

# Damage Detection in Railway Prestressed Concrete Sleepers using Acoustic Emission

A Clark<sup>1</sup>, S Kaewunruen<sup>1,2</sup>, R Janeliukstis<sup>3</sup> and M Papaelias<sup>4</sup>

<sup>1</sup>Department of Civil Engineering, School of Engineering, The University of Birmingham, U.K

<sup>2</sup>Birmingham Centre for Railway Research and Education, The University of Birmingham, U.K

<sup>3</sup>Department of Civil Engineering, Riga Technical University, Institute of Materials and Structures, Riga, Latvia

<sup>4</sup>School of Metallurgy and Materials, The University of Birmingham, U.K

E-mail: s.kaewunruen@bham.ac.uk

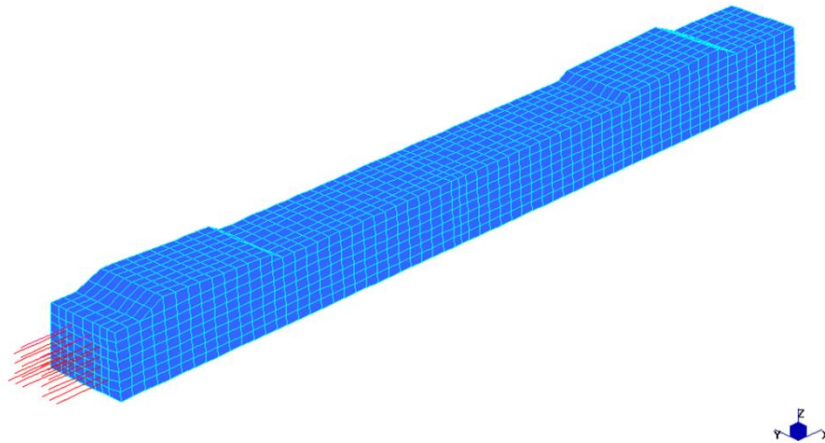
**Abstract.** Prestressed concrete sleepers (or railroad ties) are safety-critical elements in railway tracks that distribute the wheel loads from the rails to the track support system. Over a period of time, the concrete sleepers age and deteriorate in addition to experiencing various types of static and dynamic loading conditions, which are attributable to train operations. In many cases, structural cracks can develop within the sleepers due to high intensity impact loads or due to poor track maintenance. Often, cracks of sleepers develop and present at the midspan due to excessive negative bending. These cracks can cause broken sleepers and sometimes called ‘center bound’ problem in railway lines. This paper is the world first to present an application of non-destructive acoustic emission technology for damage detection in railway concrete sleepers. It presents experimental investigations in order to detect center-bound cracks in railway prestressed concrete sleepers. Experimental laboratory testing involves three-point bending tests of four concrete sleepers. Three-point bending tests correspond to a real failure mode, when the loads are not transferred uniformly to the ballast support. It is observed that AE sensing provides an accurate means for detecting the location and magnitude of cracks in sleepers. Sensor location criticality is also highlighted in the paper to demonstrate the reliability-based damage detection of the sleepers.

## 1. Introduction

Railway concrete sleepers are a safety-critical component of the railway track system as shown in Figure 1; therefore, it is essential to conduct a thorough investigation into its structural behaviours for safe operational purposes as well as guiding development for the future [1-4]. There is an existing lack of insight into the use of non-destructive technologies (NDTs) within the industry. Increasing demands placed onto track structures have pressed the need for a more adequate monitoring system. The integration of NDTs into the development of ‘smart tracks’ can reduce the risks imposed by any damage to the structure. The subsequent knowledge gained by track engineers would be valuable in future maintenance procedures and railway operations. Current detection methods, including visual observation, fail to record damage in real-time and they are not efficient enough for significant demands to reduce track possessions.



