Conference Paper

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Publication Date:
2012

Permanent Link:
https://doi.org/10.3929/ethz-a-007335088

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Engineering Technics Press

Edinburgh, UK

June 2012 11 11 English

Professor M.C. Forde, PhD, FREng, FRSE, FACI, CEng, FICE, FIET, Carillion Chair, University of Edinburgh

Abstracts and Exhibition Showguide

Structural Faults & Repair-2012, 14th International Conference & Exhibition

Edinburgh, UK

July 3-5, 2012

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LONG-TERM MONITORING OF A PRESTRESSED CONCRETE BOX GIRDER BRIDGE BY ACOUSTIC EMISSION – PLANNING AND EXECUTING

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KEYWORDS: Acoustic Emission (AE), prestressed concrete, field monitoring

ABSTRACT
The correlation between acoustic emission activity and structural safety as well as serviceability is studied. For this purpose, field monitoring of a post-tensioned concrete box girder bridge is planned. AE technique has been chosen in order to detect, localize and evaluate internal deteriorations of a bridge that is under operation. Comprehensive understanding of structural behaviour will be provided by the dynamic measurements of strain together with acceleration due to traffic. The acquisition will be activated by random events i.e. crossing vehicles with the whole range of loading or even overloading.
To obtain high quality information on structural safety and serviceability, it is necessary to focus on aspects like synchronisation and triggering of the systems as well as signal propagation in the chosen structure and data remote control and transfer.

INTRODUCTION
The purpose of any bridge assessment is to evaluate the up-to-date structural condition and ensure its safety and serviceability at least until the subsequent inspection. As a complementary to the standard applied bridge assessment methods (fib 17 2002), Acoustic Emission (AE) testing technique has been chosen. AE has proven to be successful not only in the laboratory but also in field applications in detecting existing developing internal damages in concrete bridges. The main applications consider evaluation of concrete bridge overall integrity (Shigeishi et al. 2001, Colombo et al. 2003), as well as focusing on specific aspects like wire breaks of prestressing tendons (Vogel and Fricker 2007, Ohtsu and Yuyama 2010), traffic-speed-depending-AE activity in a reinforced concrete bridge (Ohtsu and Yuyama 2010), or the influence of the use of studded tires on AE activity and signal frequency response (Schumacher 2010). A procedure of AE monitoring has been studied and proposed by some research institutions (Colombo 2003, Lovejoy 2008). AE monitoring in general and especially field monitoring require certain procedures to be followed in order to record meaningful data. The general idea of actions to be followed before, during and after the testing has recently been published in the European Standards (EN 2011). The standard procedure includes:
(1) Instrumentation (incl. sensor selection, sensor installation and coupling media, signal conditioning and processing, settings and external parameters inputs),
(2) Testing (incl. preliminary information and preparation as well as on-site preparations and data acquisition, storage and presentation),
(3) Data analysis (incl. on-line and post-test analysis),
(4) Test instruction (summary check list),
(5) Test documentation and test report.

This study considers preparation works for AE application on a post-tensioned concrete box girder bridge. Following the guidelines (EN 2011), a procedure for long term monitoring under ambient traffic is proposed. Some considerations regarding the given geometry and inhomogeneity of concrete are discussed.
TESTING – TEST OBJECT
Hermetschloo Bridge in Zurich, built in the early 1970’s, is a post-tensioned concrete box girder bridge (see Figure 1), which, as a pilot project, was constructed with lightweight concrete. Like most bridges built in Switzerland but also across Europe, it has been constructed as a continuous girder with 9 spans, each ca. 40 m long (see Figure 2), which results in a total length of 339 m. It crosses most of the railway lines leading to the main station of Zurich.

The bridge is tensioned in longitudinal as well as transverse directions. The longitudinal tendons are located in the box girder’s webs, while the transverse tendons are located in the top slab as well as in the prefabricated cross girders strengthening the top slab and in the bottom slab. Transverse cracks have been found in the top slab between the cross girders, which presence could not be explain so far. However, the general condition of the bridge after the last inspection in 2007, has been assigned to the condition class 3 according to the general standards (VSS 2003) corresponding to a damaged level.

For the monitoring, critical sections, like mid-spans and diaphragms, have been chosen (see Figure 3).

