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Acoustic Monitoring used to manage the Life of Cable Supported Bridges

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ABSTRACT: Acoustic monitoring has developed into a practical tool for bridge engineers and owners over the past decade. The technique offers the ability to track the progress of deterioration on cable supported structures. The failure rate of individual tension elements and the location of the failures within the structure can determined on a continuous, nearly uninterrupted basis. Engineers have superimposed past inspection data with the current deterioration information in order to better predict the load capacity of the bridge. Acoustics can be supplemented by other instrumentation in areas of most concern. The application of acoustic monitoring is presented in the form of two case studies. A historical suspension bridge in the United States is presented first. The second is a post-tensioned bridge in the UK. While both bridges were suspected to have structural deficiencies, in both cases, the bridges were operated with the aid of acoustic monitoring for an extended period of time rather than the alternative of closing the bridges to traffic.

1 INTRODUCTION

As bridges age, their capacity to carry load can diminish. At the same time, traffic loads have historically increased over time, thus the structural safety factors on bridges reduce and the need for confidence in these structures becomes more relevant. Management of infrastructure is becoming more important, since tracking of advanced deterioration and loss of structural capacity is much more economical than replacement of structures. Even if structures are replaced, they will be subject to the same harsh environmental conditions that were likely the catalyst to the deterioration process on the previous structure. In the meantime, without sufficient information, the traffic on the bridge may need to be restricted. A combination of up to date critical information that relates to the structural capacity of the bridge and a focused rehabilitation program can provide the bridge owner comfort, and the utility of the structure can be maintained.

Acoustic monitoring on bridges has been commercially available since the 1990's, but its use has become more widespread in the last ten years. The technique allows for tracking of deterioration of tensile, generally presetressed elements, continuously from the time the system is installed. To date, 31 bridges have been monitored by the authors capturing over 800 spontaneous wire breaks, and over 1200 wire breaks due to engineer's interventions or wires cut during testing of the SoundPrint system and wire sampling. This combined database is used to correlate and automatically select wire breaks on structures utilizing the same SoundPrint system.

2 ACOUSTIC MONITORING

Acoustic monitoring referred to in this paper is not synonymous with acoustic emission or impact echo techniques. While some are familiar with acoustic emission techniques and ultrasonic testing, there are differences and intricacies pertaining to acoustic monitoring used to detect failures of presetressed elements. There is a similar discrepancy when it comes to the concept of monitoring. Most engineers, scientists and academic researchers are familiar with short term instrumentation projects, which are most common during the construction stage or when engineers want to validate their design assumptions with respect to aerodynamics. For acoustic monitoring to be effective, it has to provide information over decades. Further it has to be truly continuous, effectively being able to capture critical data 24 hours a day.

2.1 Methodology

The concept of continuous acoustic monitoring is based on the need to detect the event when any wire of any prestressing strand breaks. In terms of the sequence of the method employed, the following stages are of interest in the process:

1. Mechanical Physics – The post-tensioning strands within the structure contain significant potential energy in the form of prestress. When one of the wires in a strand breaks, the potential energy is converted into kinetic energy, which is suddenly injected into the structure, detectable as a dynamic response.

2. Sensors – The sensors used to detect these events are multi-axial broadband accelerometers biased toward relatively high frequencies in the audible range (1 kHz to 50 kHz), that are application specific.

3. Data Acquisition – The data from all of the acoustic sensors on the structure is continuously streamed through the memory buffer of a high speed data acquisition system. The system continuously analyzes the data and detects acoustic signatures similar to known wire breaks (i.e. a trigger device). The data acquired is event based, less than one second in length.

4. Transmission - The event data is processes through a digital software filter, which further reduces unwanted events, before they are transmitted via the Internet to a central processing centre.

5. Processing – The data is backed up and correlated against a database of over 2000 wire breaks. The flagged possible wire break events are then confirmed by an experienced data processor.

6. Reporting – The wire break information is transmitted to authorized parties, and available on a secure website. Historical information is also available on the website, offering the rates of failure, as well as the location and density of wire breaks.

