Available online at www.eccomasproceedia.org
Eccomas Proceedia SMART (2023) 806-816

ECCOMAS Proceedia

X ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2023
D.A. Saravanos, A. Benjeddou, N. Chrysochoidis and T. Theodosiou (Eds)

LONG-TERM MONITORING OF A REINFORCED CONCRETE HALF-JOINT

NIKOLAOS I. TZIAVOS[*] [†], HARIS ALEXAKIS[*] [†] , CEDRIC KECHAVARZI[†] AND JENNIFER SCHOOLING[†]

[*] Aston University, Birmingham, UK
Department of Civil Engineering
e-mail: n.tziavos@aston.ac.uk

[†] Centre for Smart Infrastructure and Construction (CSIC)
University of Cambridge, Cambridge, UK

Abstract

Reinforced concrete half-joints were widely employed globally on a large number of motorway bridges over the past fifty years. Half-joints have dapped ends which enable savings by reducing the construction depth and by facilitating precast construction of concrete bridges. However, half-joints are prone to deterioration due to lack of water-tightness on the joint. In-addition, visual inspections of half-joints can be challenging, leading to ineffective and costly maintenance strategies to mitigate the risk of failure or collapse. This paper presents a field-monitoring campaign on a reinforced concrete half-joint which is located within the UK road network. For this purpose a comprehensive structural health monitoring system has been designed and installed, comprising Acoustic Emission (AE), Fibre Bragg Gratings (FBG) and environmental sensors. The monitoring scheme is described in details, along with acquired data during the first months of acquisition. AE data are correlated with the recorded dynamic behaviour and environmental conditions to provide further insight on the long-term performance of ageing concrete infrastructure.

Key words: Acoustic Emission; Reinforced Concrete; Half joint; Structural Health Monitoring

1 INTRODUCTION

A half-joint is designed with a reduced cross-sectional depth at the ends and is often referred to as a dapped end beam. Half-joints are commonly found in bridge construction around the 1970s and were particularly popular due to simple design, ease of installation and pre-cast construction capabilities [1]. Therefore, a large number of half-joints are part of the strategic road network in the UK, approximately one third of which, are reinforced concrete half-joints [2]. The concept of a half-joint on a bridge is illustrated in Figure 1. Despite design benefits, the long-term structural performance of the joint can be compromised due to reinforcement corrosion as a result of water ingress taking place due to sealant failure [2].

In 2006, a catastrophic collapse of a half-joint occurred in the de la Concorde overpass in

doi: 10.7712/150123.9834.451123

Montreal, Canada, resulting in loss of life. The collapse was attributed to shear failure of the suspended cantilever section due to several factors including but not limited to construction defects and design inadequacy. The forensic investigation revealed that no unusual dynamic loads were applied on the structure and the failure was a result of deterioration and cumulative damage [3].

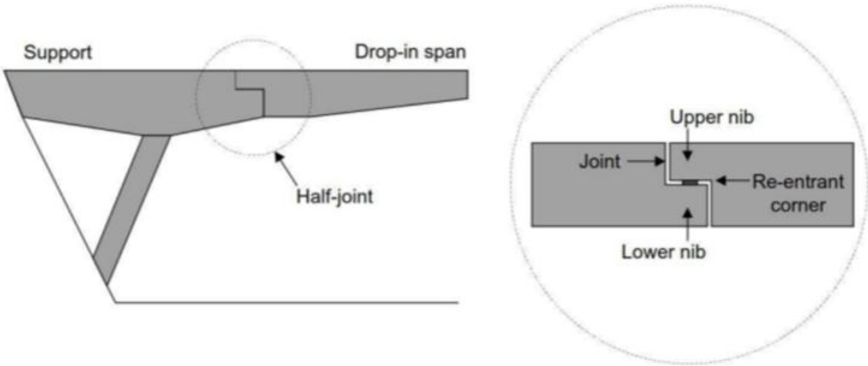

Figure 1. Schematic layout of half joint concept on a bridge [1]

Identification of deterioration on half-joints is a challenging task, as access for visual inspections is often limited. Therefore, remediation works are also difficult to conduct and rather costly without prior knowledge of the condition of the lower nib. In the UK, a strategic management plan for half-joints was initiated, aiming to record the half-joints within the road network and to allow planning of maintenance activities if necessary [1]. This revealed that for most of the inspected joints, some type of deterioration has occurred such as concrete cracking, corrosion and spalling along with a strong interdependency between them [2]. Desnerck et al. [2] also noted that classification of such defects varies significantly during visual inspections due to complex underlying mechanisms. Destructive techniques such as concrete coring, can provide some further insight, however an additional risk factor is introduced.

