# Acoustic Emission Behaviour of Prestressed Concrete Sleepers Under Quasi-Static Homologation Testing

Benard OMONDI *, Dimitrios G. AGGELIS *, Hugo SOL *, Cox SITTERS **
* Vrije Universiteit Brussel, Brussels, Belgium
** Moi University, Eldoret, Kenya

**Abstract.** Prestressed concrete sleepers (PCS) play a key role in providing lateral, longitudinal and vertical stability of railway track systems. Its capacity to fulfil these tasks is principally examined through "homologation" tests based on crack initiation and propagation. However, the current classical technique for crack detection by use of a graduated microscope inspects only the surface while its accuracy is limited. Additionally it does not offer insight on the cause of cracking in such a heterogeneous medium as prestressed concrete. The present work aims at studying the behaviour of PCS under quasi-static homologation testing based on acoustic emission (AE) parameters. The AE technique is used to determine the onset of cracking, while indices like the calm and felicity ratios demonstrate the evolution of damage for the successive loading steps. AE waveform parameters are also studied in relation to the possible fracture mechanisms i.e. matrix cracking or interface friction while AE activity is correlated to the crack width. It is demonstrated that AE technique can substantially contribute to the characterization of the damage process of PCS.

## Introduction

Railway sleepers, together with the rails are the main structural elements of railway tracks. As shown in Figure 1, sleepers are transverse structural beams resting on ballast and provide means to support rails in tracks [1]. In service, vertical, lateral and axial forces are applied to railway sleepers. These forces should be transferred to the underlying ballast layer within the admissible stress range with minimum disturbance of track quality and permanent deformation.

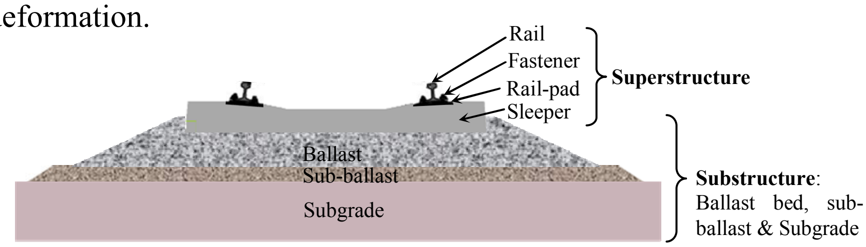



**Figure 1:** Typical structural components of a ballasted railway track

Different materials, such as timber, steel and concrete, have been employed as sleepers in railway construction. At the moment, mono-block prestressed concrete sleepers (PCS) are popular and widely used in many countries such as North America, Europe, Asia and Australia [2]. With longer life cycle, lower maintenance costs and large weight, PCS brought many technical and economic advantages to railway engineering.

PCS are expected to withstand high magnitude dynamic loads and harsh environments. Like other concrete elements and structures, PCS have their own failure modes as demonstrated by previous investigators using numerical models, field studies and experimental tests [3]. However, due to the complex interactions between different components of the track structure, a study including all structural components is very complicated. Therefore, a simplified homologation procedure has been developed in order to qualify the capability of PCS to withstand the harsh loadings [4]. The procedures capture the failure regime of concrete sleepers as influenced by static, dynamic and fatigue loads. It involves monitoring of crack initiation and propagation on the surface of concrete sleeper at different loading states using a graduated microscope. However, the use of graduated microscopes in crack monitoring is technically tedious and time consuming. Furthermore, due to the heterogeneous nature of concrete, the approach does not give correct insights in all the damage mechanisms which lead to failure of the structure.

Monitoring of the relevant damage mechanisms can be assisted by the Acoustic Emission (AE) technique due to its early detection of micro-cracks before they become visible through the graduated microscope [5]. The aim of this paper is to report on damage characterization of PCS based on the Acoustic Emission (AE) technique following standard laboratory homologation test procedures. The paper first presents a theoretical overview of the AE technique with emphasis on the parametric studies used in the current research and then discusses the obtained results with respect to the characterization of damage in PCS.

