Continuous Acoustic Monitoring of a Prestressed Concrete Bridge in Germany

Max KÄDING [1], Gregor SCHACHT [1], Steffen MARX [2], Guido BOLLE [3]

[1] Marx Krontal Partner, Hannover, Germany

[2] Institut für Massivbau, Leibniz Universität Hannover, Hannover, Germany

[3] Fachbereich Bauingenieurwesen, Hochschule Wismar, Wismar, Germany

Contact e-mail: max.kaeding@marxkrontal.com

ABSTRACT: The German road and railway networks still contain a significant number of bridges manufactured with steel endangered by stress corrosion cracking. In this case, an ongoing corrosion process can lead to the failure of the steel and, thus, the loss of the structural safety. On this occasion, specific guidelines were published. In many cases, however, the recommended methods do not lead to a (desired) result. One central problem is the poor inspectability of the tendon's condition. In this context permanent monitoring has played a subordinate role, even though acoustic emission monitoring offers promising possibilities. Wire breaks occurring in the inside of the concrete can be detected and localised with this method.

The results of various preliminary investigations with regards to the long-term behaviour of couplant agents and the suitability of sensors are presented. These findings form the bases for the implementation of such a monitoring system on a 102 m long prestressed concrete bridge. Furthermore, first results from commissioning measurements are discussed.

1 INDRODUCTION

Since the first decades of the 20th century, high-strength steels have been used for prestressing concrete bridges. The understanding that steel with high tensile strength is necessary to maintain the prestressing force beyond the creep and shrinkage of the concrete revolutionised this construction method and contributed to its unmistakable success. Many new developments and experiments characterised the rapid development in the early days. The different approaches of the engineers can be clearly seen, for example, in the different prestressing systems (Figure 1), Schacht et al (2018).

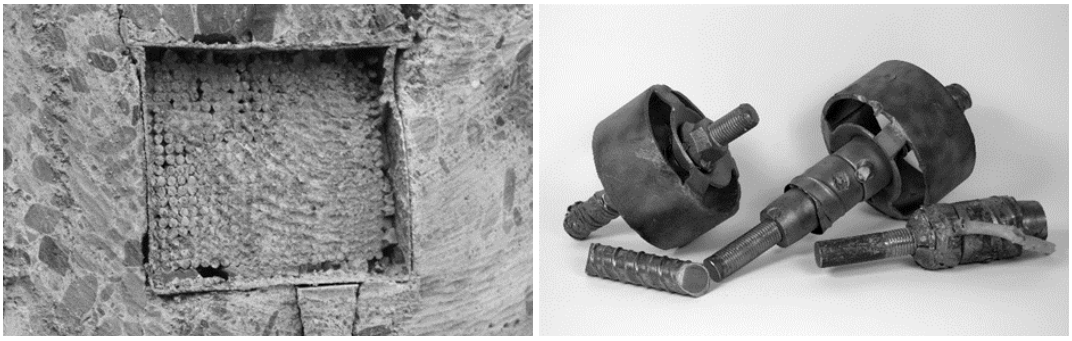

Figure 1. Baur-Leonhardt-tendon (left), DYWIDAG single bar tendon (right).

In order to meet the requirements of the construction industry, the mechanical properties of the steels were developed. The high strength was achieved by special tempering and alloying processes and led, not yet known at that time, to a particular sensitivity of these steels towards stress corrosion cracking (SCC). This sensitivity affects almost all prestressing steels from the 1950s to 1970s, Scheerer et al (2012).

In the following an overview of the current regulations in Germany is given. The limits of these procedures and the advantages by extending the evaluation with metrological methods, in particular using the acoustic emission analysis, are shown. A number of preliminary investigations are presented for this purpose. The experiences gained from this, form an important basis for the installation of a monitoring system on a bridge. First results of these measurements are presented.

