Acoustic emission and ultrasonic testing for fatigue damage detection in a RC bridge deck slab

Imane BAYANE [1], Eugen BRÜHWILER [1]
[1] Ecole Polytechnique Fédérale de Lausanne, Lausanne, Switzerland
Contact e-mail: imane.bayane@epfl.ch

ABSTRACT: There is a significant need to examine precisely the conditions of concrete road bridges because of the increasing traffic and axle loads and the fact that most existing bridges were not designed with respect to fatigue. In-situ investigations are challenging in terms of long-term monitoring of deformations and displacements, the difficulty of access to relevant zones of bridges in service, and limitations in current measurement methods and techniques.

This paper presents the case study of a specifically designed continuous monitoring system, installed in the reinforced-concrete slab of a 60-year road viaduct, in order to detect possible initial fatigue damaging events due to traffic loading, since the slab currently does not show any sign of fatigue damage in terms of cracks.

The originality of the paper lies in the combination and synchronization of four non-destructive-testing techniques, i.e. an acoustic emission system, an ultrasonic system, strain gauges, and thermocouples, to perform long-term monitoring of the RC deck slab of this viaduct under service conditions. It is found that the monitoring system is efficient to detect acoustic emission parameters as a function of traffic and temperature variations.

KEYWORD: Acoustic Emission, Ultrasonic, Reinforced concrete, Road Bridge, Non-Destructive-Testing (NDT) techniques.

1 INTRODUCTION

1.1 *Motivation and objective*

Change in mindset for a sustainable future and responsible use of material and financial resources is increasing the need to improve the service life of existing bridges. New engineering methods and techniques are required to evaluate the safety of structures in service, particularly their performance against long-term loads, due for example to traffic and environmental changes.

Repeated cyclic loading applied to reinforced-concrete (RC) bridges may damage the concrete or steel reinforcement. Fatigue failure is complex and depends on the interaction between structural elements, materials, geometries and loads. Relevant knowledge about the fatigue of steel has been accumulated during the last century, while the fatigue of concrete was not advanced and often not conclusive (Drouillard, 1994).

The repeated loads of traffic and environmental changes can lead to the apparition and evolution of microcracks in concrete. The evaluation of the safety of reinforced-concrete road bridges requires then the assessment of the state of concrete under traffic and environmental changes.

Different non-destructive-testing techniques were developed, used and standardized to detect damage. However, their potential was not always fully exploited for in-situ long-term monitoring.

Acoustic emission (AE) and ultrasonic (US) techniques were widely used in laboratory fatigue tests to detect and track the evolution of cracks, and they are appropriate for long-term monitoring, without interrupting traffic or damaging the structure. Acoustic emission is based on recording elastic waves, and ultrasonic technique is based on sending and receiving elastic waves (Maierhofer et al., 2010).
Crack apparition, friction, and propagation can generate prominent AE events and create changes in US signals, which are related to the area of surfaces, material properties and load levels (Chang and Kopsaftopoulos, 2015).
In this paper, the use of acoustic emission and ultrasonic techniques to evaluate the performance of concrete under traffic and environmental changes will be presented through a real case study of continuous monitoring of a road viaduct, in Switzerland.

1.2 *Presentation of the structure, case study*

The monitoring system was installed in a 60-year-old composite concrete-steel road viaduct, named Crêt de l'Anneau. The viaduct is situated between Neuchâtel and Travers, in the cantonal road X10 connecting Switzerland and France. It has 2 traffic lanes, with a total width of 10.5 m, and legal maximum weight transportation of 400 kN.

The viaduct comprises seven articulated spans of a length of 25.6 m and an approach span of 15.8 m. The span is made from a reinforced-concrete slab of a thickness varying from 0.17 m in the mid-span to 0.24 m, fixed in 2 steel girder beams with a height of 1.3 m.

The reinforced-concrete slab has been constructed with concrete of a minimum 28-day cube compressive strength of 35 N/mm², a raw density of 23 kN/m^3, and a modulus of elasticity of 35' 000 N/mm². The slab has longitudinal and transverse reinforcement rebars in both tensile and compression zones with diameters of 10 mm, 14 mm, and 18 mm.