The planned investigations are considered to be performed within span 8 – 9 (see Figure 2 and Figure 3), in order to capture the signals free from the noise produced at the expansion joint (abutment 10).

INSTRUMENTATION
The system consists of several in parallel running measurements that are AE, acceleration, Fiber Bragg Grating (FBG) system and a video surveillance. The main testing method is AE. FBGs and accelerations serve as supporting measurements to capture the structural behaviour. In order to correlate the measurements, an overhead camera will be installed. The adjacent purpose of the camera is to trigger the acquisition by capturing vehicles passing over the measurement area.

Acoustic Emission
The central acquisition unit is a commercial system designed specifically for AE measurements, recording the signal parameters as well as waveforms (Vallen 2012). The standard recorded burst signal AE parameters are: rise time, peak amplitude, detection threshold, duration, counts, energy, signal strength, voltage and first time threshold crossing (EN 2009). For better understanding of the material and geometry characteristics, it is important to record the full waveforms containing frequency information (Grosse 2008).
(1) Wave speed in lightweight concrete
The aggregates used in lightweight concrete are very porous, which increases signal damping significantly in comparison to normal concrete. What additionally characterizes the inhomogeneity and therefore enhances the signal propagation disturbances of lightweight concrete is an ununiformed distribution of aggregates established during concreting.

The experimentally found wave propagation speed (here referring to the propagation of a primary (P) wave $c_p$ (see Eq. 1)) of lightweight concrete $\sim 3.7 \text{ m/ms}$ is significantly smaller (Chang et al. 2006) in comparison to the regular concrete (see Table 1).

$$c_p \approx \frac{r_{\text{max}}}{\Delta t_E}$$  \hspace{1cm} (1)

Basically artificial signals that are the standardized pencil lead breaks (Hsu-Nielsen source – EN 2009) are simulated on the surface on the specimen. The propagation path between the sensors ($r_{\text{max}}$) is known and the signal arrival times’ intervals ($\Delta t_E$) are recorded. Wave speed can also be obtained through the dynamic material properties, namely modulus of elasticity $E$, density $\rho$ and Poisson’s ratio $\nu$ (see Eq. 2).

$$c_p = \sqrt{\frac{E}{\rho}} \cdot \frac{1 - \nu}{(1 + \nu)(1 - 2\nu)}$$  \hspace{1cm} (2)

According to the standards (EN 2004), the Poisson’s ratio should be taken equal to 0.2 for uncracked concrete and 0 for cracked concrete. As found in the literature (Koeppel 2002) based on the experimental wave mode speed measurements, the Poisson’s ratio rises to the varying values between 0.1 and 0.4. The given formula though is only suitable for homogenous materials. Comparison between the theoretical and measured values is given in Table 1 ($\nu$ equal to 0.2).

| Table 1 Theoretical and experimental p-wave speed for lightweight and normal concrete. |
|---------------|----|-----|-------|-----|-------|
| $f_{\text{ch,cube}}$ [MPa] | $E$ [GPa] | $\rho$ [kg/m$^3$] | $c_pT$ [m/s] | $c_{pE}$ [m/s] |
| LC-hd ($d = 3$-$15$ mm) | 40 | 19 | 1900 | 3333 | - |
| Concrete (Koeppel 2002) | 61 | 42 | 2420 | 4391 | 4800$\pm$200 |
| Reinforced concrete (Schechinger 2006) | 37 | $\sim$33 | 2500 | $\sim$3829 | 4411 |
| Numerical concrete model (Kocur 2012) | - | - | 2457 | 3987 | 4129 |

Knowing the theoretical signal propagation speed ($c_p$) in lightweight concrete and the largest dimensions of aggregates ($d_{\text{max}} = 15$ mm), frequency ($f$) is obtained, which is equal to 222 kHz. The calculated value of frequency (222 kHz) is an indication of disturbance-free signals (wavelength $\lambda \geq d = 15$ mm) that propagate with a frequency range not larger than this value. This assumption is true for an attenuation-free medium. Because of the high attenuation in concrete (~45 dB/m – Koeppel 2002), especially in lightweight concrete, it is necessary to verify the loss of amplitude between sensors.