2 CURRENT CONCEPTS FOR THE ASSESSMENT OF BRIDGES WITH STRESS CORROSION CRACKING IN GERMANY

The assessment of bridges with the potential hazard of failure due to SCC is currently defined by the instructions for road (BmVBS (2011)) and for railway bridges (DB Netz AG (2016) & (2017)). The evaluation procedures described in these regulations are structured comparably and include similar steps. The fundamental problem with the evaluation is the poor detectability of the internal damage processes from the outside. The result of the successive reduction of prestressing steel is not visible before a certain equilibrium of forces is exceeded and cracks appear in the concrete. As soon as this happens an externally visible indication of damage is present. However, this is only the case if the structure was constructed with a sufficient amount of reinforcement steel. Especially older bridges in Germany lack of that amount, so that a sudden failure is possible. Therefore, as a first step, the load-bearing of the structure is examined by a numerical analysis, with regard to a visible indication of damage. If such indication can be proved, regular visual inspections on a regular basis must be mandated. Since these inspections are discrete in time and the visibility of the cracks depends on the currently existing loading condition, a deformation monitoring represents a logical and consistent development for the assessment strategy. Conventional sensors (e.g. inclinometers) can be used for this purpose. First successful applications are documented in Bolle et al (2017).

If no visible indication is possible, the material properties are randomly examined. The corrosion condition in the tendon, the prestressing steel and the grouting are evaluated. In addition, DB Netz AG (2016) provides guidance on the application of non-destructive testing (ndt). For the investigation of tendons different *active* ndt-methods based e.g. on ultrasound or magnetism are suitable, Schulz et al (2013) & Hillemeier et al (2011). However, similar to visual inspections, only a sectional and successive examination of the structural elements is possible. Thus, the information on the condition is only available at the time of the respective examination. In order to determine insufficient grouting, these ndt-methods could be useful. But with complex geometry and tendon position they quickly reach their limits. Furthermore, wire breaks can occur again and again in all tendons, which is why continuous monitoring of the entire structure is of importance. In the case of active ndt-methods however, this would lead to a large number of recurring examinations and is therewith not economically feasible. Hence, the *passive* ndt-method based on acoustic emission analysis, has great potential for this task and delivers valuable information, before as a last option a replacement of the bridge is arranged. Nevertheless, there are only a few examples of continuous monitoring on prestressed concrete bridges with SCC.

3 ACOUSIC EMISSION MONITORING OF BRIDGES

3.1 Acoustic emission phenomena and its application on prestressed concrete bridges

The phenomenon of acoustic emission (AE) occurs during structural change, e.g. as a result of mechanical overloading. The elastic energy stored in the structural element is spontaneously released during a fracture process and converted into transient elastic waves, DIN EN (2005). However, acoustic emissions are not only a result of damage process. Background noise arises from traffic, rain or other external events. The waves propagate with a specific characteristic in the structure from the source location. During propagation the waves are superimposed by various effects (scattering, damping, etc.) depending on the material properties and the travelled path. At the surface they can be converted into an electrical signal using e.g. piezoelectric sensors. The information about the fracture process is therewith available for analysis on a PC and can be evaluated in real time, Grosse et al (2013). The method is therefore predestined for monitoring and permanent assessment of structures.

The advantages of acoustic emission analysis for monitoring applications were recognised early on and have been used on cable-stayed and suspension bridges since the 1990s. During this time, this idea was also transferred to prestressed concrete bridges. A fundamental investigation for this transfer was the monitoring of a prestressed ceiling of a parking house in 1994, Elliot (1996). Due to the lack of inspectability of the tension wires in the concrete and the large financial expenditure for a comprehensive investigation, the passive monitoring method was chosen. In the 1980s and 1990s an increasing number of damages from SCC on prestressed concrete bridges were recorded. This motivated Cullington to evaluate this method at the Huntington Railway Viaduct in 1997, Cullington et al (2001). During these investigations deliberately generated wire breaks were successfully detected and localized with very high accuracy. Further applications on prestressed concrete bridges took place by Yuyama and Fricker, including extensive instrumentation of the structures and detailed investigation of traffic and environmental noise, Fricker (2009) & Yuyama et al (2007).

3.2 Preliminary examinations

3.2.1 Suitability of sensors

The requirements for a sensor are defined by (a) the technically required information that the recorded signal must provide for a meaningful interpretation, and (b) the economic boundary conditions, which are essentially determined by the number of sensors. These aspects are influenced by the specific characteristics of the acoustic channel (material) and the source signal. It is known that in concrete strong frequency-dependent distortions (attenuation) of the propagating signal occur, which depend, among other things, on the size of the scattering bodies (aggregates, pores, etc.), Landis et al (1995). The travelled path influences the reliable detection of an event as well as the frequency content of the signal. Hinrichs et al (2018) provides an approach for a general model valid to describe these effects. Basically, it has been shown various times that after only a few meters frequencies above 250 kHz are of secondary importance. That is why for our investigations piezoelectric sensors were used, which are differently sensitive in this range (<250 kHz). These are sensors from Physical Acoustic Corp. (model: PA-15I and PA-6I) and Geotron Elektroknik (model: AE type 3 and UP DW).