2 PRESENTATION OF THE MONITORING SYSTEM

2.1 *Monitoring system*

The viaduct was instrumented with two continuous monitoring systems. The first system comprises strain gauges and thermocouples installed and calibrated in June 2016. It provides a high-frequency continuous measurement of strain in 4 transverse rebars, 3 longitudinal rebars, and the girder. The temperature of concrete, steel, and the air was also continuously measured (Bayane and Brühwiler, 2018).
The outputs of one strain measurement and one temperature measurement were linked to the second system that will be detailed in this paper. The second system comprises acoustic emission and ultrasonic systems, installed in November 2018 and calibrated in February 2019.

2.2 *Equipment*

The acoustic emission system includes:

- The data acquisition system which is a sensor Highway for in situ monitoring, comprised of a Processor Atom N2600, with a memory card of 128 Go and 32 acquisition channels of a bandwidth range from 1 to 400 kHz, at -3 dB.
- 24 resonant sensors PK15l, resonating at 150kHz with an integrated preamplifier of 26 dB gain.

The sensors detect transient waves and convert them to an electrical signal. Resonant sensors were used because of their high sensitivity to typical AE sources and the integrated preamplifiers were used to avoid any signal loss.

The ultrasonic system includes

- A card ARB-1410-150 to generate arbitrary signals, arbitrary waveforms from a text file, and pre-programmed modulation of amplitude and frequency.
- A multiplexer with 4 channels on the card ARB.
- Industrial calculator connected to the ARB card and controlled by the data acquisition system sensor Highway.
- Sensors PK15l resonating at 75 and 150 kHz.

2.3 *Sensor location and installation*

Based on finite element analysis, and the distribution of vehicle position in the cross-section, four main localized zones of the slab were instrumented (Fig. 1).

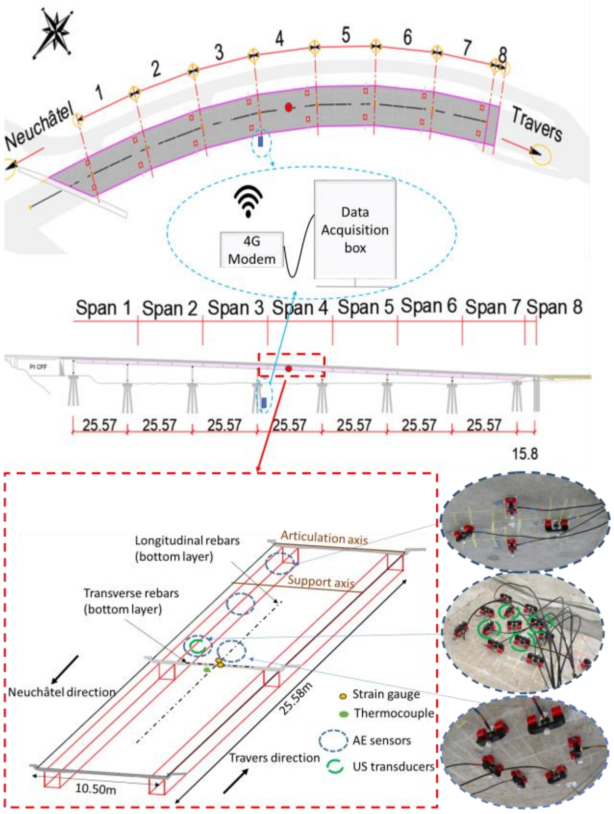

Figure 1. Drawing of the viaduct (plan view and elevation side) - data acquisition system – instrumented slab; dimensions in [m].

The sensors were mounted in the most loaded parts of the reinforced-concrete slab of span 4, in the mid-span and in three different longitudinal zones in the middle of the lane with the high number of heavy trucks. All the sensors were mounted in the underside of the reinforced-concrete slab since there is no access to the other sides. The rebars were detected with a profometer, to avoid installing the sensors underneath the rebars.
Magnetic holders were used to ensure strong fixation of the sensors in the slab. Silicone glue was used to provide a direct and flexible connection between the contact surfaces of concrete and the sensors. The surface of concrete was smoothed and cleaned for a better contact.
The electronic noise coming from the interaction between the cables of connection of the acoustic emission system and the ultrasonic system was avoided by fixing the cables far away from each other.
This mounting solution gives the possibility to have consistent and high sensitivity measurements for long-term monitoring, with the possibility to reuse the sensors after.