To inform and enhance the structural assessment of concrete half-joint bridges, non-destructive techniques (NDT) can be of great benefit as they enable robust inspection of large elements and also enhance our understanding of the performance and condition of the in-service structure, without compromising its integrity. The longevity and functionality of reinforced concrete bridges is critical nowadays as daily usage of transport infrastructure is continually increasing [4].

In bridge monitoring, NDT such as ground penetrating radar or impact echo have been employed, however their applicability is limited as early detection of deterioration processes is not possible [5]. On the contrary, for concrete and steel applications, Acoustic Emission enables the detection of internal damage mechanisms in such media at early stages. Nevertheless, there is a lack of codification when it comes to Acoustic Emission (AE) testing on bridges, as the interpretation of field data remains a challenge due to the unique characteristics of each site – material, geometry, ambient conditions and loading regime.

Additionally, very limited research has been conducted on the influence of traffic on AE on in-service bridge, as most of the published literature focuses on experimental testing [6], [7] or bridge behavior during a load test [8].

This paper presents a field monitoring campaign on a motorway bridge by means of AE and Fibre Bragg grating (FBG) strain sensors. Fibre optic sensing is intended to provide further insight on the collected AE signals which are emitted due to live traffic on the concrete half-joint.

2 STRUCTURE DESCRIPTION AND MONITORING SYSTEM

2.1 Reinforced concrete half-joint

The selected reinforced concrete half-joint is located within an operational Class A motorway of the UK road network (Figure 2) and carries traffic in four lanes in each direction. The half-joints of the bridge are under an annual visual inspection regime. The half-joint was selected in cooperation with the asset operator, considering accessibility, ease of installation, safety of equipment and access to power to enable long and continuous periods of monitoring. All the information regarding the bridge and half-joints was collected during the installation period of the monitoring system and is based on visual observations performed on site.

Figure 2: Elevation of the reinforced concrete half-joint bridge (photos taken in February 2020)

2.2 Structural Health Monitoring System

The primary NDT of interest for this study was AE testing, however in order to complement the AE data a complementary fibre optic strain and temperature sensing system has been installed along with a weather station to provide environmental data. All the AE sensors and Fibre Bragg Grating (FBG) strain and temperature sensors were installed across the lower nib of the half-joint across the total width of the joint. The installation was carried out in phases and was completed in early September 2020 for all the acquisition systems.

Piezoelectric PK6i sensors were installed and connected to a Sensor Highway III (SH-III) system (Mistras Group). A total of 24 sensors were used at a spacing of 2 m forming a linear array. To ensure fixation and acoustic coupling over time, a two-part epoxy was applied and an alluminium clamp was used to hold the sensor in place. This type of sensor has been widely employed for monitoring reinforced concrete elements as reported in previous studies [9]. A Vaisala weather station was connected to the SH-III system providing relevant environmental conditions. The AE testing system and the weather station are shown in Figure 3.

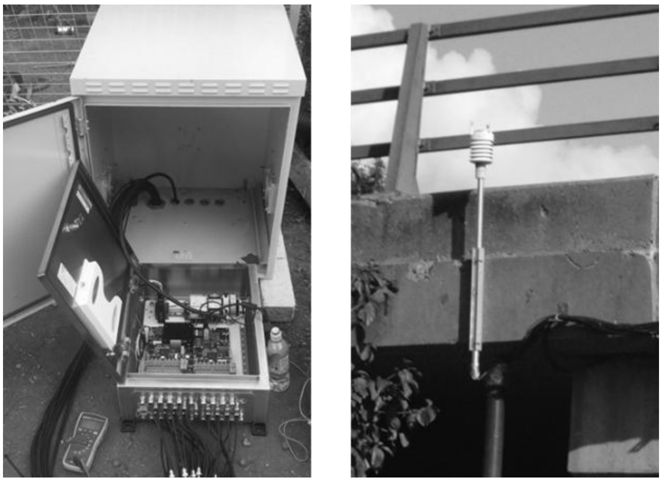

Figure 3: AE (SH-III) system during installation (left) and Vaisala WXT weather station (right)

Strain was monitored using a arrays of FBG sensors which were attached below the lower nib of the half-joint with alluminium clamps. Strain was monitored in the longitudinal, transverse and vertical directions. The FBG arrays comprised 20 sensors each with varying spacings, measuring the strain between subsequent clamps. FBG sensors were installed next to AE sensors to allow for correlations between AE data and strain. The set-up enables both static and dynamic sampling. Initial calibration studies revealed that a sampling frequency of 50 Hz was appropriate for monitoring.