The detectable reach of a signal was investigated for an impact source and evaluated on the basis of signal attenuation (amplitude and energy). A Rebound-Hammer was used to emit qualitatively and quantitatively similar signals. The signals were recorded under realistic boundary conditions at a bridge in Hanover (city in Germany). The determined values are given in Table 1.

Table 1. Experiences from the studies of other authors for the application of acoustic emission monitoring and results of own examinations.

Author	Sensor distance	Response spectrum of the sensor	Damping
Cullington et al (2001)	5 m	1..20 kHz	-
Yuyama et al (2007)	6 m	40..100 kHz	4,3 dB/m
Fricker (2009)	8,3 m	20..200 kHz	3,7 dB/m
Own investigations		10..15 kHz (UP-DW)	2..3 dB/m
		40..50 kHz (AE-Typ3)	3..4 dB/m
		30..100 kHz (PA-6I)	5 dB/m
		120..170 kHz (PA-15I)	10 dB/m

The analysis of the frequency content showed, that the rebound-hammer triggers a wide frequency range. Therewith the different sensor types are stimulated in a comparable way. Even though the rebound hammer emitted the signal on the concrete´s surface, the damping is generally low compared to normal damping in concrete. This is because the signals were emitted close to the tendons. The propagation mainly took place in the steel, thus the signal is exposed to significantly lower attenuation effects. For the event of a wire break, the same effect applies for the signal transport. The advantages of the wave being guided will also be shown latter during investigations on another bridge (chapter 3.3.3).

As mentioned before, other authors observed that higher frequencies are attenuated more strongly. This coincides with the observations of our investigations. It can be deduced, that for monitoring only the low frequency range (≤100 kHz) allows large sensor distances. However, a generally valid parameter for on sensor distances can´t be derived from this investigation. The given values in Table 1 can only serve as reference. For every structure the sensor layout must be developed and verified individually based on the structural geometry, location of the tendons and specific acoustic properties. This means, that the probability of detection needs to be quantified.

3.2.2 Permanent coupling

A good acoustic coupling between the structure and the sensor is a fundamental precondition for obtaining high quality measurement data. Air inclusions between the sensor and the rough concrete surface are usually replaced by coupling agents applied as preferably thin layers, thus creating a full-surface connection with low impedance, Theobald et al (2008). The signal transmission at the interfaces (reflections) into the coupling medium and later the sensor is influenced by the composition of the coupling medium. However, the required signal quality (amplitude, frequency), durability and processability (installation, dismantling) of the coupling agent can vary depending on the application, Colombo et al (2005). In monitoring applications, a stable transmission behaviour over long periods is needed, since unnoticed changes can lead to data loss. Therefore, viscous materials are unsuitable because stability in vertical or overhead positions cannot be assumed.

The long-term stability of coupling agents has been discussed in the past, but not investigated in detail. Own investigations with three coupling agents (dental wax, therapy plasticine, silicone grease) were carried out. The sensors were installed on a specimen and exposed to free weather for about 3 months in winter. A warm period was simulated by storage in the testing hall. The test signals were generated with pencil lead breaks. The results are shown in Figure 2.

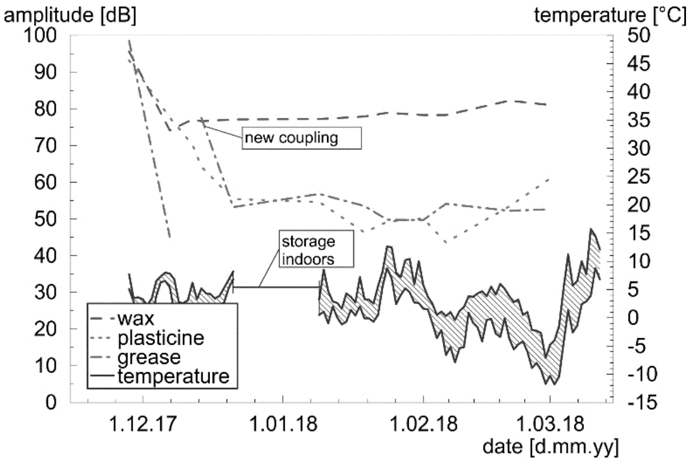

Figure 2. Investigation of the transmission quality of various coupling agents under freeze-thaw cycles.