2.4 *System mounting and calibration*

The collected AE data was visualized in real time using ARwin program.
Sensor calibration and signal attenuation were performed with the pencil break method according to the standard EN 1330-9, 2017. Pencil break test was completed for each sensor and the recorded amplitudes were evaluated. When the sensors were not giving a good response, the coupling and fixation were repeated.
Three parametric inputs were used to connect the first monitoring system with the data acquisition system: The transverse and longitudinal strains of the rebars in the mid-span of slab 4 and the temperature of concrete.
Pulsing sensors were connected to the card generating pulses controlled by the acquisition system sensor Highway. The frequency of interaction between the sensors and the card was fixed at 800 kHz to get the last arrivals of the waves while the frequency of the pulses was 150 kHz to be suitable for concrete. The pulses were generated at each hour and recorded by the acoustic emission sensors.
The evolution of acoustic emission activity under traffic and environmental conditions was preliminarily measured during December and January with different settings. The recorded signal was then analyzed to define well the filters for suitable noise precautions for a long-term monitoring.
Real-time visualization of acoustic emission activity was possible for a threshold above 30 dB. To delete totally the noise of traffic, only the AE hits between 40 and 1 000 counts and the waveforms with counts between 5 and 10 000 and an amplitude between 40 and 1 000 dB were recorded. A time filter was defined, for a Peak Definition Time (PDT) of 200 µs, a Hit Definition Time (HDT) of 800 µs and a Hit Lockout Time (HLT) of 1 000 ms (Fig. 2). Under the chosen filters, no acoustic emission activity was observed in the absence of traffic.
The remote monitoring was provided by a 4G modem and a remote access program.

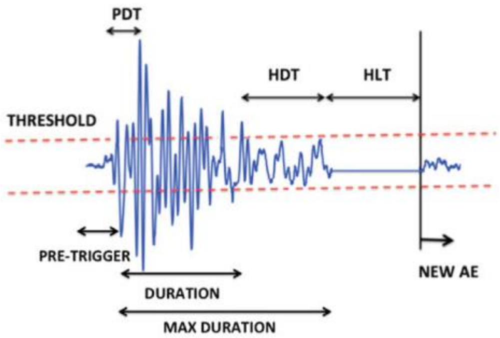

Figure 2. Time domain parameters of an AE waveform (Moradian and Li, 2017)

3 ANALYSIS AND RESULTS

The monitoring was continuous to measure possible ongoing deterioration processes under traffic and environmental changes, by capturing possible changes in the acoustic and ultrasonic signal activity. It will be running for one year to capture the effect of the annual distribution of traffic and temperature.

3.1 *Features*

Different features were used to evaluate changes in the acoustic and ultrasonic signals, i.e. the amplitude, the rise time, the duration, the energy and the counts (Fig. 3).

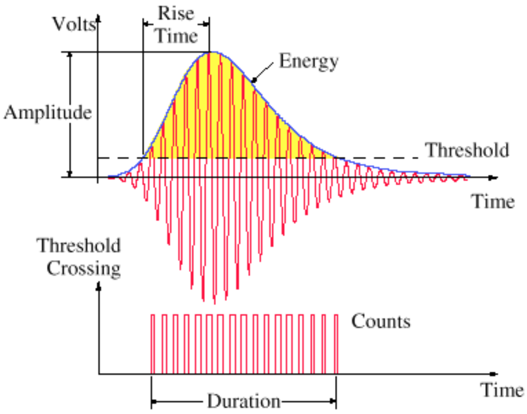

Figure 3. AE common parameters of a waveform (Huang et al., 1998)

Amplitude is the maximum voltage in [dB] of the recorded waveform. It reflects the detectability, the intensity and the attenuation of the signal.
Rise time is the time between the first point above the threshold and the maximum peak of the recorded waveform. It indicates the distance between the source of the event and the sensors.
Duration is the time between the first and the last points above the threshold. It reflects signal activity.
Counts are the number of peaks above the threshold, it depends on the activity of the signal.
Energy is the area between the first and last points above the threshold and the maximum voltage. It determines the signal intensity.

3.2 *Ultrasonic signal*

Ultrasonic transducers perform a pulse each hour, recorded by the acoustic emission sensors. The frequency of the pulses was 150 kHz, appropriate for the instrumented concrete given that the maximum aggregate diameter is 32 mm. The frequency of interaction between the ultrasonic transducers and the card generating the signals was fixed at 800 kHz to record the full waveform of the signal and get the last arrivals, which will be used to detect small changes for the period of monitoring as a further work.