Temperature was measured using a total of five FBG sensors within a fourth array and those sensors were enclosed within an aluminium clamp with a circular groove manufactured to enclose the sensor (Figure 4). The clamp enables strain transfer due to thermal expansion of the metal. The abovementioned method has been previously calibrated by Alexakis et al.[10] and the relationship between the wavelength change and temperature was found to be linear. The thermal coefficient obtained was $25\ 10^{-6}/^{o}C$, similar to that of aluminium.

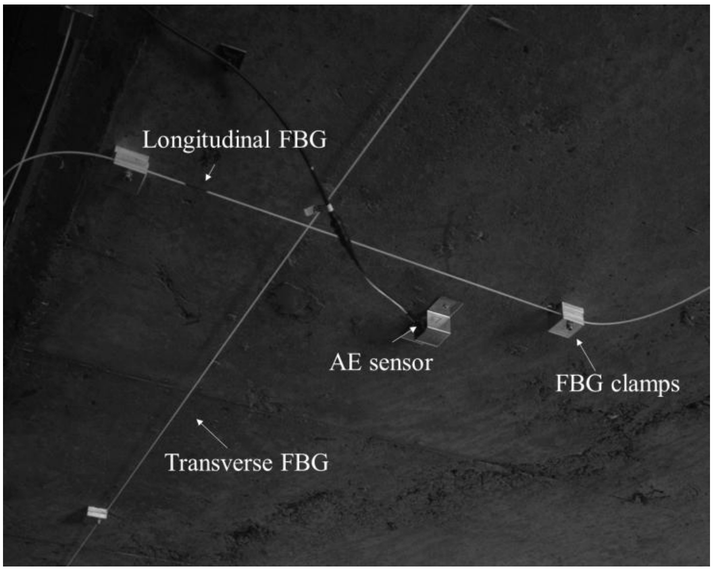

Figure 4: FBG strain sensors attached with alluminium clamps and AE sensor

3 ACOUSTIC EMISSION TESTING DATA ANALYSIS

3.1 Calibration of Acoustic Emission sensors

The sampling rate for the AE system was set to 1 MS/s allowing for parametric-based processing. A threshold of 50 dB has been set for all sensors and an analog filter between 5 kHz and 400 kHz was employed. To verify AE sensor fixation and for calibration purposes, a HSU-Nielsen source as per [11] was employed. The calibration was carried out during normal operating conditions of the motorway focusing on linear location of hits within the array, attenuation and 3-D location at the nib vicinity.

The peak amplitude attenuation with respect to distance is shown for two sensor locations. It was found that the attenuation is not particularly high between sensors (e.g., see sensor AE1 and AE2) and for some regions the spacing between sensors could be further increased. Similarly, in Figure 5 the amplitude decay in longitudinal and transverse directions against distance for various sensors is shown. In both figures, the vertical lines represent AE sensor location and the corresponding sensor is highlighted next to the vertical line.

In normal operating conditions on bridges, AE waves within the half-joint can be emitted as a result of various sources, such as ongoing traffic, noise from concrete, impacts on the bridge and deterioration mechanisms such as cracks. Looking at the total number of hits does not allow for sources to be distinguished, hence further AE features ought to be investigated. Peak amplitude is commonly used as an indicator for the intensity of a signal. During the calibration tests, it was shown that artificial hits imitating cracks result in signals with particularly high peak amplitudes up to 100 dB, if located in the proximity of the sensor (see Figure 4 and 5) and also high energy content.

