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A multi-sensing monitoring system to study deterioration of a railway bridge

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Abstract

This study presents a multi-sensing monitoring system recently installed in a Victorian railway viaduct in Leeds, UK. The viaduct is in continuous use since its construction during the 19th century and suffers extensive cracking due to the combined action of increased train loads and environmental effects. The bridge was retrofitted in 2015 and there was the need to assess the effectiveness of the intervention and better understand the ongoing deterioration process. For this reason, a multi-sensing system was designed that comprises a fibre Bragg grating network to measure distributed dynamic deformation across three arch spans of the bridge, acoustic emission sensors to detect rates of cracking, and high sensitivity accelerometers to study the dynamic response at critical locations. The system is self-sustaining, self-powered and remotely controlled, and uses an algorithm that combines information from the three different types of sensors to track variations of response parameters of the bridge over time.

1. Introduction

The recent motorway bridge collapse in August 2018 in Genoa, Italy, which costed the lives of 43 people, was a sad reminder that poor maintenance and lack of monitoring of existing infrastructure is a serious problem. As the population grows, an increasing number of people rely on these assets, which deteriorate with time. For instance, 50-60% of the railway bridges in UK and Europe are masonry arch bridges, the majority of which have been built more than a century ago before the enforcement of building codes (Orbán et al. 2009, Ye et al. 2018), and many have suffered damage due to increased train loads and environmental effects.

Traditional maintenance practices of infrastructure owners include costly site visits and condition assessments based on limited monitoring data. Assessing the level of deterioration is even more challenging for ageing masonry structures, given that masonry is a non-uniform material of discontinuous nature, which is particularly difficult to model, despite the wide range of sophisticated structural analysis methods available today (Roca et al. 2010).

The emerging concept of the self-sensing bridge (Lau et al. 2018), which combines advanced sensing techniques with streaming statistical modelling and big data analytics, aims to enhance our understanding of the life-cycle performance of the structure and provide a tool for better asset management and operation of infrastructure networks. Aligned with this idea, this paper presents a multi-sensing monitoring system for the deterioration study of a Victorian railway viaduct in Leeds, UK. The system combines (i) a network of fibre Bragg grating (FBG) strain sensors, (ii) acoustic emission (AE) sensors and (iii) high-sensitivity accelerometers and was designed to be self-sustaining, self-powered and remotely controlled.

The results from continuous remote monitoring of the bridge presented in this paper offer a new understanding of the global dynamic deformation and local masonry deterioration of the structure, together with new opportunities for development of structural alert systems for railway bridges based on real-time streaming statistical modelling.

Fig. 1. The southern side view of the Marsh Lane Viaduct in Leeds, UK

2. Description of the structure and the multi-sensing system

The Marsh Lane Viaduct is located next to the Eastern entrance of Leeds Railway Station, in the centre of the city. The bridge was constructed between 1865 and 1869 (Hoole 1973). Today it carries two electrified tracks with a traffic load that exceeds 200 trains per day, ranging from typical passenger trains to multi-wagon freight trains. Fig. 1 shows the southern side of the investigated section of the bridge, which comprises the Arches 37, 38 and 39. Fig. 2 shows the main cracks observed under the arches. The most severe damages are concentrated over the relieving arches at the centre of the piers due to a spreading mechanism that forces the relieving arch keystone to descend and the walls to bow outwards (Acikgoz et al. 2018). For this reason, Network Rail, the owner of the bridge, conducted in 2015 an extensive repair by filling in the relieving arches with concrete and installing steel ties to arrest transverse movements of the piers and the spandrel walls. In addition, a longitudinal crack below the North track is observed in Arch 37, which is the most damaged arch of the bridge.