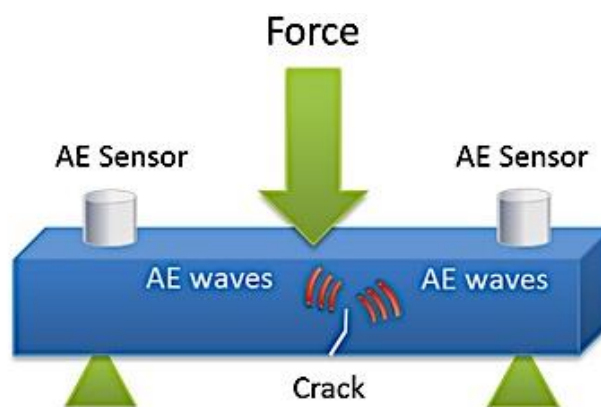
Acoustic emission technology has been a useful application in many other fields of engineering, thus its application of these principles to railway sleepers is highly potential. By investigating the competence of these technologies as a means to collect real-time damage information, it could eradicate the aforementioned flaws in detection leading to safer railway tracks whilst minimising long-term maintenance costs. This study will determine the adequacy of AE sensing for the evaluation of static loading responses of sleepers. In addition, it will establish an engineering assessment and guideline for structural health monitoring of railway sleepers that may be used for practical application.



**Figure 1.** Railway sleeper [5].

## 2. Acoustic Emission Sensing

The first studies using AE were conducted in the 1950s, and a number of different ideas regarding its most useful application, whether commercially or industrially came about. The subsequent decades saw a rapid advance in the technology and by the 1970s it was an integral method of structural monitoring. Crack initiation and propagation is the stress source of interest with concrete railway sleepers. When a load is applied by rolling stock, instigating crack growth, a signal is emitted from the tip of the crack identifying its location and growth rate. A passing train may interfere with the AE signals producing disturbances known as extraneous noise. Extraneous noise is identifiable by its distinct frequency spectra therefore making it possible to determine the relevant AE signals [6]. Additionally, modern technology addresses this by using the master-slave technique that uses ‘guard sensors’ to eliminate extraneous noise [7].



**Figure 2.** Acoustic emission technique.

### 2.1. Application

AE sensing is particularly useful in circumstances that require long-term observation. Once the AE technology has been installed it can be left to perform structural health monitoring without physical maintenance, this is an important advantage to distinguish it as a feasible method. In 2012, repair works to the Hammersmith flyover in London used over 400 AE sensors for the detection of tendon failure [8]. The AE system was only partially effective because the sensors were installed decades after the initial construction, so the already defected structure was taken as the base condition [9]. Implementation on railway structures would have the same flaw, as damage to the sleeper may only be identified from the moment of installation, even if failure had already occurred. However, the data is still valuable as the sleepers with the most progressive cracking can be identified.

### 2.2. Kaiser effect

The Kaiser effect describes the phenomenon that AEs may only become detectable once the previous load has been exceeded. Joseph Kaiser observed that under elastic behaviour, a material produces virtually no detectable emission waves until the previous maximum stress level is obtained [10]. This phenomenon is therefore very relevant for cyclic loading of rail tracks. Other investigations have also indicated that a cyclic load will not influence the AE results until the previous maximum stress level is achieved [7].

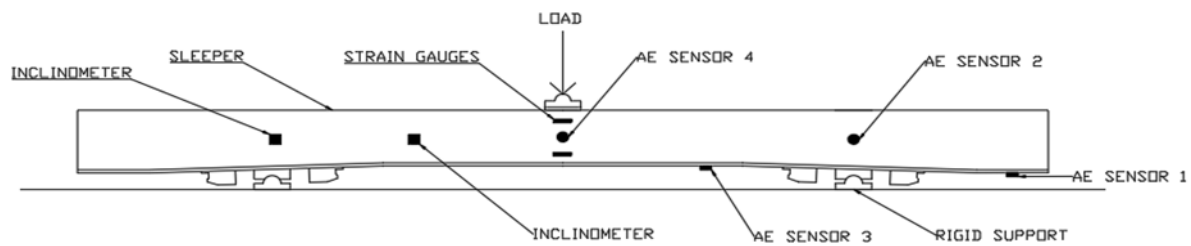
### 2.3. Equipment

AE measurements were carried out during the mechanical tests of all the specimen types to monitor and evaluate damage evolution during loading. The AE signals were detected and recorded using a 4-channel DAQ AE system procured from Physical Acoustics Corporation (PAC, now Mistras). The data acquisition was performed using “AE-Win” software. The AE signals were detected using wideband PAC-WD piezoelectric acoustic emission transducers operating at frequency range of 20-1000kHz. The data acquisition system used was a custom-built AE and vibration acquisition system capable of continuously recording the complete waveform for periods of few seconds. The custom-built acquisition system consisted of the following components:

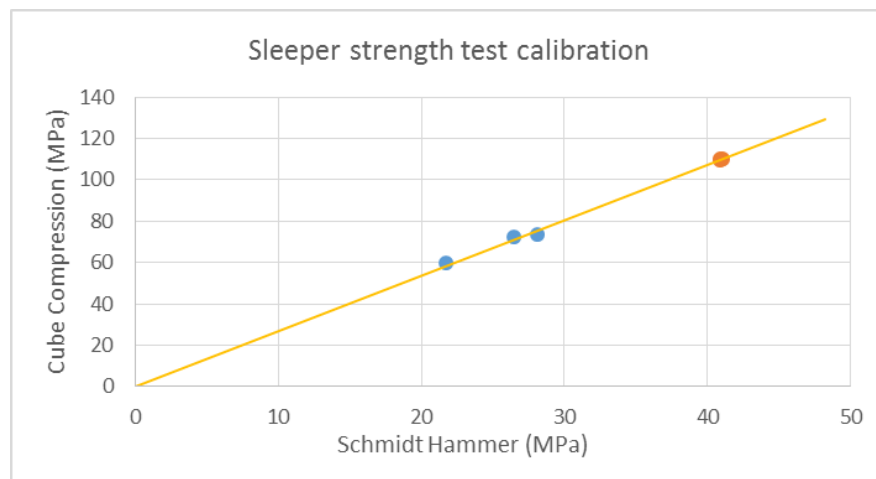
- A computer with a customised data logging software.
- An Agilent U2531A 4 channel data acquisition card.
- A 4 channel decoupling hub.
- A MISTRAS Wide bandwidth AE amplifier provided by PAC.
- A PAC model 2/4/6 preamplifier operating in the frequency range of 20-1200 kHz.
- A wideband PAC-WD piezoelectric AE sensor operating in the frequency range of 20-1000 kHz.

## 3. Experimental Method

CEMEX have generously supplied four sleepers for, these are manufactured to industry specifications as used throughout the UK. For the sleeper to meet Eurocode standards a Schmidt Hammer test will be conducted to check the concrete strength is sufficient to comply with BS EN 13230-1 that requires a minimum concrete strength of C45/55 MPa [11]. For this study, a static load is applied at mid span to cause negative 3-point bending cracks and failure as shown in Figure 3. The 3-point bending behaviour will stimulate the center-bound problems associated with poorly-maintained ballast beds. When the sleeper is not evenly distributing load into the ballast, it will generate negative bending to the structure. As shown in Figure 3, locations of acoustic emission sensors have been strategically placed to determine the location criticality of the sensors and to evaluate the sensing signal clarity. In addition, Schmidt Hammer has been used to estimate in situ concrete strength of existing specimens.



**Figure 3.** Negative bending test setup.



**Figure 4.** Non-destructive compressive strength correlation.

#### 4. Material Testing

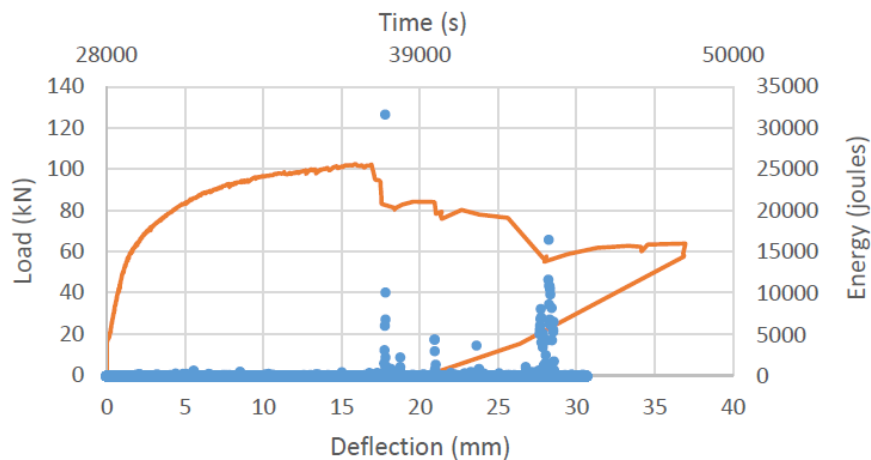
CEMEX specifies a 28-day design strength of 110 MPa. This shows a good correlation with the data extracted from the Schmidt Hammer. The results are very similar for each of the four sleepers with all strength values within 0.5 MPa of each other, demonstrating good manufacturing control. The strength values are then used to make numerical calculations of the ultimate loads and to compare them with the stress values obtained as shown in Figure 4. It is clear in Figure 4 that the compressive strength can be linearly extrapolated. Note that these comparative results are based on 100x100x100 mm<sup>3</sup> cube compression tests in accordance with British Standards.