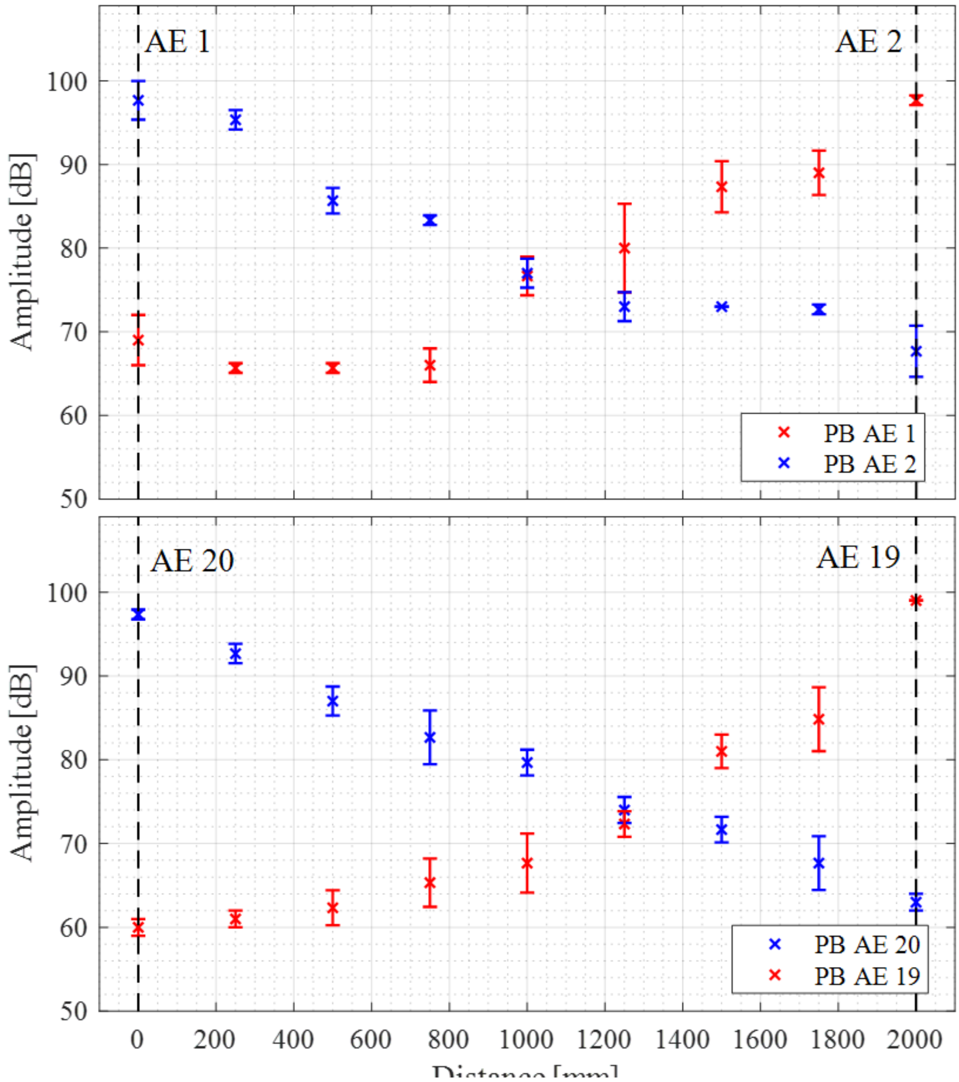

Figure 4: Attenuation of AE sensors at West (top) and East side (bottom) of Half-joint during linear location pencil breaks at 250 mm intervals