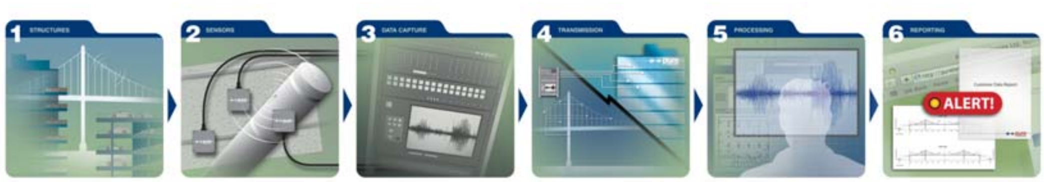


Figure 1: Stages of the acoustic monitoring process

2.2 Measure of Acoustic Response

The basic measure of the acoustic response recorded by the data acquisition system is a time domain representation of the signal sampled at up to 100 kHz per channel, for all channels used for monitoring the post-tensioning system. The measures used to analyze the signals are many fold, and are derivatives of time-frequency analysis popularized in electrical engineering disciplines over the past 30 years.

An important parameter used to discern between ambient noise and wire breaks is an autocorrelation of the time-frequency-energy representation of a signal (Figure 2) to known wire breaks captured on similar structures. Another useful parameter that can be calculated using time-frequency analysis is the absolute amount of energy captured, which is proportional to the size of the wire break. This allows for distinguishing between fully grouted, ungrouted and partially grouted wire breaks. This categorization of wire breaks is possible after just a few wire breaks are recorded on a particular structure.

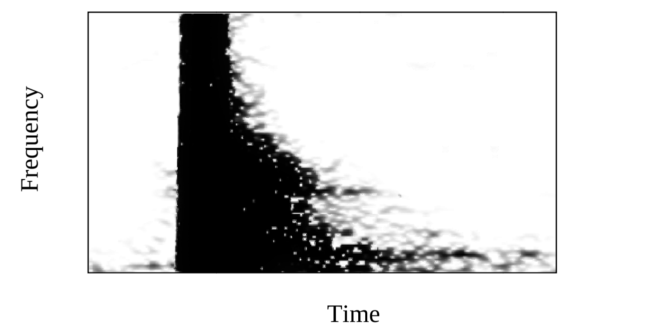


Figure 2: Basic measures of acoustic response for each channel on bridge – Time Frequency Plot

2.3 Operation of Continuous Acoustic Monitoring Systems

For a little over a decade, it has become apparent that for monitoring systems to be useful, certain challenges have to be overcome, and a number of important conditions must be assured. The following is not meant to be an exhaustive list, but is based on the authors' experience in structural monitoring using acoustics for the past 12 years:

Verification – the techniques used need to be verified by third parties at laboratories, universities and at demonstration tests specific to the application.

Long Term Perspective – deterioration of tensile structural elements may take many years to develop, while repairs on the structure may reduce or delay the wire break rate; short term instrumentation approaches are not appropriate for wire break detection.

Diagnostics – technologies are now available that include external hardware that can continuously check the data acquisition system for problems related to power, communication, proper operation of the operating system, and proper operation of the high speed data acquisition process.

Data Management – capturing data over hundreds of sensors at many hundred kilo-samples per second can quickly become unmanageable; filtering of the data is paramount while rejecting structurally critical data is unacceptable; acoustic monitoring systems have generally adopted an event-based data model, rather than continuously recording and storing gigabytes of information on a daily basis.

Monitoring Operating Structures – bridges are noisy structures; the ability to monitor for wire breaks during noise posed by traffic and expansion joints is essential; monitoring cannot be considered fully effective during times of concrete chipping and drilling operations; however, it has been shown that over 93% of the wire break or wire cuts can be captured during construction works

System Uptime – a monitoring system is not effective if its sensors are not responding, data cables are cut or damaged, or the acquisition system is locked up; bridge monitoring systems over the past 12 years have been shown to operate 95% to 99% of the time; such high uptime statistics are essential if structural engineers are to have faith in the data.

Data Processing & Classification – advanced signal processing, correlation techniques to compare data to known acoustic events, and timely reporting of the information to owners and engineers is essential; longevity of the data processing knowledge has to be ensured; data has to be processed daily and usually requires a dedicated entity for high quality service.

