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Smart Structural Health Monitoring with Acoustic Emission

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ABSTRACT:
It is common sense that civil infrastructure like tunnels or bridges are coming in age and needs to be renewed in the next years. These issues are, amongst others, related to massive increased traffic load nowadays compared to the time of construction and material issues which turned out after many years of operation. In concrete structures with tendons, the stress corrosion cracking of the used steel is one of the main issues and leads to tendon failure with significant impact on the stability of the structure.
SHM with Acoustic Emission is used successfully for many years to detect tendon failures. The products on the market have been adapted since many years to the needs of the customers and the full measurement chain from a self-checking smart sensor network, high performance and scalable data acquisition systems to automate data analysis, processing and alarming is available. A cloud-based dashboard rounds up the package and makes processed data available for customers. Since May 2024 a guideline from DGZfP "Richtlinie SE 05 Detektion von Spanndrahtbrüchen mit Schallemissionsanalyse" is available and give a general frame about the approach, definitions ad help to specify tenders in a correct way.

KEY WORDS: Acoustic Emission, Structural Health Monitoring, Smart AE sensors, Wire break detection, SE 05

1 INTRODUCTION

Acoustic emission (AE) testing is a well-established nondestructive testing method for pressure vessel, pipeline and tank inspection in industry [1]. Integrity, leakage and corrosion tests are in the focus. Apart from these applications, the demand increases for continuous monitoring of civil structures like bridges and tunnels. The civil infrastructure e.g. in Germany is coming in age and was mainly constructed 50 or more years ago. The structures face nowadays a much higher traffic load than at the time of planning and it turned out that some of the materials used, especially the steel for tendons, had not the predicted quality in the long term perspective. The tendons are facing the risk of stress corrosion cracking which can lead to a catastrophic collapse of the structure in the worthed case. To ensure the availability of the structure, operators often choose various inspection and maintenance strategies. Therefore, acoustic emission (AE) can be an outstanding tool to support the operators. Davies [2], Nakasa [3], Allevato [1] and others have shown that acoustic emission is a suitable method for permanent monitoring applications. In the last years, the number of projects increased especially in Germany and more than 25 structures were equipped with Acoustic Emission to detect wire breaks. The time period of the projects varies between a few months to several years. To fulfill the requirements the Acoustic Emission hardware and software had been improved significantly to enable a continuous, reliable and available permanent monitoring of the structure.

Civil infrastructure like bridges and tunnels are mainly in public hand and the size of monitoring projects requires tender processes. The community in Germany developed over the last years a guideline as general frame about the approach, definitions and help to specify tenders in a correct way. The guideline "Richtlinie SE 05 Detektion von Spanndrahtbrüchen mit Schallemissionsanalyse" from DGZfP is availible since May 2024 [4].

2 ACOUSTIC EMISSION AND TENDON FAILURE DETECTION

Acoustic Emission (AE) is a well-established NDT Methode and has been applied for many years in various applications in the industry like pressure vessel testing or testing of above ground storage tanks. The "passive" character of AE makes the method suitable for permanent monitoring of the structures and to "listen" for tendon failures. The available AE equipment was mainly driven by the requirements of the above-mentioned industrial applications, and it was the starting point for further investigations to adapt the AE equipment to the needs of permanent monitoring of civil infrastructures like concrete bridges. Several publications are available on the detection and location of wire breaks by Acoustic Emission [7-8]. Investigations were carried out to identify suitable AE sensors to detect wire breaks in concrete. In one internal feasibility study several sensors with different peak frequency sensitivities and preamplifications were mounted on a concrete beam (Figure 1) with tendons at different positions on the beam. Artificial AE was triggered with HSU-Nielsen source and several tendons where cut to see the behavior of the acoustic waves and the response of each individual sensor. It turned out that low frequency sensors around 30kHz peak frequency are suitable.