## Acoustic Emission Technique

An acoustic emission is defined as the transient elastic wave generated by the rapid release of energy from a localized source or sources within a material [6]. Overstraining a material results in localised zones of deformation thereby setting elastic energy free (AE event), which propagates through the structure in the form of elastic waves that can be recorded as transient acoustic emission (AE) signals. The elastic energy propagates as a stress wave in the structure and is detected by one or more AE sensors. In concrete, the AE events may be generated by moving dislocations, crack onset, crack growth and crack propagation, fibre breaks and debonding in fibre reinforced composites, slip between concrete and reinforcement, plastic deformation, etc. By investigating their origin and characteristics, AE techniques provide an insight into deterioration processes of a tested object [7].

Some fundamental studies with small-scale specimens have shown that, in principle, AE analysis is an effective method for damage assessment [8]. Research on various laboratories tests up to full scale models of real structural components intended to relate observed AE characteristics to failure mechanisms in reinforced or prestressed concrete [9]. Both reinforced concrete (RC) and prestressed concrete (PC) materials emit discrete bursts of AE energy when undergoing stress. Monitoring of the AE activity rate has been a vital tool in depicting the formation or propagation of cracks in concrete. Initial studies carried out indicated that the formation or propagation of cracks in concrete is preceded by significant increase in the AE activity rate. Furthermore, studies have demonstrated differences in AE behaviour between ordinary and prestressed concrete [10].

The most important phase is the correlation of the cracking mode to the AE indices [11]. In most types of RC structures when load is applied, shear cracks develop after the formation of tensile cracks [11]. AE parameter analysis is the fundamental method for identifying types of damage in a structure. It utilises features that describe the detected waveform. Typical parameters investigated include amplitude, energy, counts (number of threshold crossings), duration, average frequency (counts over duration), and rise time. The shape of AE waveforms is reported to be characteristic for the fracture mode as shown in Figure 2.

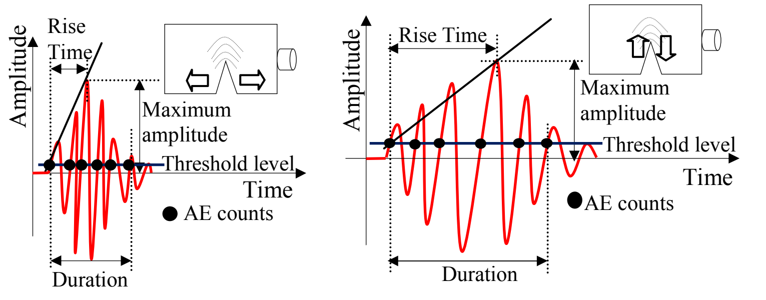



**Figure 2:** Typical AE waveforms depending on the fracture mode [12]

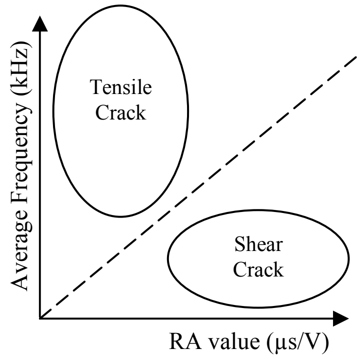



**Figure 3:** Crack classification based on the average frequency and RA value [19]

Shear events are characterised by a longer rise time and usually a higher amplitude than tensile events [12]. According to many researchers [11, 13, 14], the relationship between RA values (rise time/amplitude) and average frequencies (counts/duration) can be used for classification of crack types in concrete structures. They reported that when an AE signal has a low average frequency and a high RA value, it is classified as shear crack/movement. However, when it has a high average frequency and a low RA value, it is classified as a tensile type of crack as depicted in Figure 3.

Damage qualification has also been successfully conducted through AE techniques by applying the principle of high redundancy of structurally stable concrete corresponding to low AE activity in a sound structure [15]. This phenomenon has been described by the Kaiser effect and Felicity effect. Kaiser effect is defined as the absence of any detectable signal, until the previous maximum load is exceeded while Felicity effect is the presence of the AE signals before the previous maximum stress level is reached. Since Kaiser effect and Felicity effect are closely associated with structural stability, ratios (Felicity ratio and calm ratio) to qualify the damage are defined in the recommended practice [16]. The Felicity ratio is the ratio between the load at which AE signals reappear and the previous maximum load. The lower the ratio, the greater the extent of damage. On the other hand, calm ratio is defined as the ratio of the number of cumulative AE activity during the unloading to total AE activity during the whole cycle. In the case of a sound structure, AE activity is seldom observed during unloading and the calm ratio is small. In the recommendation [16], the damage is defined as minor, intermediate and heavy as shown in Figure 4.