(2) Sensor selection & signal conditioning
The positioning of the sensors suggested in this project have to meet challenging field conditions, meaning large dimensions as well as complicated geometry and the characteristics of lightweight concrete. Bearing in mind, the changes of the signal properties with the increasing source-sensor distance (Grosse and Ohtsu 2009, Schechinger 2006), it is necessary to choose appropriate sensors’ type and spacing. An appropriate sensor sensitivity frequency range has to be chosen.

AE sources release a wide range of frequencies, but taking into consideration that different wave modes travel at different speeds and the influence of signal attenuation, only limited frequency ranges can be recorded at certain distances. Schechinger (Schechinger 2006) mentions a signal detectability of 1 m when using a resonant sensor that has operating frequency between 25 and 150 kHz. Nevertheless, recommendation of narrow band resonance sensors (EN 2011) is not ultimate as a lot of relevant
information may be lost. For the purpose of monitoring, conical wide band sensors are used, which characteristics are flat within 4 dB over a frequency range from 25 kHz to approximately 2 MHz (McLaskey and Glaser 2011). For comparison, resonant sensors operating within 25 kHz to 80 kHz (Vallen 2012) are also applied.

In a first approach, to obtain a general map of signal activities, the sensors will be spread in maximum feasible distances. Once the high AE activity zones are identified, the sensors will be moved to a denser array for a detailed study of the detected AE sources.

The proposed signal conditioning settings are listed in Table 2:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Setting</th>
</tr>
</thead>
</table>
| Sample rate: &nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&nbsp;&n

(3) Data analysis
The recorded AE signals will be analysed in a qualitative but also in a quantitative manner. The analysis will focus on separation of the irrelevant to the purpose of the test signals, i.e. noise signals, and on identification as well as evaluation of zones with high AE signal activity. The analysis focuses on the signal activity evaluation rather than on the recognition of destructive processes in order to establish reference signals (in a non-destructive manner) of processes in general that develop in a structure under regular operation, such as friction in existing cracks.

Input of external parameters
In order to correlate the AE signal activity with the structural behaviour, external values, namely dynamic strains as well as accelerations, will be measured.
To capture the stress state of the top slab of the bridge, eight optical Fiber Bragg Grating (FBG) deformation sensors are mounted along the traffic flow direction, measuring the longitudinal direction deformations (RocTEST Group 2011). The readings are temperature correlated. The considered sensor array (see Figure 3) should serve two purposes: stress state of the top slab as well as information on direction of traffic movement.

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1 Duration Discrimination Time (DDT) defines the detection of the end of the hit (Vallen 2012).
2 Rearm Time (RAT) defines when the channel shall be ready to generate a new hit data set (Vallen 2012).
Figure 3 Localization of the sensors in longitudinal direction.

For the global dynamic behaviour of the bridge (spans 7-8, 8-9 and 9-10), three accelerometers are installed in the middle of each span. The accelerometers are recorded as parametric inputs of the AE system.

The challenge was to integrate the FBG reading unit (MuST Reading Unit) with the AE acquisition unit (AMSY). For the purpose of this project, an acquisition procedure has been developed (see Figure 4). The main purpose of the LabVIEW code is the systems’ integration and a system activation sequence.

Figure 4 LabVIEW code: triggering signal, acquisition enable: Smartec and AE.

The idea is to have the system running continuously over 24 hrs, but recording only when triggered by traffic. For this purpose, an overhead camera will be installed above the street to capture passing vehicles over the measurement zone, considered as trigger events (see Figure 5). Saved images allow also correlation of the recorded strain peaks.

Once an image of a vehicle is captured, the strain readings are activated within the LabVIEW environment and AE system is in parallel enabled.
DISCUSSION
The correlation between AE activity and ambient traffic is studied. Dynamic strain measurements seem to be a reasonable representation of live traffic, which is in general problematic to measure. Automatic synchronized activation of the measurements is provided by trigger events, namely vehicles passing over the considered measurement area. This solution allows also reducing and pre-selecting the recorded data.
The planned outcome is a procedure that automatically detects warning signals and supports the prognosis of the degradation of a structure.

FURTHER WORKS
An on-site verification of the proposed procedure will be performed with an emphasis on the study of correlation between structural behaviour, namely strains and accelerations and AE activity. Based on the obtained results, general criteria for testing and monitoring of post-tensioned concrete bridges shall be established.
Further, verification of the final procedure on a similar bridge is included in the project.

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