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Figure 1: Evaluation of several AE sensors on a concrete beam to investigate the capability to detect wire breaks

During the investigation it turned out that the typical artificial AE source, a HSU-Nielsen source (Figure 2 (top)), is suitable to verify the sensor mounting quality close to the sensor but the artificial source is not strong enough to be detected by an AE sensor in several meters distance to the sensor due to the high attenuating properties of concrete for the propagation of acoustic waves. After several tests, it turned out that a rebound hammer, which is normally used by civil engineers to evaluate the quality of concrete, is a suitable tool to trigger artificial sources. The rebound hammer (Figure 2 (bottom)) is spring loaded and a reproducible source. Detection of a rebound hammer hit in 20 to 30m distance to the AE sensor is possible.

Figure 2: HSU-Nielsen source (0.5mm) to verify the sensor mounting quality (top).
Rebound hammer to trigger reproducible artificial AE sources on concrete structures (bottom)

Another difference between industrial applications and wire break detection is the preamplification of the sensor output. Observing the data after an artificial wire break, it turned out that measurement channels with a typical amplification for industrial applications like 34dB or 40dB were saturated related to the high energy released by the wire break. Based on the results, preamplification with 0dB is beneficial and the preamplifier purpose is to convert the sensor output to be transported over long cable distances (approx. 600m) without significant losses.

2.1 Permanent monitoring of a concrete bridge in southwest Germany

The following example of the SHM is part of a bigger project and published in [5]. In autumn 2018, a concrete bridge in the southwest of Germany was equipped with a monitoring system consisting out of several NDT methods. A renewal of the bridge is required, and the existing structure should be permanently monitored during planning and approval phase. Apart from acoustic emission, various other parameters like temperature, displacement and strain (strain gauge) are part of the monitoring system. Acoustic Emission and temperature are recorded by an integrated system, whereas strain gauge and displacement parameters are fused and analyzed in post processing.
Bridge construction was finalized in 1950 and traverses the river Danube (Figure 3). It has a length of 96 m and a max. span of 81m. The width is 18m and the bridge has 4 lanes and 2 sidewalks. Damages caused by corrosion were found at the tendons of the bridge. Because the damage is unrepairable, a replacement of the bridge is planned. The bridge operator, an engineering office, a service provider and Vallen Systeme as measurement equipment provider are working together in this project [5].

Figure 3: Gänstorbrücke

The Acoustic Emission measurement system and data analysis must run automatically, recognize changes in the condition and trigger alarms if predefined criteria are fulfilled. Low frequency AE sensors with IP68 rating were used for the installation and the first version of a spring-loaded mounting mechanism which can be screwed to the concrete was used in this approach. The mounting mechanism has protection covers to protect the AE sensors against vandalism and animals (e.g. birds). AE sensors were installed in a linear setup on the beams with sensors distances between 12 to 14m and the line of sensors follows the course of the tendons in the concrete as good as possible. The acoustic emission measurement system AMSY-6 with 36 channels is stored in a cabinet which is installed in the bridge abutment at a height of 5m to guarantee flood protection. Besides acoustic emission measurement system, measurement

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computer, communication equipment for a mobile network and additional measurement equipment for recording data of 71 temperature sensors are included in the cabinet. AE and temperature measurements are recorded with a synchronized time stamp and so data analysis is comfortable for the service provider. The other NDT methods were recorded with separate equipment, but all data is transferred to a cloud-based dashboard and the service provider can do further analysis across all data [5].

The project is still running, and the monitoring concept provides the security to operate the bridge in a safe way till renewal is properly planned.

Figure 4: First approach for a sensor mounting device including protection cover [5]

2.2 *Tendon failure detection with AE and other NDT methods: "Altstädter Bahnhof"*