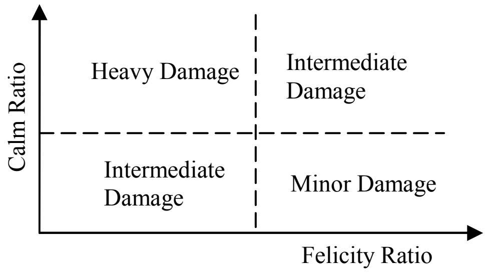


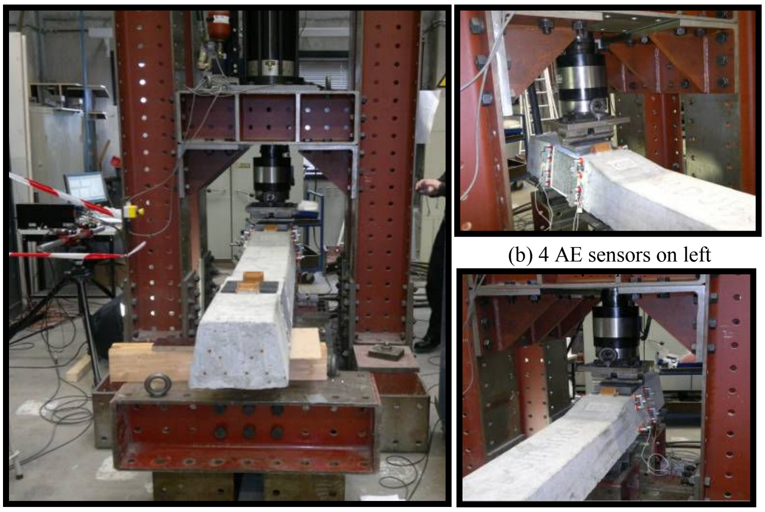

**Figure 4:** Damage qualification by the Felicity ratio and calm ratio [16]

From the foregoing, it is clear that there is great potential in using AE techniques for damage characterisation.

## Experimental Program

The Acoustic Emission monitoring was carried out on two prestressed concrete sleepers (PCS) of type M41 which is commonly used in Belgian railways. The two PCS used in this work were kindly availed by a Belgian concrete manufacturing company called Dupuis. The properties of the sleepers were reported as follows: concrete class of C50/60, maximum aggregate size of 20 mm, prestressing with eight 7-strand tendons each of diameter 8 mm and tensile strength of 1670 MPa. The initial prestressing force in the wires was reported as 500kN.

The experimental setup consisted of a servo-hydraulic loading frame of 500 kN capacity and an AE monitoring system as shown in Figure 5. The specimens were tested under displacement control at different rates. The surface deformation (crack initiation and propagation) was measured using the digital image correlation (DIC) technique [17] in order to provide validation for the damage process.



(b) 4 AE sensors on left

(a) Front elevation (c) 4 AE sensors on right elevation

**Figure 5:** Laboratory experimental set-up for AE studies at the rail-seat of PCS

The specimens were monitored using a multi-channel Physical Acoustic Corporation (PAC) system in combination with AE win software to analyze AE signals. Eight acoustic emission sensors were installed to measure the acoustic emission activities that correspond to the damage level of the specimens under flexure. A highly viscous agent was used to improve the acoustic coupling between the sensors and concrete. Magnetic clamping holders were used to hold the sensors in place during the tests. The sensitivity of the installed acoustic system was verified using the Hsu–Nielsen source methods [6]. The AE signals were amplified with a gain of 40 dB in a preamplifier. The threshold level was fixed to 33 dB to eliminate electric and mechanical noise. The sensor positioning is presented schematically in Figure 6.