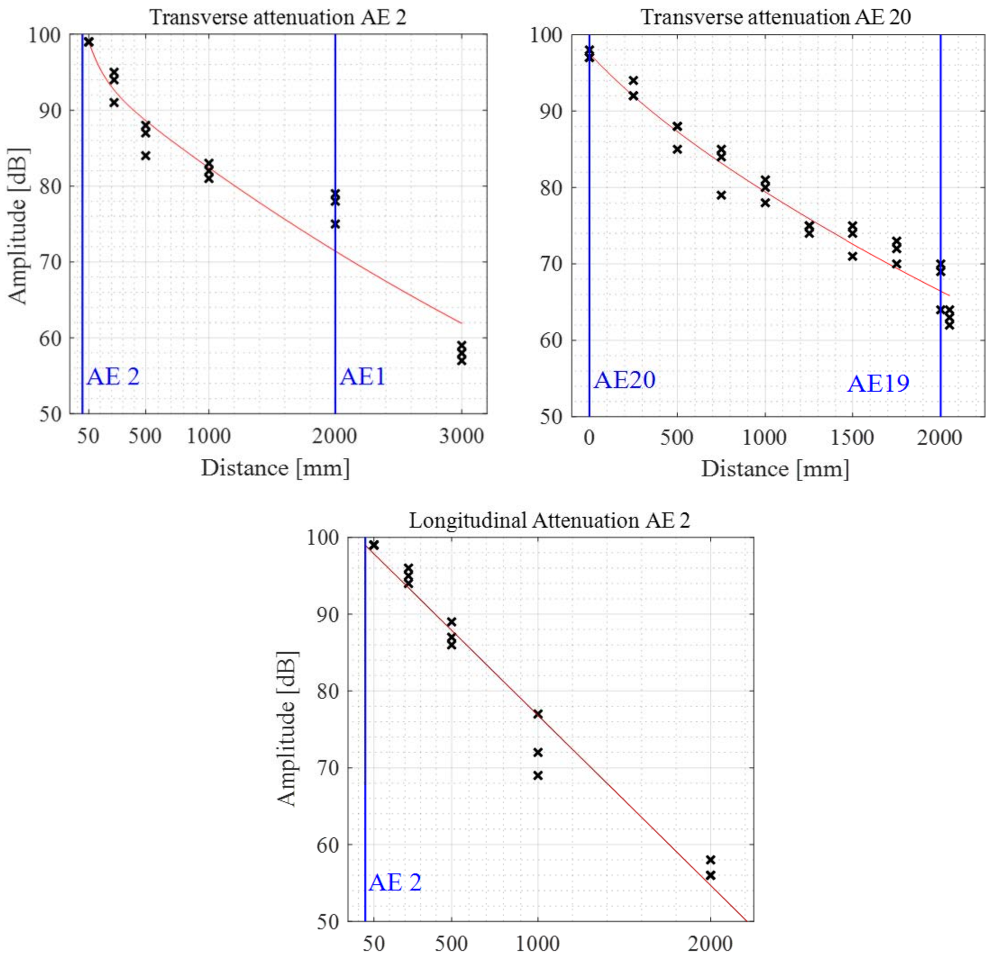

Figure 5: Longitudinal and transverse attenuation for sensors AE 2 and AE 20

3.2 Influence of traffic

In the following figures the influence of traffic on AE activity is illustrated during peak and off-peak hours. For this study, traffic between 07:00-09:00 in the morning was considered to be peak hours and off-peak was between 19:00-21:00. Figure 6 depicts the amplitudes recorded during September 2020 for sensors 2, 10 and 16 during peak and off peak hours. A comparison is made between the most active AE sensor (AE 16) during the first months of acquisition, a sensor on the opposite direction (AE 2) and one AE sensor located approximately underneath the central reservation (AE 10), which was the least loaded region of the half-joint as expected. During peak times, AE 16 recorded amplitudes even up to 100 dB with signals collected during the weekends having lower amplitudes in general. Overall, AE 16 also recorded signals with lower intensity during off peak hours, however high-amplitude signals were also recorded, with variations being attributed to the continuously changing traffic conditions. Sensor AE 10 peak amplitudes were much lower and well below 70 dB, whereas sensor AE 2 captured signals with amplitude up to 80 dB approximately.