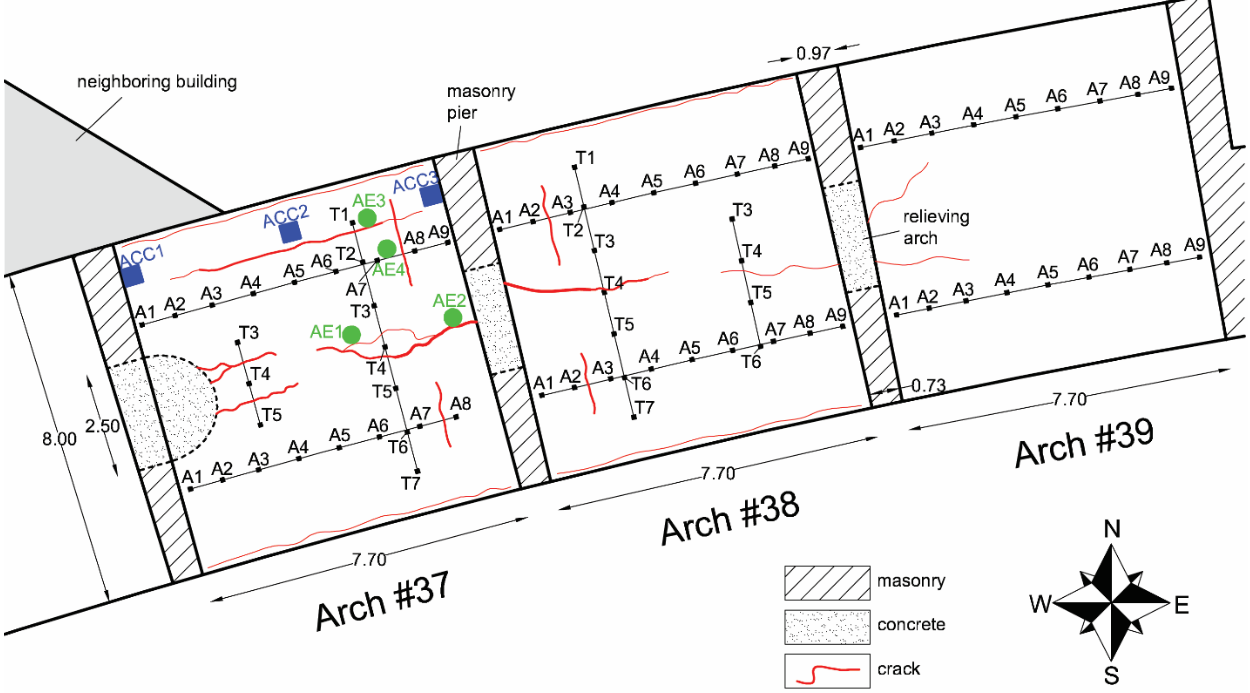

Fig. 2. Plan view of the investigated section of the Marsh Lane Viaduct, showing the main damages (in red), the fibre optic sensors network (thin black lines), the acoustic emission sensors (green circles) and the high-sensitivity accelerometers (blue squares)

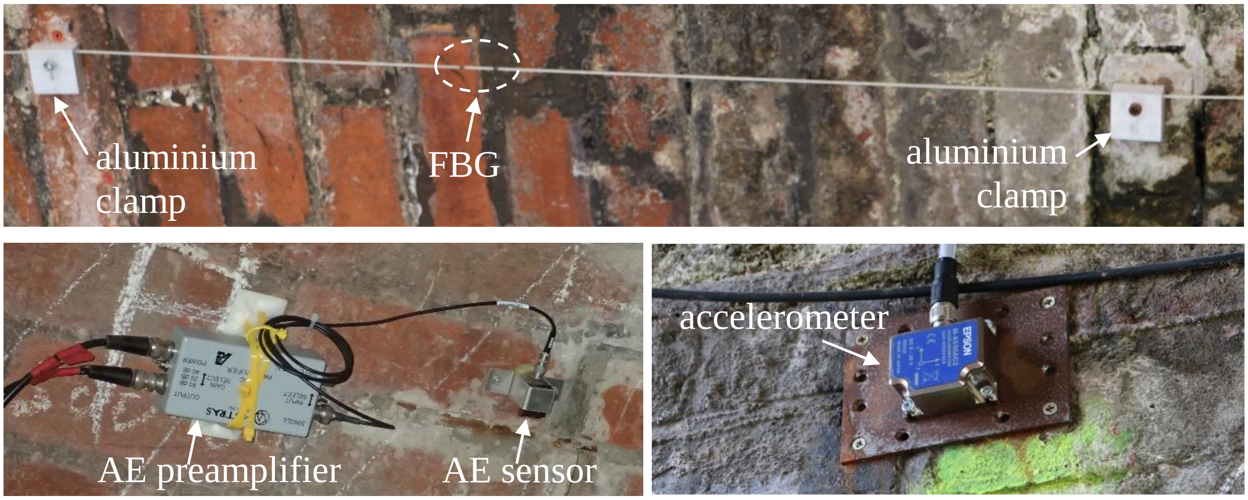

Fig. 3. Top: FBG strain sensor. Bottom-Left: AE sensor and preamplifier. Bottom-Right: High-sensitivity accelerometer

After the 2015 retrofitting intervention, a network of FBG strain sensors was installed underneath the Arches 37 and 38, allowing for the detailed study of their dynamic deformation (Acikgoz et al. 2018). This successful installation was followed by the permanent FBG network installation shown in Fig. 2, which comprises 68 FBG strain sensors in the longitudinal and transverse direction of the investigated section of the bridge, together with 5 FBG sensors calibrated to measure temperature. For this installation, four cables of a Germanium doped single-mode silica fibre were clamped to the masonry surface, as shown in Fig. 3 (top). Every FBG sensor measures strain between two clamps that appear as small black squares in Fig. 2 and are numbered from West to East as A1-A9 and from North to South as T1-T7 for each arch.