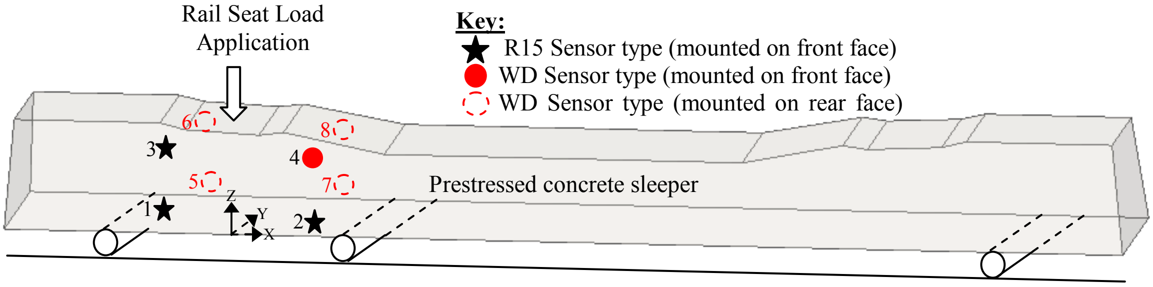



**Figure 6:** Schematic representation of sensor positions for rail-seat tests

## Results and Discussions

The acceptance criteria for PCS is based on crack initiation and crack-width opening of major crack(s) propagating with the increase of applied load. Figure 7(a) and (b) show the trends in crack growth and crack-width opening measured using DIC technique for the two reference tests: PCS1_RS1 and PCS1_RS2. Additionally, cumulative AE events versus the load is plotted in the same graphs of Figure 7 for correlation of AE activity with the mechanical response of PCS.

From Figure 7, it is seen that the trend of cumulative AE events matches that of the crack growth for both PCS1_RS1 and PCS1_RS2. Both curves of cumulative AE events and crack growth for the two tests show three distinct stages which can be attributed to micro-cracking, macro-cracking and tendon slipping (depicted by sigmoid curve).

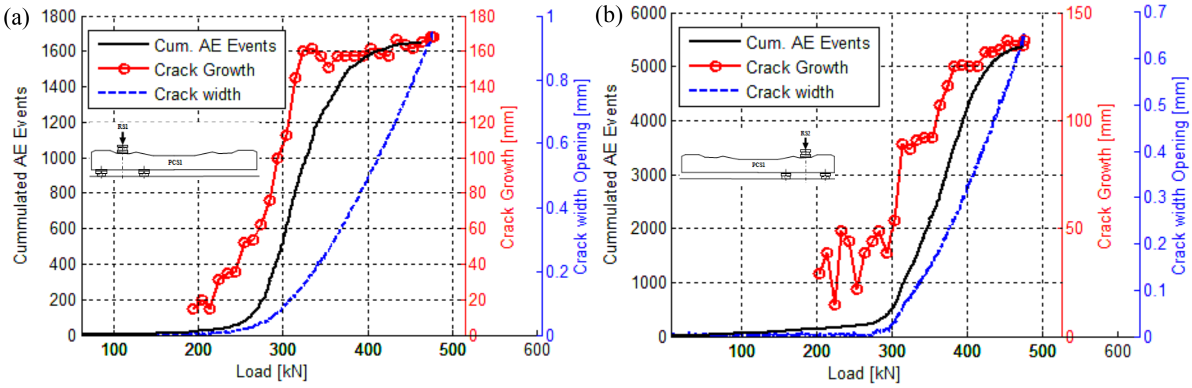



**Figure 7:** Trends of AE Events due to applied load at the rail seats (a) PCS1_RS1 (b) PCS1_RS2

Furthermore, from Figure 7, it is noted that the total number of AE events recorded for PCS1_RS1 (1650 AE events) was considerably less than that recorded for PCS1_RS2 (5500 AE events). This was attributed to the rate of loading: PCS2_RS1 was loaded at the rate of 0.2 mm/min while PCS1_RS2 was loaded at the rate of 0.5 mm/min. This result was expected since the rate of loading has been reported to have an influence on the AE activity [9, 7]. In order to correlate AE events with the crack-width opening, a plot of crack-width opening versus load is given in the same Figure 7; it can be seen that the initial increase in acoustic activity coincides with an increase in crack-width opening demonstrating that the AE is sensitive to cracking. However, the crack-width opening does not follow the sigmoid curve. The connection to the crack-width is reasonably weaker, since the crack length has an indirect correlation to the crack-width opening.