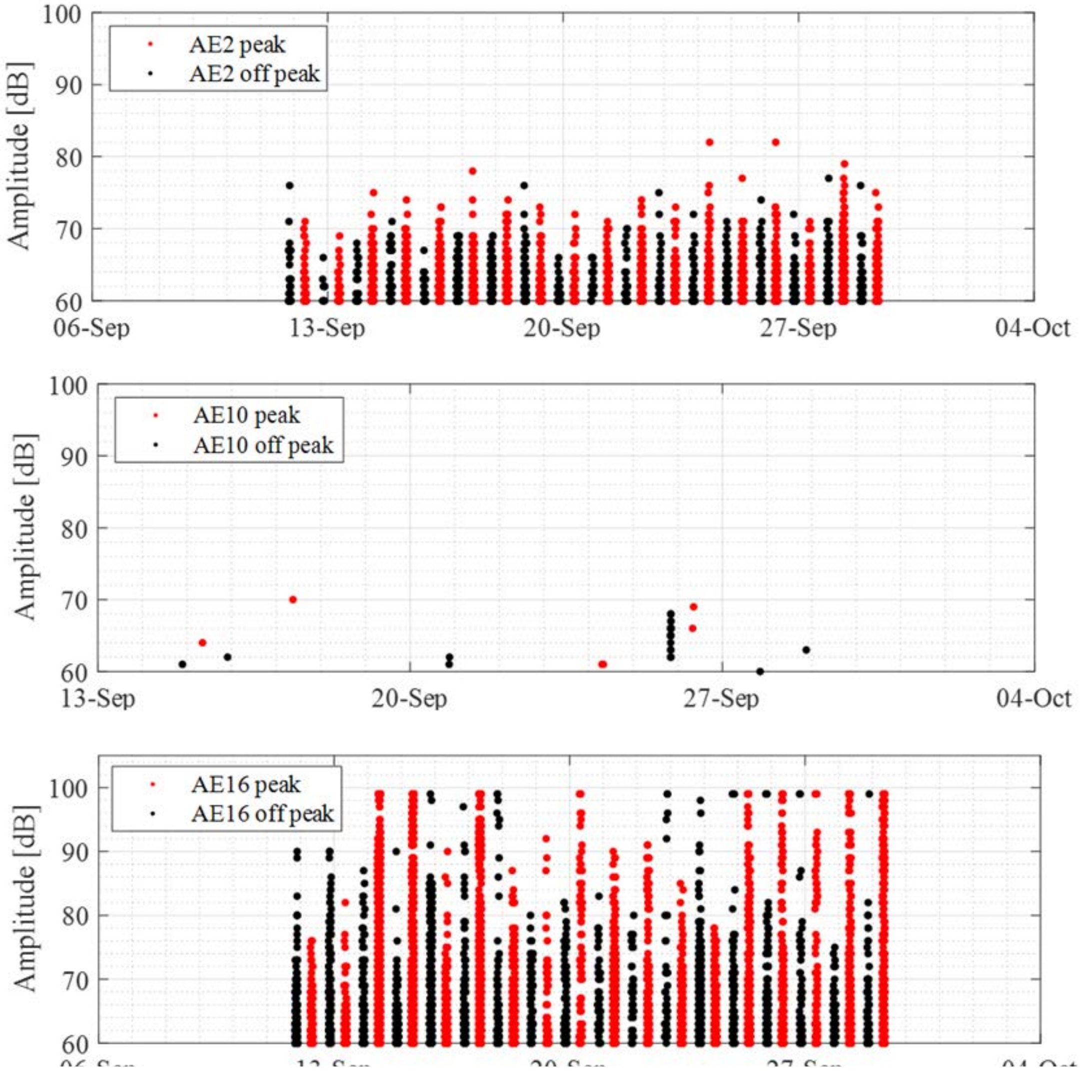

Figure 6: Peak amplitude for sensors 10 and 16

The Cumulative Energy (in aJ) of the recorded hits is shown in Figure 7. The Absolute Energy was used to derive the Cumulative Energy as a true measure of the energy content of the signal. The Cumulative Energy of three sensors is presented in Figure 7, for peak, off-peak and overnight traffic hours (03:00-04:00). AE2 was found to capture amplitudes of similar levels during peak and off-peak hours (see Figure 6), however the Cumulative Energy is much higher during the peak hours as demonstrated below. This is also confirmed for sensor AE 17, for which the recorded Cumulative Energy was found to be significantly higher than AE 10 which is located under the central reservation, confirming that AE activity is directly related with in-service conditions. AE activity was also verified with the peak strains recorded from the FBG sensors shown in Figure 8 for the same dates in September. Similarly, in Figure 9 the Cumulative Energy of the sensors is compared to highlight the change in signal intensity between the North and Southbound directions. It is shown that for sensor AE 17 the total Cumulative Energy is of higher order of magnitude indicating significantly higher activity within the vicinity of the sensor.

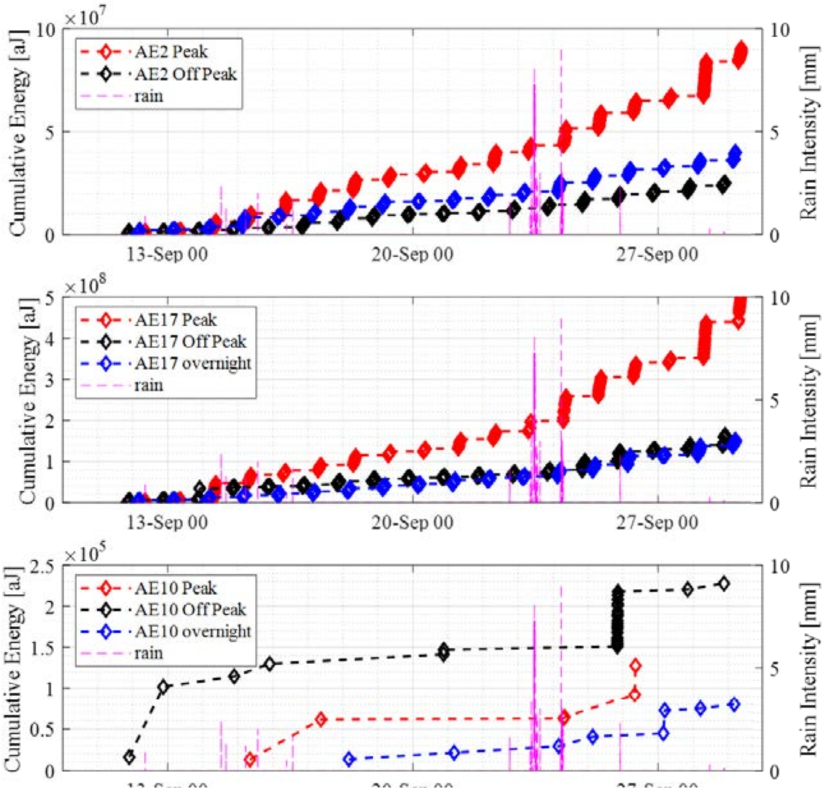

Figure 7: Cumulative energy of recorded signals for different sensors during September