The following example is part of a bigger project published in [6]. The bridge at the "Altstädter Bahnhof in Brandenburg an der Havel" was opened in the year 1969 and tensioned concrete structure was used. The used steel, "Hennigsdorfer" steel, was state of the art at this time. Today it is known that this type of steel has a high risk for stress corrosion cracking. Inspections and investigation on the bridge revealed significant and irreversible damages and a new construction was decided. In the meantime, a monitoring system including Acoustic Emission was installed as early warning system in case of detected tension breaks. Before final removal of the "old bridge" several measurement techniques were applied on the bridge to investigate their potentials on such objects during artificial damaging of the structure. The approach was to cut parts of the bridge including the tendons with a "wire saw" (Figure 6). Two parts of the bridge were cut, one with known, existing damages and the other with no existing damages. The focus in this text is on Acoustic Emission results provided by Bilfinger Noell. The acoustic emission signals triggered by the wire breaks at the sensors are displayed by the acoustic emission system with a delay of a few milliseconds. The analysis of the acoustic emission data is carried out immediately on-site in monitoring and test mode. A classification of the data into the classes wire break, construction noise, background noise could be done immediately. The determination of the source location of the acoustic emissions was automatically done by the measuring system. The investigation showed that acoustic emission analysis is very well suited to detect wire breaks reliable and in real time.

2.2.1 Construction of the bridge

For the bridge at the Altstädter Bahnhof, the "clamping block method" was used on the main supporting structure in a longitudinal direction. Tension wires with a cross-sectional area of 35 mm² were used. Additionally, a larger tensioning box was necessary to accommodate the total of 392 individual wires and to be able to introduce a tension force of 12 MN per main girder. The 392 individual wires were installed in layers and secured in their position by spacers, as can be seen in Figure 5.

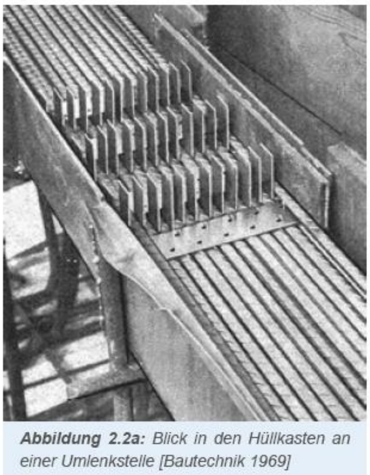

Figure 5: Photography of the open concentrated tendon before grouting [6]

The typical brand for such tendons at this time was "Hennigsdorfer" steel. The hardened and tempered tension wires were used as pretensioned steel.

2.2.2 Monitoring concept and results

Due to the described material properties of the tension wires, it was necessary to implement a monitoring strategy. This was the only way to ensure the safety of the traffic passing the bridge. The monitoring concept included a regular inspection combined with a permanent structural health monitoring. For the permanent monitoring, next to others, acoustic emission was selected as method to detect tendon breaks.

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The acoustic emission system with 75 sensors was installed and put into operation in June 2020 by the company Bilfinger Noell. Until the demolition of the bridge in May 2021, 111 spontaneous tension wire breaks were detected. There were no technically related downtimes during the runtime of the system.

2.2.3 Comparison of NDT methods

Due to the condition of the bridge, it was decided that the bridge has to be removed and replaced by a new construction. The bridge was selected by the Federal Ministry of Transport and Digital Infrastructure to do an extensive case study to compare different NDT methods. The following NDT techniques were used: Strain gauging, geodesic measurement, vibration analysis, fiber optic measurements, photogrammetry and acoustic emission. The approach was to cut parts of the bridge, including the tendons, with a "wire saw" [6]. Two parts of the bridge were cut, one with known existing damage and the other with no existing damage.

Early-stage failure of this bridge, with concentrated tendons, is not indicated by flexural cracks at a span's center. It was shown that for this bridge about one third of all wires in one concentrated tendon must fail before the cracks reach the concrete surface. One outcome of this evaluation study is that Acoustic Emission is the only technique that detects wire breaks in real-time and without the need to be close to the origin of the wire break. In addition, AE can locate the wire breaks origin. Vibration and geodesic measurements can detect changes in the rigidity of the structure if sensing elements are close to where failure occurs. Strain measurements, photogrammetry and fiber optic sensors are suitable for detecting cracks in the concrete structure [6]