After installation, a drop in signal intensity can be detected for all coupling agents. This drop continues for the silicone grease and the therapy plasticine. The best transmission properties can be found for wax. This can be a result of the application process, where heat was applied and the wax was temporarily fluid. The good transmission properties of highly adhesive materials are confirmed by the observations of Colombo et al (2005).

3.3 Case Study – Stennert bridge

3.3.1 Structure and initial situation

The Stennert bridge in Hagen-Hohenlimburg crosses the B7 over the river Lenne with a total length of 102.70 m (Figure 3). The bridges cross-section consists of a three-cell box girder. The building was erected in 1959. The prestressing steel used from Hüttenwerke Rheinhausen can be classified as particularly endangered towards SCC, BmVBS (2011). The numerical analysis revealed sufficient residual safety in the supporting areas and the midfield. All other areas were below the required limit. As result an indication of damage could not be observed for the entire bridge. Since the structure is in a (visually) considerably good condition, a continuous monitoring was chosen in order to obtain information about the damage process actually occurring in the inside and to ensure operational safety for the remaining life time.

Figure 3. View of the Stennert bridge in Hagen/Hohenlimburg.

3.3.2 Measuring concept

Each web of the superstructure was instrumented. A total of 66 sensors with a response spectrum of 25 to 80 kHz were installed. The distance between the sensors is about 10 m. The exact location of the tendons was previously determined by scanning the local positions with geo-radar.

Since the indication of damage (through crack initiation) could be proven for certain areas, the changes of the stiffness of the superstructure is monitored, too. Therefore inclination sensors were installed. From the inclinations a zonal curvature between two sensors can be derived. The curvature is proportional to the stiffness. As soon as changes in stiffness occur, these can be directly seen in the measuring signal. The inclination sensors are conventional technology and therewith give a redundancy in the measurement system for evaluating the damage process. An overview of the sensor layout is shown in Figure 4.

3.3.3 Experiences from the first months of AE-monitoring

The monitoring system was planned and implemented in the first quarter of 2018. After installation in April, a series of commissioning measurements were carried out to verify the specific acoustic properties and the functionality of the measuring system. Among other things, a few wire breaks were generated and the signals recorded. In this context the condition of the grouting, cladding tube and prestressing steel (surface corrosion) were evaluated.