3.3 *Acoustic emission signal*

Preliminary analysis of acoustic emission signal using conventional feature parameters shows that amplitude was sensitive to both traffic and temperature changes, while energy, counts, and duration gives a clear indication of traffic. To evaluate the different changes of the RC slab, different correlation plots were analyzed, and preliminary localization of AE events was performed.

3.3.1 Connection Girder-slab

Figure 4 shows the plot of the hits versus channels for 24 hours of record.
Relatively higher acoustic emission activity was observed at sensors placed near the girder (in yellow, Fig. 4). This could be attributed to the presence of discontinuities or relative displacement between the girder and the slab connection, as it was seen in (Nair and Cai, 2010).
The friction between the RC slab and the girder produced many AE events during the passage of vehicles. A threshold of 5 000 Hits can be clearly defined to separate AE events in the RC slab and those occurring near the connection slab-girder.
The evolution of the acoustic emission activity of sensors crossing that threshold provides qualitative information about the performance of the connection slab-girder.

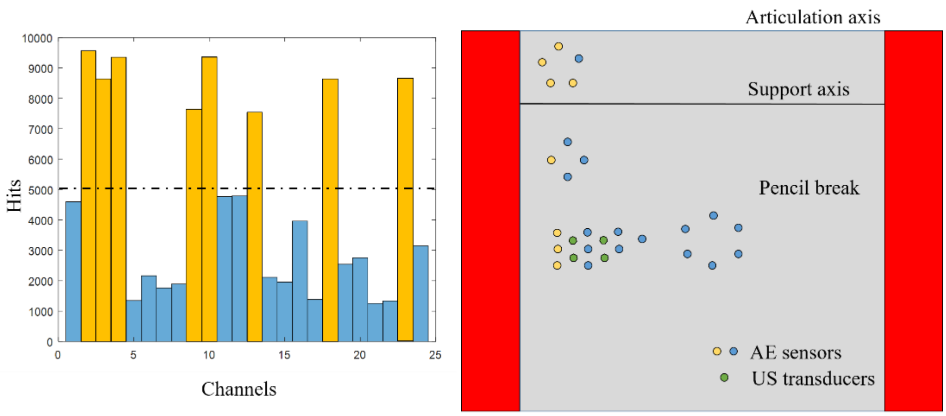

Figure 4. Hits versus channels (left), bottom view of the instrumented slab (right)

3.3.2 Traffic and pencil break test

In figure 5, the results of the pencil break test performed under traffic on 6 February at 12 pm are shown. Correlation plot of duration versus amplitude shows that two clusters can be defined, acoustic emission activity due to traffic, and acoustic emission activity due to pencil break.

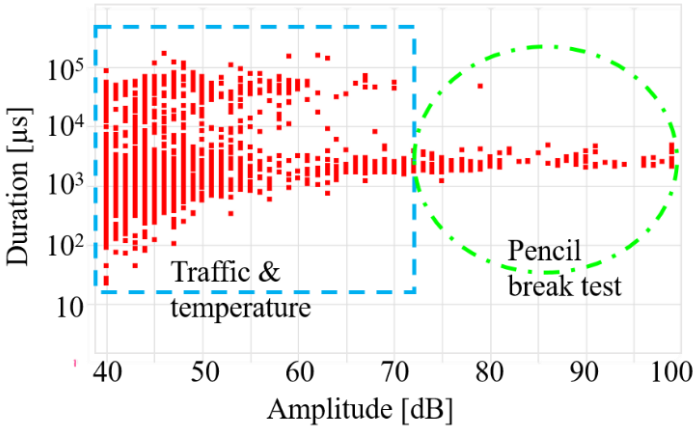

Figure 5. Duration versus amplitude

The amplitude of AE events due to traffic was lower than the artificial AE events due to pencil break test. AE pencil-break events simulate the AE activity due to macrocracking of concrete, the AE activity due to traffic does not present the same intensity as a pencil break, which reveals that the RC slab does not develop any macrocracking activity under traffic.

3.4 *Localization*

The localization was performed using AEwin program. Two modes were used to localize the acoustic emission events, i.e. the zonal location, and the planar location.

In zonal location, the closest sensor to the source was identified using relative arrival times of the hits. The localization was performed when one sensor or more detect the event and it was mostly used to evaluate the AE events outside sensor grids.