In order to successfully qualify damage in concrete sleepers, a three point bending test was conducted at the rail-seat in accordance with the European standard specifications [4]. Figure 8 shows the actual AE events recorded and superimposed on the loading history for the PCS2_RS2 test. At the peak of each load cycle, the crack-width opening was measured in mm by the DIC technique as indicated in square brackets.

As shown in Figure 8, the crack was visible with a digital microscope at load 294 kN. At this point, the DIC was able to measure a crack width of 0.029 mm. A confirmation of the existence of a crack is also manifested by the recorded AE events during unloading just after the visualization of the crack by the digital microscope. The recorded AE events during unloading reveal shearing of cracked concrete while the crack is trying to close due to the prestressing effect (cracks in structurally stable prestressed concrete have a tendency to close when the load causing deformation is removed [18]).

Furthermore, it is seen that as the crack width increases, the number of AE events recorded during unloading increases too. Another interesting phenomenon in Figure 8 also is the trend of the cumulative number of AE events: significant increase in the cumulative

AE events (shown by an arrow) is seen just before the crack is visualized by the digital microscope. This confirms the effectiveness of the AE technique in early detection of cracks in concrete.

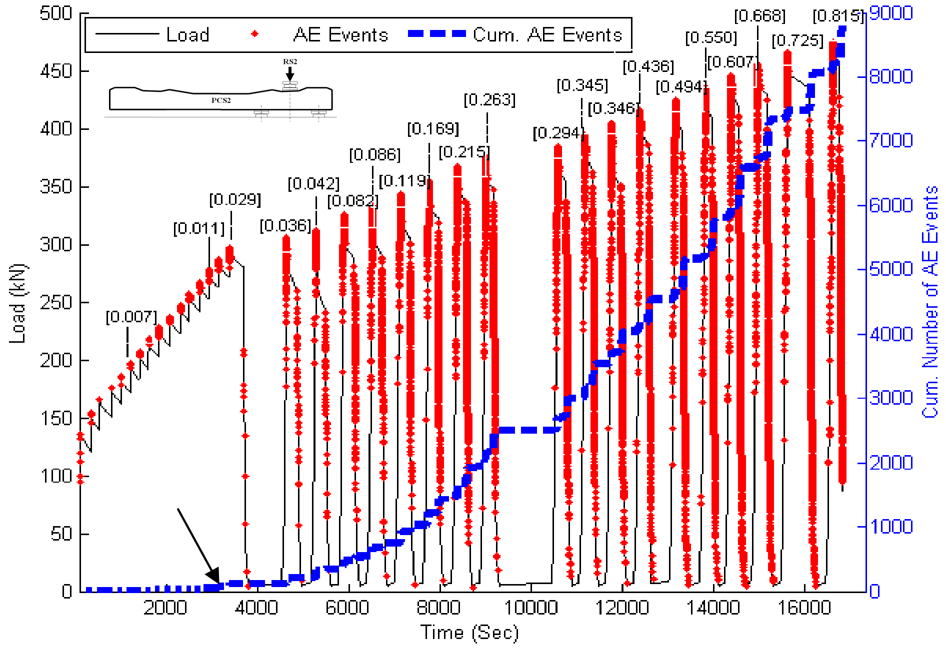



**Figure 8:** Actual AE events recorded superimposed on the loading/unloading history compared with cumulative AE events and crack width opening in square brackets for PCS2_RS2

The damage qualification for PCS2_RS2 was then represented in a chart as required by the recommended practice. As shown in Figure 9, three levels of damage could be easily identified based on crack width opening. The first level was identified as 'Minor damage' and it corresponds to a damage level causing crack widths of less than 0.1 mm. The second level was identified as 'Intermediate damage' corresponding to a damage level causing crack widths between 0.1 mm and 0.5 mm. The last level was identified as 'Heavy damage' and it corresponds to a damage causing crack widths greater than 0.5 mm. Based on the maximum crack width opening measured by the DIC technique in the loaded PCS, classification limits were set as 0.6 for the *Felicity ratio* and 3 for the *calm ratio*.