3 WALDO HANCOCK BRIDGE

Name and Location: Waldo Hancock Bridge, Maine, USA
Bridge Opened to Traffic: 1931
Client: Maine Department of Transportation
Spans: 244 m main span, 107 m side spans
Structural system: two suspension cables (245 mm DIA), 37 strands per cable (35 mm DIA), 37 wires per strand (5.0 mm DIA)
Start of Structural Health Monitoring: 2003
Number of acoustic sensors installed: 22

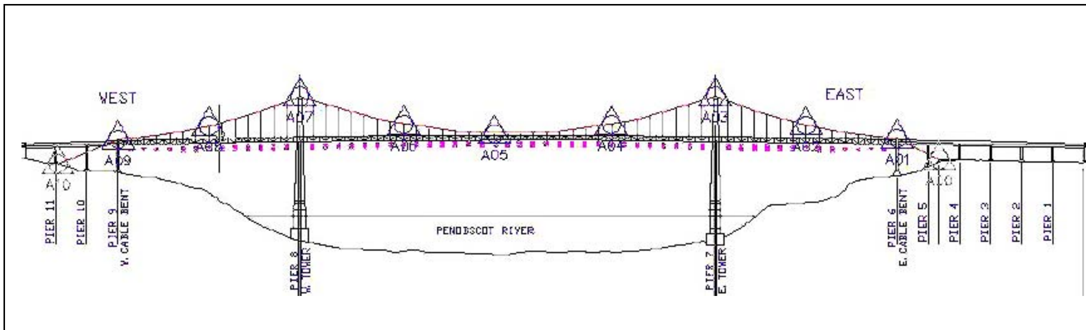
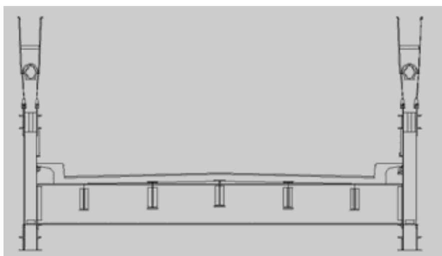


Figure 3: Waldo Hancock Bridge – Typical Cable Sensor Layout

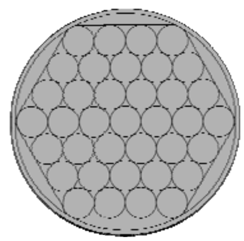
The Waldo Hancock Bridge in the state of Maine, in the United States was completed in 1931. Its deck carried one lane of traffic per direction, while two narrow reinforced concrete sidewalks were used for pedestrian traffic. Partially due to the National Bridge Inspection Standards (NBIS) stipulated by the Federal Highways Administration (FHWA), a number of inspections of the superstructure were carried out starting in the early 1990s. Portions of the main cables were unwrapped and inspected in 1992, 1998, and 2000. Due to some signs of stage 3 corrosion during the 1998 small scale investigation, the 2000 investigation was expanded to include more panel points on the North cable.

This investigation included four openings on the North cable, and one opening on the South cable. The safety factor had originally ranged from 3.0 to 3.2, based on no damage of the main cable. The wire breaks counts observed reduced the safety factor to just below 2.4 at two of the five locations investigated. Typical damage at one of these two locations is shown in Figure 5.

Since the condition of the cables was worse than anticipated, the bridge owner decided to implement a significant rehabilitation program in order to extend the life of the structure. The major components was to replace the external main cable protection system. This replacement enabled an extensive visual inspection of the strands, with further wedging performed at select areas. During this exercise, it was discovered that the extent of the corrosion was beyond of what the five panel inspection showed. At the worst location, 10 of the 37 strands were not carrying load, and one these was 100% corroded (i.e. discontinuous at this location). This occurred on the South cable, where previously only one panel was inspected, reducing the calculated safety factor to 1.5 at the posted carrying limit of 12 tons.

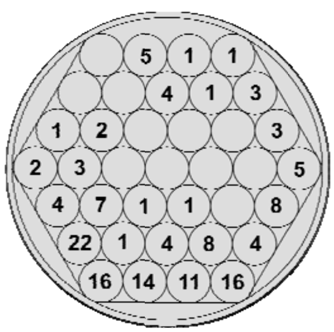


Original Deck Configuration

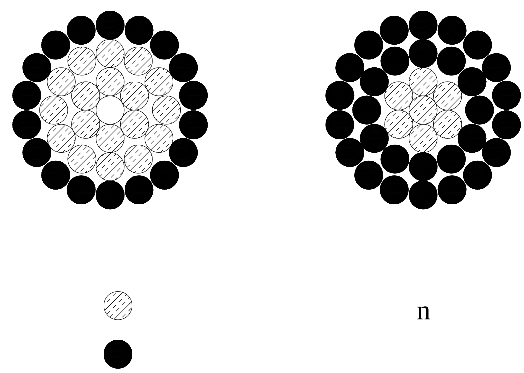


Typical Main Cable, 37 strands in a hexagonal configuration

Figure 4: Typical Details of the Deck and Main Cable



Typical Broken Wire Count at panel point 12E-14E (North cable, East side span)



Typical Distribution of Stage 4 Corrosion
Left: 38% of strands, Right: 57% of strands at panel point 12E-14E

Figure 5: Typical Damage found. [Stages of corrosion are according to the Federal Highways Administration (USA) guidelines. A 4 stage system is used with stage 4 representing the most advanced stage of corossion.]

