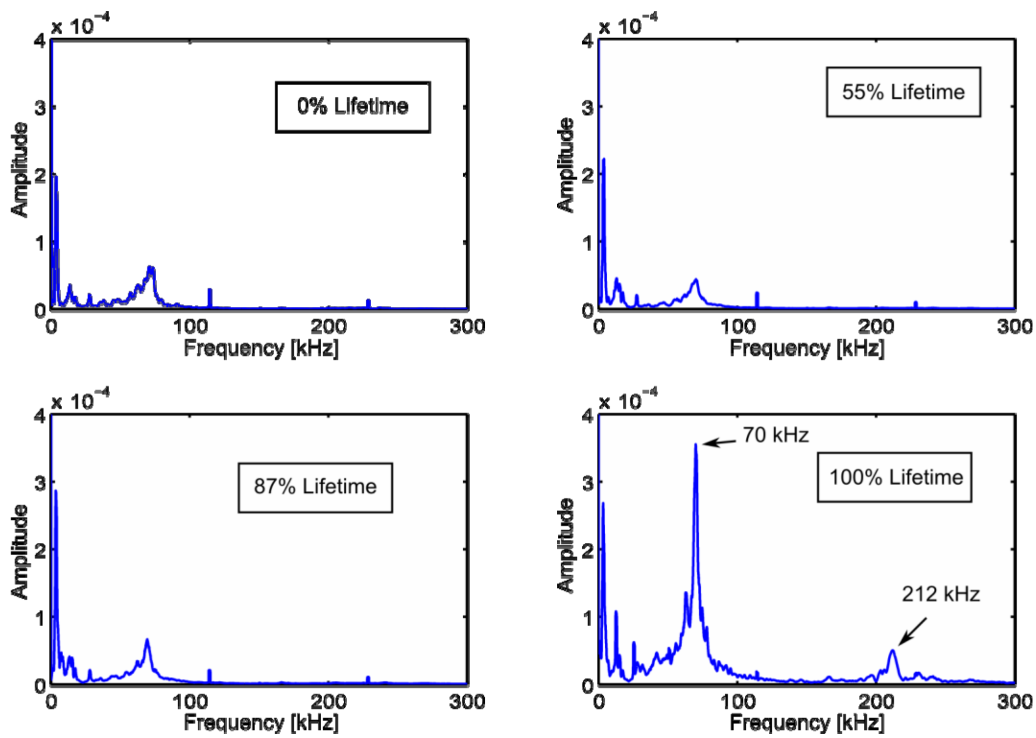
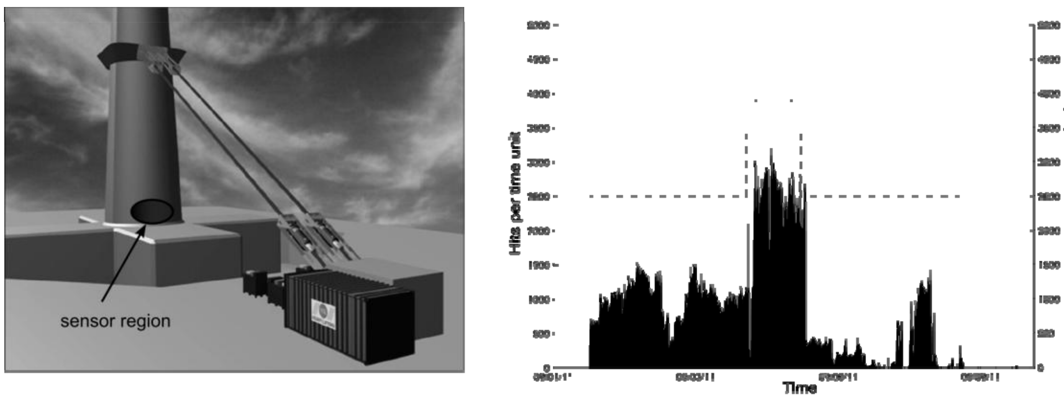


Figure 5. Frequency spectra of AE-Raw signals for different states in the specimens lifetime.

LARGE SCALE TESTS

A monitoring system consisting of several AE and US sensors was implemented on a concrete gravity base foundation (GBF) of a wind energy plant. The GBF is constructed for off-shore operation, but for this test campaign it has been realized on-shore. The fatigue processes were induced due to injection of artificial dynamical loads via a towing device (see Figure 6 a)).



a) b)

Figure 6. a) GBF with towing apparatus, b) Hitrate during a load scenario.

The sensors have been placed on the most severely fatigue endangered zones at the bottom of the GBF's shaft (see fig.6). Various loading scenarios (from operation load to storm events) were executed over several months and in total more than 1 million load cycles have been applied. In Figure 6 b) a result for AE is shown. The hitrate is displayed together with the mean load levels applied. Load cycling was done around this mean level with frequency of 0.25Hz, and amplitudes from +/-900 to +/-5000 kN. The hitrate shows correlating rise and fall according to the average load level.

With the US sensors the signal wave velocity was measured as in the laboratory experiments. No changes in the wave velocity have been detected so far. This result is in accordance with the GBF-maintainers calculations. With the induced integral amount of loads no recognizable damage should have been induced to the structure so far.

CONCLUSIONS

We demonstrated the principal feasibility of a concrete fatigue monitoring system using US and AE methods.

A test campaign was performed on small concrete cylinders and indicated the capability of the proposed methods to trace the process of fatigue in concrete.

The strength of the proposed sensing technologies lies in their combination of sensing domains. While the AE reacts to local effects (crack generation, crack growth), US is an integrative method. In the US signal all the signal influencing effects on its path summed up to form the measure of an integral property of the monitored area.

The AE hit-energy and the characteristic of the AE raw signals frequency spectrum could turn out to be useful parameters to detect the transition from the rather uncritical fatigue phase of slowly increasing damage to the phase were severe damages occur that lead to a rather fast collapse of the structure.

A goal for further tests is perform cyclic loading at lower dynamic load levels and represent real life conditions. The duration of the test will increase dramatically, since at lower load levels the number of cycles to induce the same amount of damage grows exponentially [4].

Large scale tests showed that the methods developed in the lab could be transferred and applied to real life concrete structures. Results achieved with AE are in good accordance with induced load levels. Further research and testing has to be done to verify, elaborate and improve on the results for the concrete fatigue monitoring system.

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