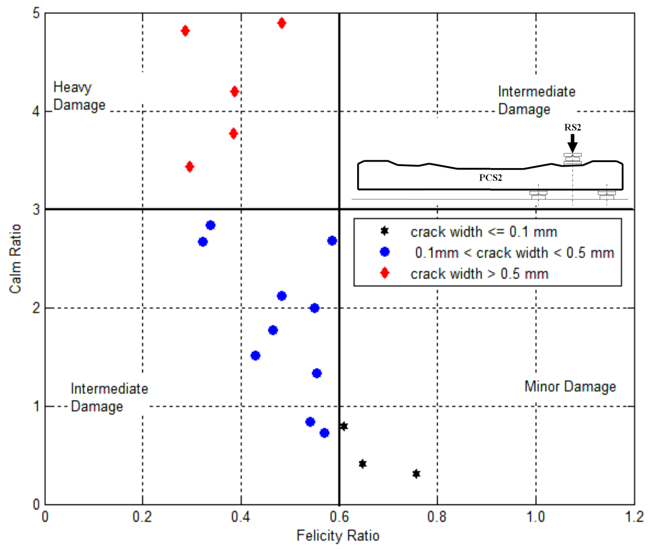



**Figure 9:** Typical Damage qualification chart for PCS2_RS2 test

To classify AE sources (cracks) in the damage process, an AE parameter analysis was performed. Variations of RA values and the AF were based on different damage stages. For demonstration, a typical test for PCS1_RS1 is used and presented in Figure 10.

Stage I: *micro-cracking stage:* The concrete damage starts with internal aggregate-cement paste disintegration and thus cannot be detected or measured by the DIC at the surface of the sleeper. At this stage, the AE recordings can be attributed to tensile stresses at the bottom of the sleeper. This phenomenon is validated in Figure 10(b) corresponding to stage I of the damage process. As shown, this stage is characterized by high average frequency and low RA value. However, it can also be seen that some AE events were recorded just below the demarcation implying that 'other' damage mechanisms are also coming into play at this stage. This was attributed to 'slipping' of the tendons against the concrete matrix as the sleeper is loaded.

Stage II: *Appearance of first visible crack*: More AE events are recorded and crack growth could be measured easily. The crack growth was attributed to tensile stresses at the bottom of the sleeper. However, two points could be seen where 'crack arrest ' was recorded due to the presence of the first and the second layer of the prestressing tendons. This phenomenon could not be demonstrated by use of the AE technique but it could with the DIC crack growth measurement. Hence, in the crack classification, it is expected to have major tensile records and only few 'shear' effects due to slipping of the tendons against concrete matrix at the 'crack arrest' points. This phenomenon is depicted in Figure 10(c).