#### 5. Acoustic Emission Signals

A load-deflection curve shows the elastic and plastic behaviour of the sleeper with the linear portion representing the elastic zone. When the curve reaches ultimate load substantial loss of tensile strength will occur. By overlaying the AE data, the damage events picked up by the sensors correlate with the transition into the plastic zone (when concrete cracks/crashes, steel wires yield, and sleeper plastically deforms) and its nonlinear behaviour thereafter. It is expected that the most substantial AE energy hits will occur at the ultimate load, and provided the sleepers still have tensile capacity, significant activity may continue after failure. By controlling the rate of deflection, it can be plotted against time to give meaningful results, but controlling this rate can be challenging which gives some minor inconsistencies. Deflection was recorded using a linear variable differential transformer (LVDT) under the mid span.

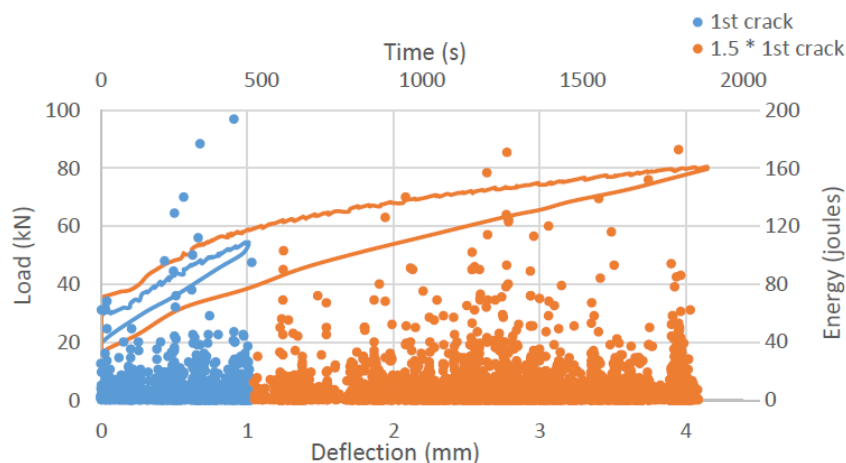
Figure 5 shows the elastic zone extends to approximately 60 kN at which point the first crack occurs, a lower value than visual observations of 70 kN. Energy from the first crack event is negligible, thus it cannot be seen due to the magnitude of later events. The highest energy signal of 31,600 joules takes place at the ultimate load of the specimen, 102 kN. Beyond this point, the steel tendons assume the tensile load, allowing further deformation to take place, hence AE activity continues. At 78 kN post failure, another substantial event leads to a dense concentration of high energy hits up to 16,500 joules. There is a significant loss of tendon prestressed force and concrete

disintegration here. The CEMEX G44 sleeper is a relatively brittle design with just six tendons making the behaviour less predictable.