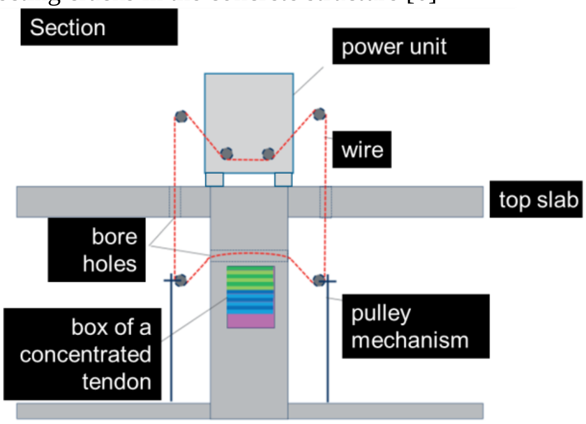

Figure 6: Wire saw to cut the concrete and tendons

3 IMPROVED ACOUSTIC EMISSIONE EQUIPMENT FOR SHM

It is necessary to provide a solution covering the entire measurement process, including data analysis, alerting and information dissemination workflows. Third-party acquisition modules need to be supported. Expandable and versatile monitoring systems can be configured using modular components and customized products where necessary.

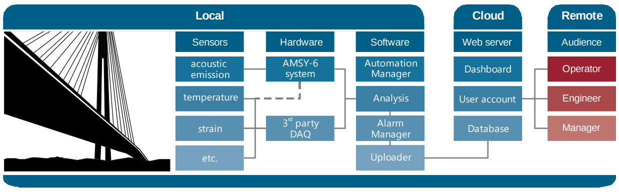

Figure 7: Example of a schematic Workflow of a monitoring system

3.1 AE sensors

Sensors need to work reliably 24/7 throughout the monitoring period, withstand varying and extreme conditions, moisture, and rain as well as excessive heat and frost. Special, low frequency sensors are available meeting the harsh demands of permanent monitoring. The sensors are optimized for the specific requirements of the application. Each AE sensor is connected to the AE data acquisition system with a single cable. The commonly used acoustic emission sensor for monitoring is e.g. VS30-SIC-V2-0dB sensor or the specifically developed SHM-MP1 measurement point for structural health monitoring. The SHM-MP1(Figure 8) measurement point offers several advantages over conventional monitoring sensors:

Vallen Smart Line™ sensor technology with automatic registration of the device at the monitoring hardware and reliable self-checking of its function and sensitivity that can be automatically triggered in regular intervals or on demand are some benefits. The reliable self-checking functionality enables the operator to verify the sensor mounting quality on a regular basis to proof the sensitivity of the sensor network without accessing the sensors personally which is beneficial in cases where the sensors are hard to access. The easy-to-install mechanical device, including strain relief and rugged protection lid is an additional improvement in sensor technology compared to the first approaches like in Figure 4.

Both sensor types have integrated preamplifiers with 0dB amplification and the power for the preamplifiers is provided by the data acquisition system via phantom power along the sensor cable. The temperature range from -40°C to +85°C of both variants is designed for operation in all seasons of the year and covers cold and hot temperatures during winter and summer.


Figure 8: SHM-MP1 Vallen Smart Line™ sensor

3.2 AE hardware and software

The AE data acquisition hardware needs to be scalable and flexible in the number of channels to provide a suitable system size related to the structure. The AE system needs to be integrated into an enclosure specified for the environmental

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conditions at the bridge. 19” racks are beneficial including data acquisition PC and mobile data communication.

A reliable and state-of-the-art software complements the measurement hardware. Flexible analysis is required to be adjusted to specific requirements of a job. Even user-specific evaluation routines need to be implemented and executed during the measurement. Fast online location, even at high data rates from many channels, is a key aspect of data analysis. Criteria for alarms and warnings can be set and notifications received via email or digital outputs.

On top of data analysis runs the Vallen Automation Manager software. It enables an autonomous operation of the data acquisition system and is an instance designed to inform the operator or other selected audience about alarms and the general status of the system. Amongst simple tasks is, for example, an automatic start-up of the monitoring system after a power outage, switching between data storage files in regular intervals and carrying out sensitivity checks of the installed sensors. Beneficial is the maintenance mode, which can be activated for a user defined time span. In this recording mode, all data is recorded but the alarm chain is blocked. It is used when, e.g. construction work is done on the bridge which will generate lots of activity and fails alarms.