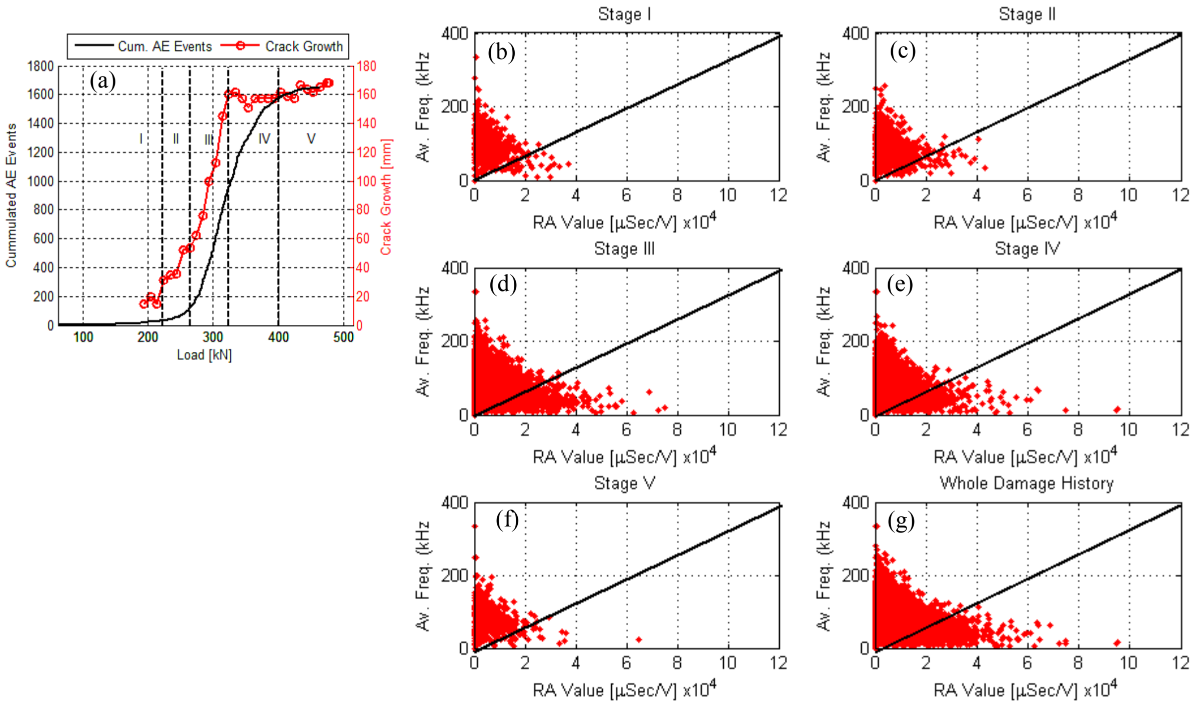



**Figure 10:** Damage classification for PCS1_RS1: (a) Damage stages, (b) Stage I, (c) Stage II, (d) Stage III, (e) Stage IV, (f) Stage V (g) Whole damage history

Stage III: *Macro-cracking*: The crack growth increases sharply and correspondingly, the cumulative AE events increase considerably. During this stage, it is also expected to have considerable 'slipping' of tendons during the reduction of the prestressing effect and thus paving way for significant crack-width openings. Therefore, the crack classification at this stage will consist of tensile cracking and a significant shearing effect as depicted in Figure 10(d).

Stage IV: *Total loss of prestressing effect*: The crack is past the neutral axis which is approximately 100 mm from the bottom surface, while the load is taken majorly by the prestressing tendons. At this stage, the crack growth is stagnating, initially reducing due to crack 'arrest' by the upper prestressing tendons. However, more AE events are recorded due to two mechanisms: total loss of the prestressing effect and the 'slipping' effect of the tendons. The loss of the prestressing effect is accompanied with an acoustic bursting effect [18] which are recorded parametrically as tensile cracking. This stage too gives two distinct damage phenomena as depicted in Figure 10(e).

Stage V: *Extension of macro-cracking*: All prestressing effects have been exhausted and crack tends to grow on a slow rate. Correspondingly, the rate of AE events is lower. The developing crack is purely tensile and is depicted in Figure 10(f).

In general, the damage in PCS is majorly driven by tensile cracking and 'slipping' effects between the tendons and the concrete matrix in all the failure regimes as depicted in Figure 10(g). These mechanisms are certainly overlapping in time but the relative shift of the population of AE events in terms of AF and RA allows to characterize the different stages in agreement with the knowledge of the fracture behaviour of the member and the information from the DIC.

## Conclusions

Based on above experimental results, the following major conclusions can be drawn:

[1] Cumulative AE events give a good correlation with the damage process and are good indicators for determining the structural integrity and damage levels of PCS.

[2] The recommended practice (NDIS 2421) is applied to cyclic bending tests of prestressed concrete sleepers. The applicability of the criterion for qualifying damage is confirmed. Thus, it is demonstrated that the criterion to assess damage is useful for inspection of PCS.

[3] Different AE derived parameters (the average frequency and the RA values) exhibit strong sensitivity to the fracture mode and can be utilized for the characterization scheme in PCS. Furthermore, tensile cracking is accompanied with 'slipping' and bursting effects in the damage process of PCS.