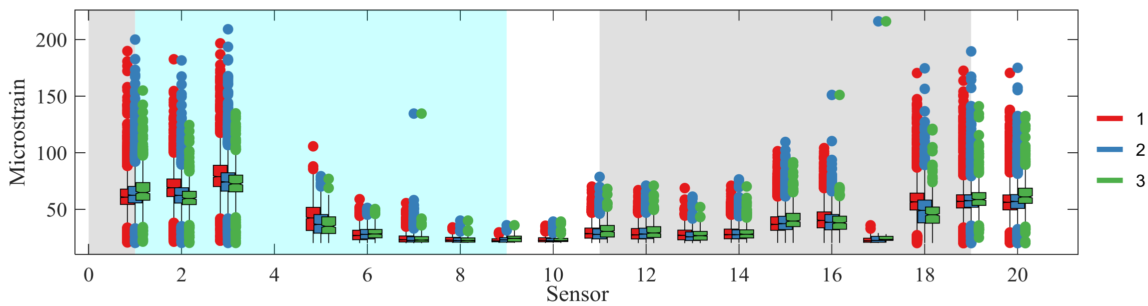

Figure 8: Peak strain recorded at each AE sensor location during three consecutive weeks in September

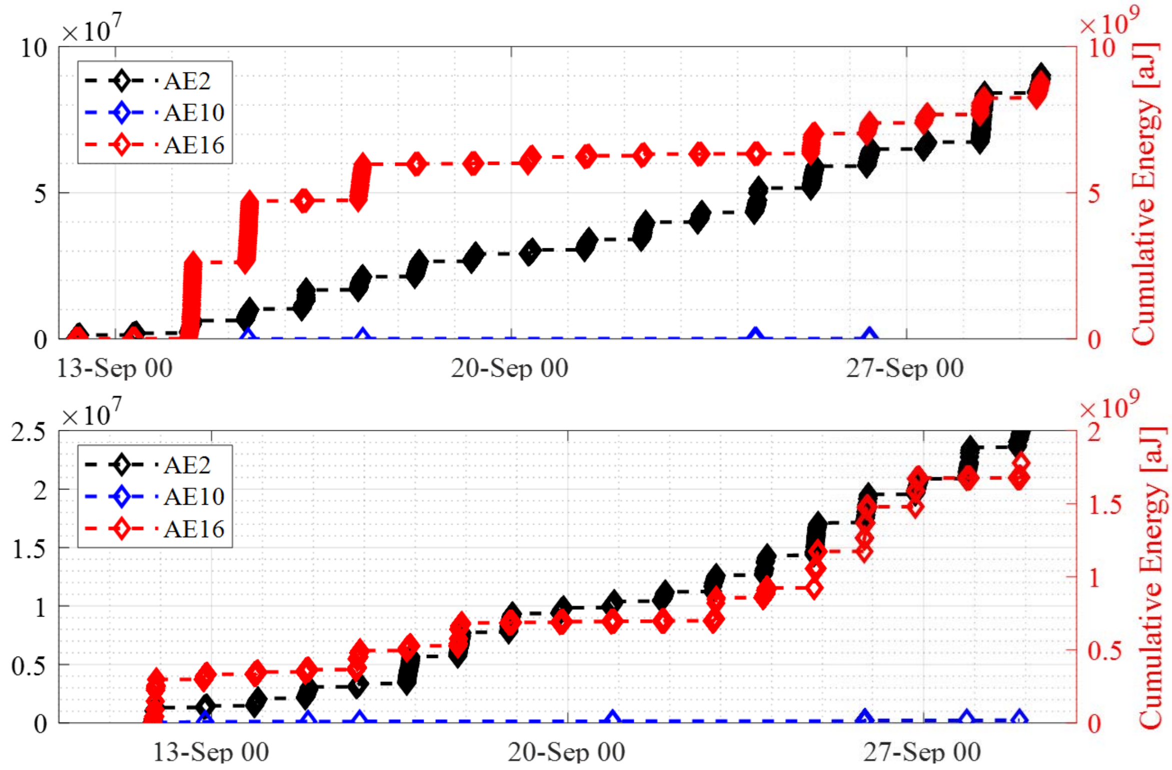

Figure 9: Comparisons between cumulative energy of various AE sensors. AE16 is plotted against the right hand axis to indicate the change in order of magnitude