This situation required emergency strengthening measures to be implemented. First, an acoustic monitoring system was installed on both main cables. In order save installation time, a wireless system with 22 sensors was used. Load restrictions were placed on the bridge. Until the acoustic monitoring system was fully functional, the bridge was restricted to one way traffic for a short time. A total of eight supplementary strands were placed above each main cable, connected directly to each cable band with supplementary suspenders. The heavy concrete sidewalk was removed and replaced with a steel-wood combination.

The acoustic monitoring system detected 4 wire breaks in the first 50 days of monitoring the cables (1 on the North cable, and 3 on the more damaged South cable). Once the supplementary cables were installed and the deck lightened, the wire breaks on the main cables stopped. In order to give all parties involved confidence, wires were periodically cut so that the acoustic monitoring system's effectiveness could be demonstrated. Nine wires were cut and successfully recorded before the monitoring began, and a further 14 individual wires were cut and recorded over the following two years.

In this case, the acoustic monitoring system was used to (i) provide utility during the critical period when strengthening measures were required, and (ii) to extend the life of the bride for an additional *three years and four months*, until a replacement bridge could be designed and built. In terms of cost approximately $1.1 million was spent monitoring the bridge using acoustics over this time period. The client estimates the economic benefit of removing the load restrictions for heavy trucks, and not fast tracking the new bridge – was in the range of $25 to $36 million.

4 MOSSBAND VIADUCT

Name and Location: Mossband Viaduct, Cumbria, England
Client: Highways Agency
Spans: Twin decks each made up of eight spans, with an overall length of 255 m
Structural system: Each deck consists of four post-tensioned cast in situ concrete table spans and four suspended spans supported by the table spans on half-joints. Constructed in 1963/1964 and replaced in 2008
Start of Structural Health Monitoring: 2001
Number of acoustic sensors installed: 210

a. Southbound Deck b. Northbound Deck

Figure 6: Cross-section of bridge showing acoustic sensor layout at each monitored location

The Mossband Viaduct was comprised of twin decks. One deck was made up of concrete girders butted up against each other, with a top cantilevered slab. The second deck was a voided box-girder. Half of the spans were post-tensioned cast in-situ concrete table spans and four were suspended spans supported by the table spans on half-joints. The bridge carried traffic over a roadway and a railway.

Conventional visual investigations were performed in 1990, 1995, and 1999, respectively. The first investigation discovered water ingress at all the deck joints and next to drainage pipes. This was believed to have been occurring over many years. General corrosion of the surface reinforcement in these areas had resulted in surface spalling.

The second inspection revealed the presence of several corroded and broken tendons in the in-situ table spans. The damaged tendons were located in the deck over the pier supports, where the cable profiles approached the top surface of the deck. A deck construction joint within a meter of the pier support provided a direct water path to the tendon ducts. The cable profiles descended from this location into the mid-span of the table span and to the half-joint, which was the anchorage area.