[4] The combination of AE and DIC techniques has the potential to provide the state of damage in PCS effectively and especially the onset of damage which so far is evaluated by optical microscopy.

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## Bibliography

[1] J. Taherinezhad, M. Sofi, P. Mendis and T. and Ngo, "A Review of Behaviour of Prestressed Concrete Sleepers," *Special Issue: Electronic Journal of Structural Engineering,* vol. 13, no. 1, 2013.

[2] F. N. Okonta and S. G. Magagula, "Railway Foundation Properties of Some South African Quarry Stones," *Journal of EJGE,* vol. 16, no. A, pp. 179-197, 2011.

[3] B. Omondi, H. Sol and S. Shitote, "Finite Element Simulation of the Quasi-static Homologation Procedure for Prestressed Concrete Sleepers," in *Proceedings of the First International Conference on Railway Technology: Research, Development and Maintenance*, Grand Canaria, 2012.

[4] prEN-13230, *Railway applications - Track - Concrete sleepers and bearers - Parts 1 and 2,* 2007.

[5] J. H. Kurz, F. Finck, C. U. Grosse and H. W. Reinhardt, “Stress Drop and Stress Redistribution in Concrete Quantified Over Time by the b-value Analysis,” *Structural Health Monitoring,* vol. 5, no. 69, pp. 69-81, 2006.

[6] ASTM-E976-11, “Standard guide for determining the reproducibility of acoustic emission sensor response,” American Society of Testing Material, United State, 2007.

[7] B. Schechinger and T. Vogel, “Acoustic emission for monitoring a reinforced concrete beam subject,” *Construction and Building Materials,* p. 483–490, 2007.

[8] S. A. Koppel and T. Vogel, “Localization and identification of cracking mechanisms in reinforced concrete using acoustic emission analysis,” in *Proceedings of the fourth international conference on bridge management*, Surrey, 2000.

[9] M. Ohtsu, M. Uchida, T. Okamoto and S. Yuyama, “Damage assessment of reinforced concrete beams qualified by acoustic emission,” *ACI Struct J,* vol. 99, no. 4, p. 411–418., 2002.

[10] C. K. Shield, “Comparison of Acoustic Emission Activity in Reinforced and Prestressed Concrete Beams Under Bending,” *Construction and Building,* vol. 11, no. 3, pp. 189-194, 1997.

[11] D. Aggelis, “Classification of cracking mode in concrete by acoustic emission parameters,” *Mech Res Commun,* p. 153–7, 2011.

[12] T. Shiotani, “Evaluation of repair effect for deteriorated concrete piers of intake dam using AE activity,” *Adv Mater Res,* p. 175–80, 2006.

[13] K. Ohno and M. Ohtsu, “Crack classification in concrete based on acoustic emission,” *Construction and Building Material,* p. 2339–46, 2010.

[14] H. A. Elfergani, R. Pullin and K. M. Holford, “Damage assessment of corrosion in prestressed concrete by acoustic emission,” *Construction and Build Material,* p. 925–33, 2013.

[15] M. Ohtsu, T. Isoda and Y. Tomoda, “Acoustic Emission Techniques Standardized for Concrete Structures,” *Journal of Acoustic Emission,* vol. 25, pp. 21-23, 2007.

[16] NDIS-2421, “Recommended Practice for In-Situ Monitoring of Concrete Structures by AE,” Japanese Society for Nondestructive Inspection, 2000.

[17] Z. Wua, H. Rong, J. Zheng, F. Xu and W. Dong, “An experimental investigation on the FPZ properties in concrete using digital image correlation technique,” *Engineering Fracture Mechanics,* vol. 78, p. 2978–2990, 2011.

[18] E. G. Nawy, Prestressed Concrete: A Fundamental Approach, Upper Saddle River, NJ: Prentice-Hall, Inc., 2000.

[19] JCMS-III-B5706, “Monitoring Method for Active Cracks in Concrete by Acoustic Emission,” Federation of Construction Materials Industries, Japan, 2003.