4 CONCLUSIONS

This paper presents preliminary results from a field monitoring campaign on a reinforced concrete half-joint in order to assess the applicability of AE testing for structural assessment purposes. A total of 24 piezoelectric AE sensors were installed across the lower nib of an in-service half-joint covering a region of approximately 40 m. During the first months of acquisition it was found that the loading pattern is symmetrical without any unusual loads, however, two southbound regions appear to be recording a much larger AE activity. This highlights the ability of AE to be used for short-term monitoring campaigns to acquire a snapshot of the bridge condition. The reported initial data focused on the attenuation of signals within the concrete body and a qualitative analysis of the influence of traffic. It was found that attenuation was not particularly high which could allow for sensor redundancy and larger spacing between adjacent sensors. AE activity signal features such as amplitude and Cumulative Energy can be used as in-service indicators for the half-joint's performance.

ACKNOWLEDGEMENTS

The authors are grateful to Highways England, UK for providing financial support for this project. In addition, the authors would like to acknowledge KIER Group plc for supporting and accommodating field installation. The field work and installation was supported by the Centre for Smart Infrastructure and Construction (CSIC) supported by EPSRC, Innovate UK, and industry funding (including Grant Numbers EP/I019308/1, EP/K000314/1, EP/L010917/1, and EP/N021614/1).

REFERENCES

[1] P. Desnerck, J. M. Lees, and C. T. Morley, "The effect of local reinforcing bar reductions and anchorage zone cracking on the load capacity of RC half-joints," *Eng. Struct.*, vol. 152, pp. 865–877, 2017, doi: 10.1016/j.engstruct.2017.09.021.

[2] P. Desnerck, J. M. Lees, P. Valerio, N. Loudon, and C. T. Morley, "Inspection of RC half-joint bridges in England: Analysis of current practice," *Proc. Inst. Civ. Eng. Bridg. Eng.*, vol. 171, no. 4, pp. 290–302, 2018, doi: 10.1680/jbren.18.00004.

[3] R. Johnson, P.M., Couture, A. and Nicolet "Report of the Commission of inquiry into the collapse of a portion of the de la Concorde overpass." Goverment of Quebec.

[4] D. V. Achillopoulou, S. A. Mitoulis, S. A. Argyroudis, and Y. Wang, "Monitoring of transport infrastructure exposed to multiple hazards: a roadmap for building resilience," *Sci. Total Environ.*, vol. 746, no. July, p. 141001, 2020, doi: 10.1016/j.scitotenv.2020.141001.

[5] I. Bayane and E. Brühwiler, "Structural condition assessment of reinforced-concrete bridges based on acoustic emission and strain measurements," *J. Civ. Struct. Heal. Monit.*, vol. 10, no. 5, pp. 1037–1055, 2020, doi: 10.1007/s13349-020-00433-0.

[6] M. K. Elbatanouny, P. H. Ziehl, A. Larosche, J. Mangual, F. Matta, and A. Nanni, "Acoustic emission monitoring for assessment of prestressed concrete beams," *Constr. Build. Mater.*, vol. 58, pp. 46–53, 2014, doi: 10.1016/j.conbuildmat.2014.01.100.

[7] A. A. Abouhussien and A. A. A. Hassan, "Application of acoustic emission monitoring for assessment of bond performance of corroded reinforced concrete beams," *Struct. Heal. Monit.*, vol. 16, no. 6, pp. 732–744, 2017, doi: 10.1177/1475921716681460.

[8] A. Nair and C. S. Cai, "Acoustic emission monitoring of bridges: Review and case studies," *Eng. Struct.*, vol. 32, no. 6, pp. 1704–1714, 2010, doi: 10.1016/j.engstruct.2010.02.020.

[9] A. Behnia, H. K. Chai, M. GhasemiGol, A. Sepehrinezhad, and A. A. Mousa, "Advanced damage detection technique by integration of unsupervised clustering into acoustic emission," *Eng. Fract. Mech.*, vol. 210, no. February 2018, pp. 212–227, 2019, doi: 10.1016/j.engfracmech.2018.07.005.

[10] H. Alexakis, F. D. H. Lau, and M. J. DeJong, "Fibre optic sensing of ageing railway infrastructure enhanced with statistical shape analysis," *J. Civ. Struct. Heal. Monit.*, vol. 11, no. 1, pp. 49–67, 2021, doi: 10.1007/s13349-020-00437-w.

[11] B. E. 1330-9, "Non-destructive testing - Terminology - Part 9: Terms used in ccoustic emission testing." 2017.