Acoustic emission (AE) is a phenomenon where transient elastic waves are generated by the rapid release of energy, typically due to sudden irreversible changes in the internal structure of the material such as cracking. AE sensors are piezoelectric sensors used to detect elastic waves, which have extremely small amplitude (in the order of nm) and very high frequency (in the order of 10 kHz to over 1 MHz), requiring data acquisition systems with high sampling rates. In this study, AE sensors have been installed to detect rates of cracking at four critical locations in Arch 37, as shown in Fig. 2, numbered as AE1-AE4. Fig. 3 (bottom-left) offers a closer view of sensor AE2, together with its preamplifier. MISTRAS R6α general purpose sensor was selected, with 60 kHz resonant frequency and 35-100 kHz operating frequency range. Sensors AE1-2 have been placed next to the crack that develops over the relieving arch at the Eastern side of Arch 37, with AE2 measuring cracking rates at the beginning of the crack, having width > 2 cm, and AE1 at the ending of the crack near the keystone, having width < 2 mm. Sensor AE3 was placed next to the longitudinal crack of Arch 37. Sensor AE4 was placed near FBG sensor "37NA7A8", meaning the strain sensor at the North side of Arch 37 between clamps A7-A8. This last location was selected based on a recent study by Alexakis et al. (2019), who presented a statistical analysis of FBG data that compares the dynamic deformation of the bridge between July 2016 and June 2018, revealing an amplification of the dynamic strain at this location, where crushing of bricks has been observed. To this end, it is noted that before the permanent installation of sensors AE1-4, different healthy regions (with no cracking) were explored, where no acoustic emissions were recorded. This finding confirms that AE sensors are recording exclusively the stress waves produced from micro/macro-cracking events in neighbouring cracks and are not affected by the substantial vibrations of the bridge caused by the train loading.

In order to study the dynamic response of Arch 37 with its piers, three high-sensitivity accelerometers were installed at the springings and keystone, as shown in Fig. 2, numbered as ACC1-3. Fig. 3 (bottom-right) offers a close view of ACC2. A CAN (Controller Area Network) interface 3-axis accelerometer was selected, with 0.06 μG/LSB reported resolution and 500 Hz maximum sampling rate.

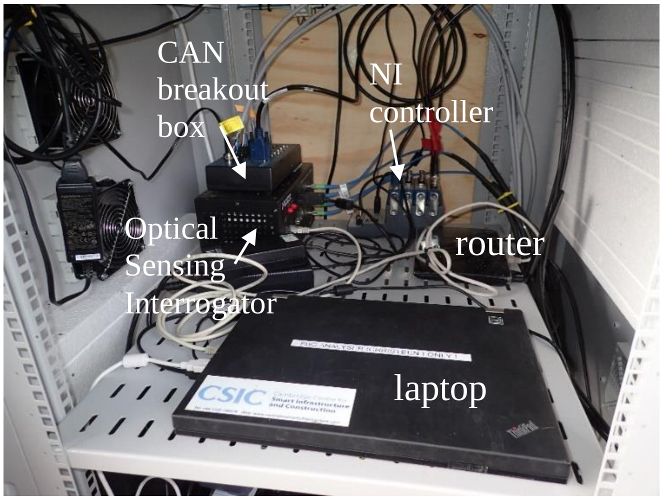

Fig. 4. Data Acquisition System

Fig. 4 shows the main parts of the Data Acquisition System (DAQ). The 4-channel sm130 Optical Sensing Interrogator of Micron Optics, Inc. used in this study offers up to 1 kHz sampling rate per sensor and 2-3 micro-strain ($\varepsilon\mu$) resolution. A National Instruments (NI) cRIO controller was used for the AE sensors, offering up to 1 MHz sampling rate. The accelerometers-controller connection was achieved through a CAN breakout box. The DAQ is permanently installed under Arch 37, inside a temperature controlled cabinet. The DAQ is connected to a laptop with a router, which remotely transmits daily data through a 4G internet connection. The system is powered up by the solar panel shown at the top left corner of Fig. 1.