Planar localization requires the detection of the events by more than one sensor and provides the localization of the source in a 2D plane. The localization was more precise, and it was performed principally for the events inside sensor grids.

Pencil break test was performed between sensor 22 and 6, and 21 and 5 to evaluate the possibility to localize AE events under traffic. Planar localization was used to detect the position of the events. Figure 6 shows the sensor grid and the 2D localization of the pencil break events.

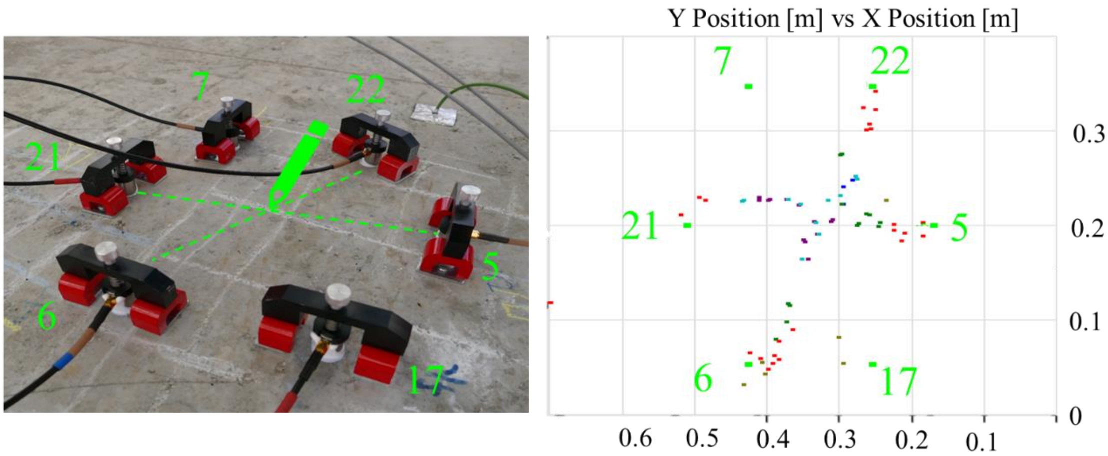

Figure 6. Planar localization of pencil break events

4 CONCLUSION

The design, installation, and calibration of the monitoring system comprised of AE and US techniques to evaluate the fatigue safety of a RC slab were presented. Data recorded during calibration tests and one day of continuous monitoring were analyzed. AE events were successfully combined with strain and temperature measurements.

It was found that the monitoring system was efficient to detect acoustic emission feature parameters as a function of traffic and temperature variations. Initial results show that there was no macrocracking activity in the instrumented parts of the RC slab and that the performance of the connection slab-girder can be tracked with AE activity.

The presented results indicate the potential of the presented monitoring system as a promising diagnostic tool to evaluate and localize damage under traffic and temperature variations. Further work is required to exploit in detail the measurements for different correlations and a long period of monitoring.

5 ACKNOWLEDGMENT

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6 REFERENCES

AFNOR-French standard institute, standard institute, European Standard, 2017. EN 1330-9:2017 Non-destructive testing - Terminology - Part 9 : terms used in acoustic emission testing.www.afnor.org.

Bayane, I., Brühwiler, E., 2018. "Pocket-Monitoring" for fatigue safety verification of a RC bridge deck slab.

Chang, F.-K., Kopsaftopoulos, F., 2015. Structural Health Monitoring 2015: System Reliability for Verification and Implementation. DEStech Publications, Inc.

Drouillard, T.F., 1994. Acoustic emission: The first half century (No. RFP-4875; CONF-9410182-1). EG and G Rocky Flats, Inc., Golden, CO (United States). Rocky Flats Plant.

Maierhofer, C., Reinhardt, H.-W., Dobmann, G., 2010. Non-Destructive Evaluation of Reinforced Concrete Structures: Non-Destructive Testing Methods. Elsevier.

Moradian, Z., Li, B.Q., 2017. Hit-Based Acoustic Emission Monitoring of Rock Fractures: Challenges and Solutions, in: Shen, G., Wu, Z., Zhang, J. (Eds.), Advances in Acoustic Emission Technology, Springer Proceedings in Physics. Springer International Publishing, pp. 357–370.

Nair, A., Cai, C.S., 2010. Acoustic emission monitoring of bridges: Review and case studies. Eng. Struct. 32, 1704–1714. https://doi.org/10.1016/j.engstruct.2010.02.020