Additional to the software running on site at the local PC, processed data can be uploaded to a cloud-based dashboard. The Vallen Dashboard is an important part of the software solution if the monitoring results need to be distributed to a broad audience. It provides an encapsulated and safe environment for viewing and analyzing data. Access and rights/privileges for this service can be restricted based on user roles. Data available in the dashboard has been transferred to it from the acquisition PC avoiding the necessity to log-in and possible manipulation of the running monitoring system.

It can be hosted on any Linux Ubuntu server. This may be rented services from local providers or a company-controlled internet server. Rented services can provide guarantees for accessibility, data safety (back up, but also storage locations in your own country) and security (access). An encrypted connection is established between the dashboard and the acquisition PC via internet.

Data upload from the acquisition PC is automated. If the connection is interrupted, upload data is cashed and transferred once the connection is working again. The Dashboard engine informs selected users when the internet connection to the measurement system is lost.

Under the hood, the Vallen Export processor and Uploader program running on the data acquisition PC are responsible for supplying the dashboard with data. Both pieces of software can be configured according to the requirements of the scope/job/user. One has full control of what is uploaded and how frequently it is uploaded. The Vallen Dashboard displays the information in a user-defined layout.

The dashboard and layouts can be easily adapted and customized by the user. The administrator of the dashboard sets out the rules which information may be viewed, and which actions are available to certain users. Information can be displayed in bar charts, scatter plots, heat maps, line charts, tables, static images, and texts. Data can be downloaded for archiving purposes or offline analysis. The responsive design of the front-end enables equally well access experience from PCs and mobile devices.

The open API of the Vallen Dashboard provides the possibility to integrate third-party time series measurement data to be uploaded, stored, and fused with acoustic emission data. This data does not even have to come from the acoustic emission data acquisition system or PC. The Vallen Dashboard is a true multi-source, multi-channel data management, visualization, and analysis tool from a single source.

4 GUIDELINE TO “DETECT WIRE BREAKS WITH AE”

The increasing demand of monitoring post-tensioned concrete structures in Germany and the complexity of how to setup such projects and how to involve all required parties motivated the development of a guideline to solve the issue. The German Society of Non-Destructive Testing (DGZfP) published in May 2024 the guideline “Richtlinie SE 05 Detektion von Spanndrahtbrüchen mit Schallemissionsanalyse” [5]. The guideline is written by civil engineers, bridge responsible from the public authority, Acoustic Emission specialists and AE measurement equipment suppliers.

It is a detailed guideline with more than 30 pages on the planning, tendering, installation and operation of monitoring systems to detect wire breaks. One focus of this guideline is, of course, the description of the use of Acoustic Emission in order for successful monitoring

The guideline covers all required topics right from the beginning, like explanation of the terms e.g. how is a wire break defined or what artificial reference AE sources are available. It covers the topic Acoustic Emission and the capability for wire break detection, requirements for measurement equipment and data analysis as well as sensors, sensor distances and limitations. A summary of the requirements for the measurement technology is in Table 1 Next to the technical part another focus is on the project implementation and project participants, proposed sensor networks related to the different construction types like box girders, T-beams etc. It finally results in a guideline on how to set up the tender specifications.

NDT technique	Acoustic Emission (AE)
Codes	EN 1330-9, EN 13477, EN13554, EN 14584
Temperature Range for AE sensors	-40 °C to 60 °C
Type of AE sensors	Piezoelectric
Pre-amplification	0 dB or higher
Frequency range acquisition	5 kHz to 200 kHz
Resonant frequency AE sensor	20 kHz to 80 kHz
Sampling frequency AD converter	2 MHz or higher
Resolution AD converter	16 bit or higher
Dynamic range AD converter	65 dB or higher
Measured Features from Hits	RMS or equivalent Amplitude and/ or Energy Arrival Time (resolution µs) Frequency information Waveform recording
Analysis in time	Occurrence of wire breaks
Analysis with location	Position of wire breaks by linear or planar location
No. of sensors for wire break location	Linear: 3 or more Planar: 4 or more
Accuracy of location	+/- 2 m or better
Sensor cables	Coaxial cable (50 Ohm)
Reference sources	Hsu-Nielsen Source (0,5 mm 2H) Rebound Hammer Type N with an impact energy of 2.207 Nm