3. Results

Alexakis et al. (2019) developed a signal processing and statistical analysis algorithm that uses FGB data to identify changes in dynamic strain of the bridge over time. The algorithm identifies the type of train loading (train direction, velocity, number of carriages, relative axle distance) and presents variations of the minimum and maximum strain per sensor under the same type of load. An example is shown in Fig. 5, where strain variation for the 3-carriage Class 185 train, heading in a specific direction, are presented. The change in the response of sensor 37NA6A7 over the last 2 years, where AE4 sensor was installed, is indicated with a dashed box. Using this information, it is possible to present variations of cracking rates over time for each AE sensor location under the same load. For instance, Fig. 6 presents (i) the cumulative number of counts per train loading, meaning the number of times the AE signal exceeds a preset threshold above the noise level, which was 40 dB for this study, and (ii) the maximum signal amplitude per train loading. The results shown in Fig. 6 are always for the 3-carriage Class 185 trains, heading in a specific direction. The keystone crack next to AE1 was considerably more active compared to the other crack locations and the sensor was triggered 96% of the times the Class 185 train passed over the bridge. The triggering rate was 12% for AE2, 39% for AE3, and 21% for AE4.

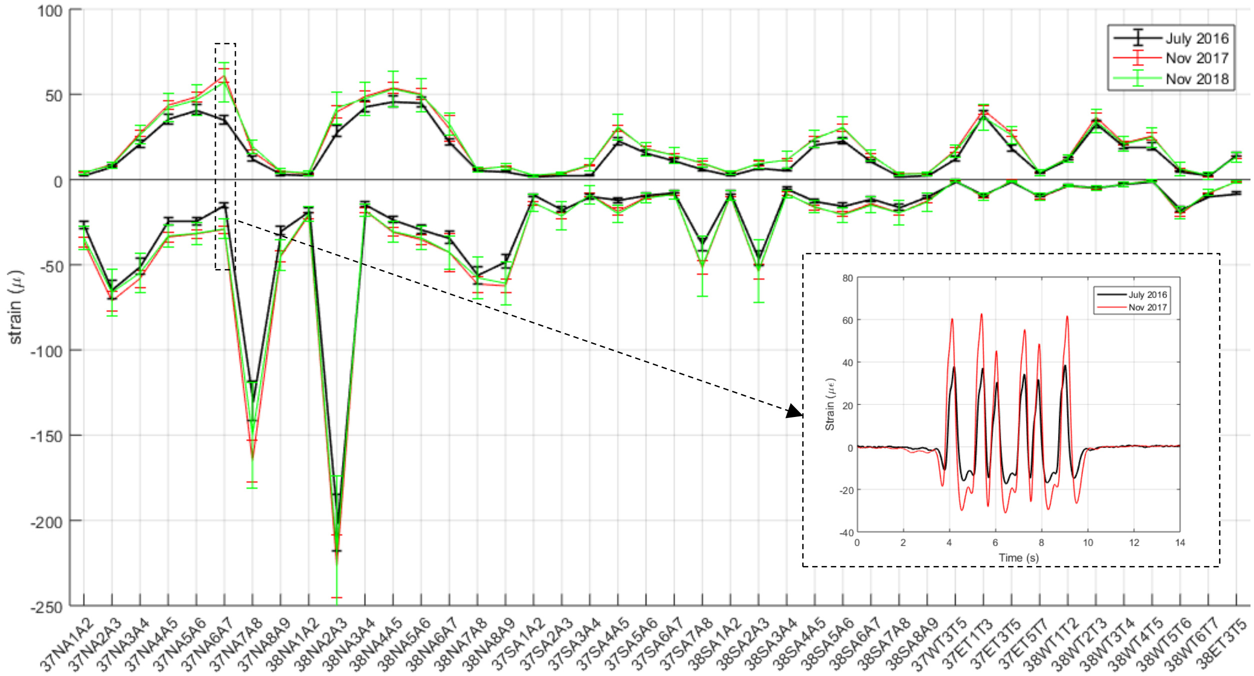

Fig. 5. Mean value and standard deviation of the maximum and minimum peaks of FBG signals for 42 sensors underneath Arches 37 and 38, for the Class 185 3-carriage train that is heading East, exiting Leeds Station