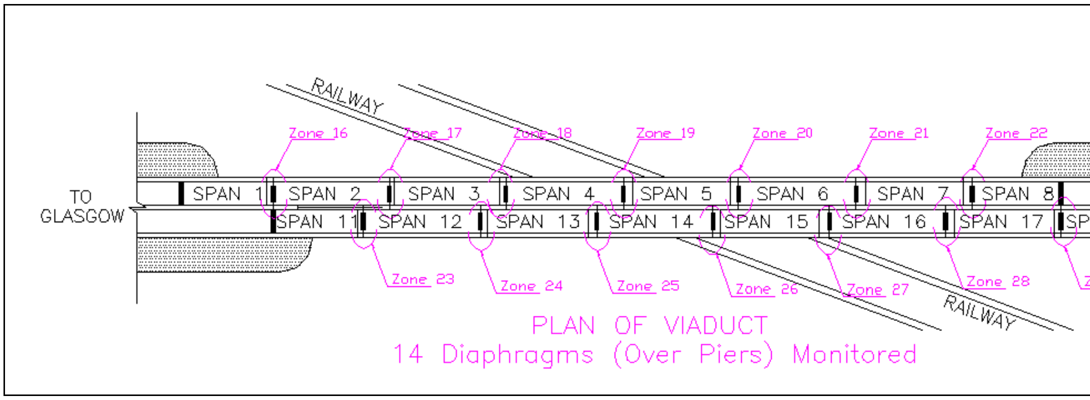


Figure 7: Overall acoustic monitoring plan for entire viaduct

As is often the case with selective visual investigations, one location often showed severe corrosion while an adjacent location appeared undamaged. In this case, the third inspection showed that some of the longitudinal tendons over the piers had all the strands completely corroded whereas only two meters away, they appeared in good condition. Clearly, the tendons at the half-joint locations were at risk at all 14 locations, but the extent of deterioration at every location was unknown.

The Highways agency implemented a comprehensive bridge management plan starting in 1999, to access the rate of deterioration of the post-tensioning, and if necessary, to intervene and strengthen the structure. The final plan consisted of (i) monthly visual inspections of critical sections, (ii) the installation of vibrating wire stain gauges to monitor cracks on the sides of the sections and soffit of construction joints, (iii) load testing to compare stain changes, and (iv) an installation of a SoundPrint acoustic monitoring system to monitor the rate of deterioration of the post-tensioning system.

Table 1: History of wire breaks at Mossband Viaduct

Event	Date	Time	Event Type	Condition	Pier Location	Section
1	3-Mar-2001	14:54:11	Wire Break	Grouted	C7	Southbound
2	29-Oct-2004	08:06:59	Wire Break	Ungrouted	C13	Northbound
3	4-Dec-2006	23:55:36	Wire Break	Grouted	C16	Northbound
4	18-Aug-2006	01:29:01	Wire Break	Grouted	C1	Southbound
5	31-May-2007	16:51:17	Wire Break	Ungrouted	C2	Southbound
6	6-Feb-2007	21:53:43	Wire Break	Grouted	C17	Northbound

All fourteen negative moment regions over the piers were monitored using acoustics, with five sensors arranged in three rows on each pier, spaced between 5.0 to 5.5 meters apart. Figure 6 shows the relative position of the acoustic sensors with respect to the cross section of the viaduct. Spatial multiplexing was used due to the fact that wire breaks were unlikely to occur at multiple piers at exactly the same time. This greatly reduced the channel count down to 29 channels that could be more easily acquired at 100 kHz compared to the daunting task of doing so over all 210 sensors on separate channels. Figure 7 shows all the monitored piers (designated as zones 16 through 29).

Table 1 summarizes the wire break events detected. Due to calibration tests and experience on other structures, it was possible to determine the condition of the grouting at the wire break locations. The ungrouted wire breaks showed much larger energy releases than those in the fully grouted condition. The wire break rate found was lower than expected. The fact that only 6 wire breaks were detected during the extended life of the structure, gave the engineers and owners confidence that the bridge management program was effective. Further, strain readings during the AIL annual load tests showed that the structure was not experiencing severe changes in deflections, and that the serviceability requirements were being met. The crack growth was also monitored, and was thought to be consistent with the rate of deterioration observed with the acoustic system.

In this case, the acoustic monitoring system was used to extend the life of the structure by *seven years and 10 months*, until a new bridge could be built as part of the A74 Cumberland Gap. In terms of cost, approximately $1.4 million was spend on the two monitoring systems and the load tests over 8 years, including the system related inspection and reporting functions by engineers. The client estimates that the economic benefit in delaying the permanent bridge replacement and not fast tracking a temporary structure that would not be heavily used once the A74 was built – was in the range of $30 to $40 million.

5 CONCLUDING REMARKS

As the use of acoustic monitoring becomes more widespread, bridge owners and engineers will gain more confidence in the cable supported structures they are responsible for. Indeed, the approach of using an acoustic monitoring system, a smaller scale strain and crack monitoring system, and regular load testing - is becoming the norm in the UK for post-tensioned highway bridges that have shown signs of advanced deterioration. In both case studies presented, the life of bridges was extended, and the deterioration rate monitored using acoustics. While these bridges were eventually replaced, at the time of this writing, there were 27 bridges that have been monitored in a similar fashion that do not require replacement.

6 AKNOWLEDGEMENTS

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