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Table 1: Overview of the recommended measurement equipment [5]

It is common sense that each bridge is different, and it is not possible to copy one project 100% to another. It is recommended to do a feasibility study before tendering to evaluate amongst other parameters the noise level, the attenuation and the speed of sound. Artificial triggered AE can be used to evaluate the parameters and additionally it is recommended to open the concrete and remove a piece of the tendon for further analysis in the laboratory. In this case cutting of tendons are required and so a “real” wire break can be detected and the propagation of the waves in the structure evaluated. The target is to find a suitable sensor network with ideal sensor distances. It brings the public administration the position to make a clear and transparent tender specification about the size and dimension of the required monitoring system.

Figure 9 shows the peak amplitude in dB(AE) from one wire break of a post-tensioned concrete bridge. It is part of the guideline and gives an orientation on the relation between wire breaks and the artificial source from a rebound hammer. Sensors were positioned at three different distances from the location of the artificial wire break. The acoustic emission signals from the wire break and from the use of the reference source were recorded. The reference source was triggered in the closest possible proximity to the wire break location. Each position has its own value of K. It is recommended to use the smallest value of K to calculate the maximum possible sensor distance. For example, the signal from the wire break at a distance of about +200 cm in Figure 9 is saturated with a maximum amplitude of 134 dBAE, which means that the true peak amplitude cannot be determined. Therefore, the smallest value of K from Figure 9 with 101 dBAE - 121 dBAE results in -20 dB.

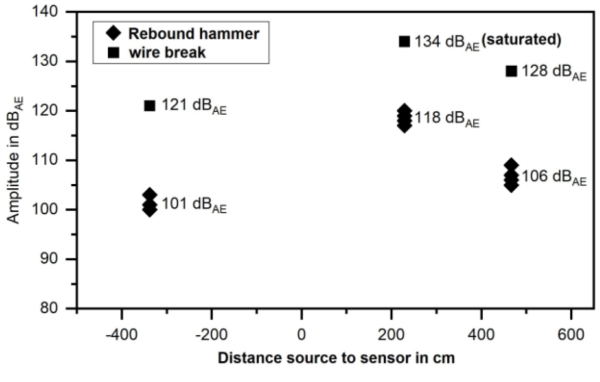

Figure 9: Representation of the peak amplitude(s) of a wire break and triggering of the reference source (rebound hammer type N) at three different distances in order to determine the value of K [4]

The method described here represents one possibility for determining the maximum possible sensor distance. However, other procedures or procedures based on this are also conceivable. The maximum possible sensor distance is the maximum distance between sensors to allow reliable detection and localization of sources (here: wire break). The wire breaks differ from the reference source by the value of K in dB. This method is based on EN14584 [10], which describes the use of planar location for the testing of pressure vessels. The use of a fixed detection threshold is assumed. In contrast to EN14584, the reference source defined here is the rebound hammer type N and not the breakage of a pencil lead (Hsu-Nielsen source).

5 CONCLUSION

Wire break detection with Acoustic Emission is nowadays state of the art and a well-documented application. The NDT method AE has proved to be able to detect and locate wire breaks in concrete structures in many investigations and practical approaches and projects.

AE hardware and software have been optimized over the last years to the needs of the engineering companies and service providers to be a reliable tool. Easy to install, comfortable to use and stable in the long run. The automated alarming makes it possible to handle several projects in parallel and next to routine checks detailed analysis is required in case of alarms.

The alignment of more data sources in one platform like the dashboard gives more confidence and reduces the risk of false alarms.

Finally, guideline SE 05 was established to line up all approaches and to create a common sense of the application, the benefits and limits of AE and give public administrations a tool to formulate tenders in a way to get what they require.

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