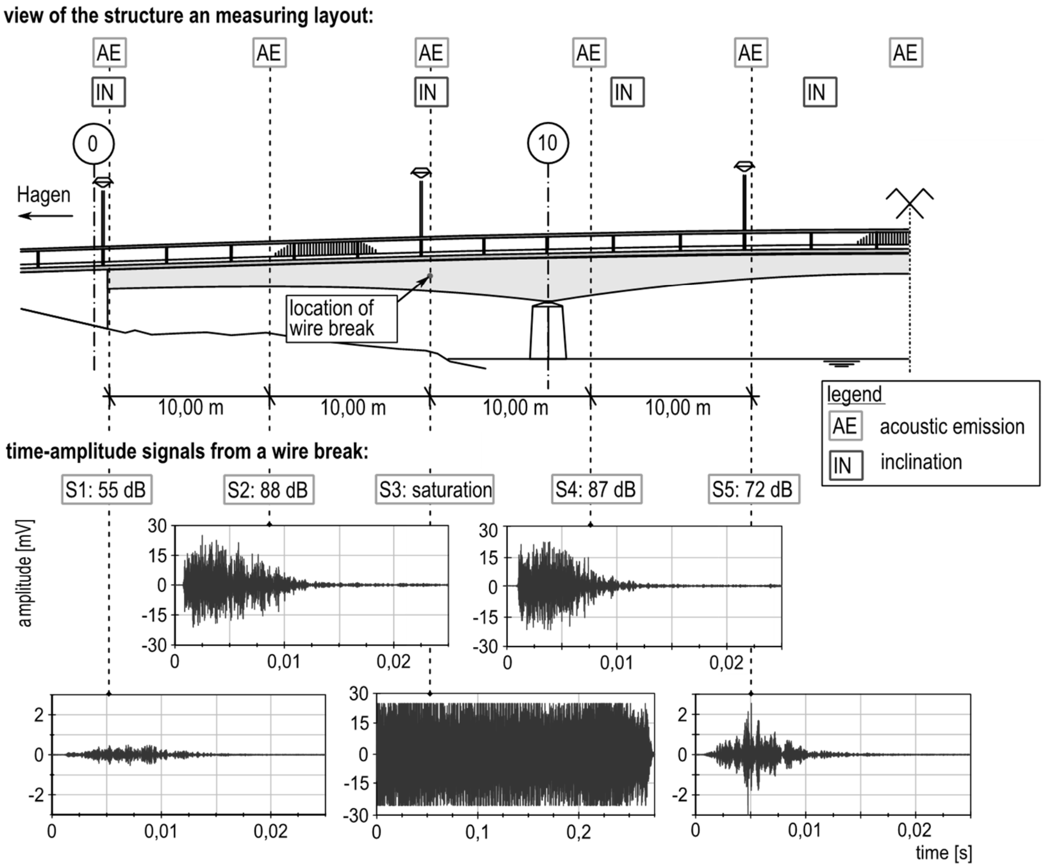

Figure 4. Construction overview with sensor layout; time-amplitude curves of wire break signal generated at the construction (reference signal).

An example of a wire break signal is shown in Figure 4. The break location is approximately at the position of sensor 3 (S3). As expected, this signal is strongly saturated and has a particularly long signal duration of approx. 270 ms. After 10 m, this signal has already been strongly attenuated and lasts only 15 to 20 ms. The amplitude is close to the saturation limit. Furthermore, it can be stated that even at a distance of 20 m a reliable detection is still possible. Assuming that the generated wire break signal is rather of high intensity compared to spontaneous breaks, a reliable detection is still very well possible for less strong signals. The effective amplitude attenuation is only approx. 3 dB/m. Therewith, between two sensors a maximum damping of only approx. 30 dB is expected. From this investigation it can clearly be seen that the signal propagation is strongly affected by the tendon. The propagation velocities reflect these effects, too. For the wire breaks velocities between 4.4 to 4.9 m/ms can be stated. These are high values compared to concrete, which lie depending on its properties mostly under 4,0 m/ms. Taking that into account, these effects can be very helpful when classifying events. In general it was possible to localise the generated signals with deviations of 1-2 % with regard to the sensor distance.

The measuring system is currently in continuous operation. The signal parameters or waveforms are evaluated in a multi-stage procedure. This procedure consists of (i) thresholds for different signal parameters, (ii) pattern recognition based signal classification, (iii) consideration of the sensor network and material properties through localization and (iv) an individual visual and audible evaluation. After 9 months of monitoring no indications for wire breaks were found.

4 SUMMARY

Structures at risk of SCC continue to pose a major problem for infrastructure managers, as the financial resources and planning capacities do not allow an immediate replacement for every structure. In addition, a contemporary and responsible handling of the building stock should be in the foreground, especially if the general condition of the structure demands this. In such cases, metrological monitoring is an excellent alternative for obtaining information on the damage process and securing the remaining life time.

Especially problematic are buildings without indication of damage, as the degradation processes occurs in the interior of the concrete and is not visible from the outside. Acoustic emission monitoring offers promising possibilities for obtaining information on the activity of the damage process. From the measuring data, conclusions can be drawn about the number and location of the wire breaks. For a successful monitoring, however, the permanent coupling and selection of suitable sensors are of decisive importance. Therefore, preliminary investigations were conducted. Important findings could be gained which enabled the authors to implement such a monitoring system on a structure in the first place.

At the Stennert bridge a measuring system was installed and successfully put into operation. In the case of artificially generated wire breaks, it was confirmed that the signal attenuation is very low and the propagation speed high, compared to concrete. From this, criteria for the evaluation of the recorded events were derived. The measurement layout and the selected properties of the sensors proved to be very suitable. After 9 months of monitoring no indications for wire breaks were found.

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