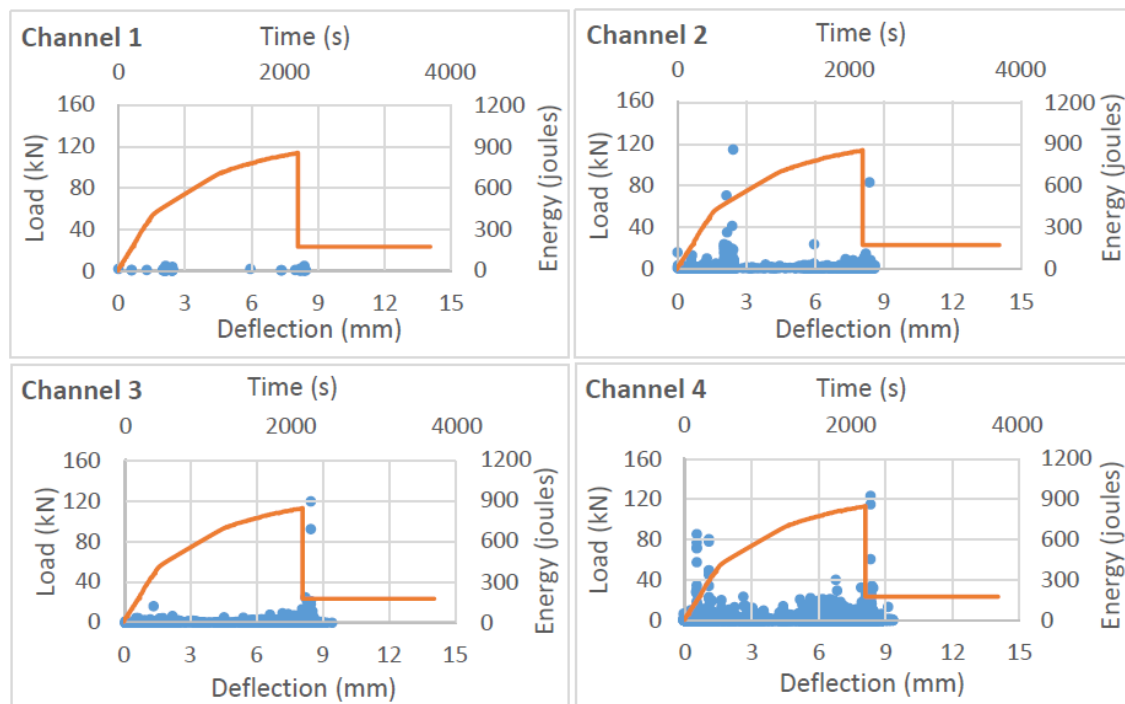


**Figure 5.** Load-deflection against acoustic emission energy under ultimate static loading.

Figure 6 shows the incremental loading pattern from the crack progression test. In comparison to the failure curve, the energy hits are very low, but it does confirm the observed initial cracking in Figure 5 at 53 kN. Activity prior to the initial surface cracks corresponds to minor internal cracks and extraneous noise. Due to the Kaiser effect, when the sleeper is unloaded then reloaded back to the force required for the initial crack, there is no AE activity, so it is possible to put these in a single time sequence. Cracking alters the flexibility of the sleeper, hence why for 1 mm deflection the load is 6 kN greater. Beyond the first crack, the slope of the curve indicates the transition into the plastic zone, where regular AE activity is maintained. Comparing the crack progression to the AE energy hits, there is a strong correlation between them, supporting the competence of using AE in damage detection. There are clearly peaks and troughs in the energy sequence that display when any major cracking events that are taking place.



**Figure 6.** Load-deflection against acoustic emission energy under cyclic loading.



**Figure 7.** Sensing location criticality.

As shown in Figure 7, the exact location of damage can be found based on the time taken for a signal to arrive at each sensor, this method is called linear localisation. Separating the sensors into individual channels means that by identifying the sensor corresponding to an energy event, the damage location can be spatially approximated. The first crack is identified by sensor 4 at the mid span, this is expected since the first crack is flexural. It matches well with the load deflection curve as it marks the transition in the plastic zone. Sensor 2 – located at the rail seat, records a high energy hit just after the initial cracking, which represents spalling of the concrete at the supports. At the ultimate load, sensors 3 and 4 record high energy hits, as expected, since they are located nearest the mid span.

## 6. Conclusions

The experimental investigation into acoustic emission probe has successfully guided its structural health monitoring capabilities. With limited existing research into this field, this paper realises the potential of self-monitoring systems, providing a positive case for their implementation on track structures. The study has also presented many challenges that remain before a functional monitoring system can be feasibly applied to a railway track. However, our results are the first to show that the AE sensing technology is effective in the detection of initial crack events. The energy jump induced by these cracks correlate well with other variable parameters. Due to the brittle nature of the specimens tested in this study, AE is unsuccessful in anticipating when failure is about to occur, which suggests that the failure mechanisms for these sleepers should be reassessed. The data obtained through AE confirms the behaviour of concrete sleepers under flexural bending. The deflection curve provides a simple method of real-time damage detection, because vertical displacement recordings can identify changes in structural integrity.

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