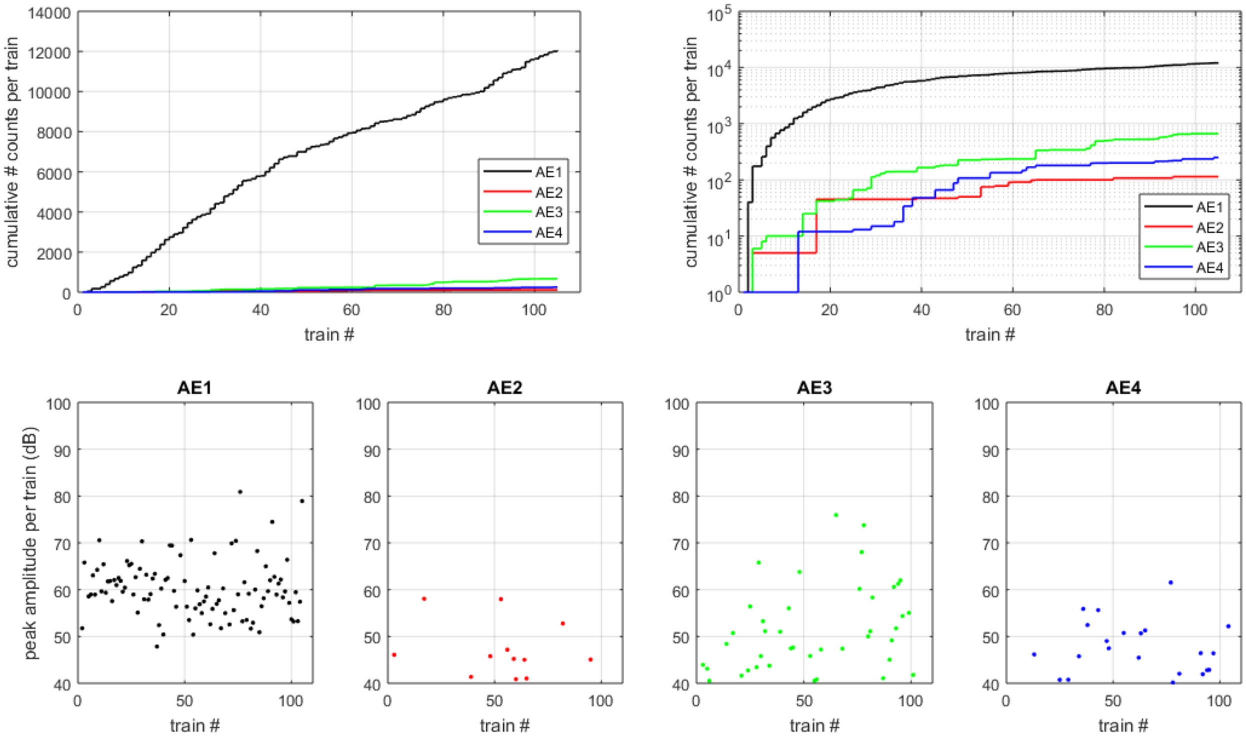

Fig. 6. Top: Cumulative number of counts for AE1-4 sensors in linear and logarithmic scale. Bottom: Maximum AE amplitude per Class 185 train passage for each sensor

To evaluate the effect of cracking on the global dynamic response of a bridge span, the span opening at the top of the piers is of interest. High sensitivity accelerometers were tested to evaluate their accuracy for low amplitude, low frequency displacement measurement. Fig. 7 shows an example result for a Class 185 train, and is obtained from double integration of the high-sensitivity accelerometers data. The result is in excellent agreement with the FBG data demonstrating good capability of this monitoring technique.

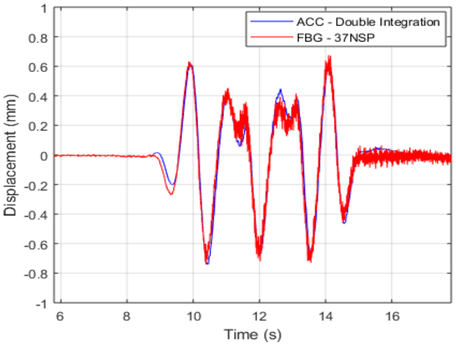

Fig. 7. Span opening at the top of the Arch 37 piers under the Class 185 train load, obtained from FBG and ACC data

4. Conclusions

This paper presents a multi-sensing system for the remote long-term SHM of masonry railway bridges. The system is self-sustaining and capable to track with precision variations in cracking rates, dynamic displacement and strain at multiple locations over time.

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