Structural Health Monitoring (SHM) and detection of corrosion in Prestressed Concrete Structures using the Acoustic Emission (AE) Technique

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Abstract

Failure of prestressed concrete structures due to corrosion is significant issue that has high economic impact and in some cases results in loss of life. Predicting and detecting corrosion at its early stages has been an engineering challenge that provides the opportunity to protect the structure from further deterioration. The Man-Made River Project, which transports water from the Libyan dessert to the coastal areas, is an example on the high expenses of ignoring structural health monitoring (SHM). The project suffered from unpredicted catastrophic failures in pipes due to corrosion. This paper presents an experimental investigation into the effectiveness of Acoustic Emission (AE) technique as SHM tool to detect corrosion of steel wires in prestressed concrete. Experimental results show that AE is efficient in detecting the early stages of corrosion of steel in prestressed concrete structures.

Keywords: Structural health monitoring, Acoustic emission, Corrosion, Steel reinforcement.

الملخص

يعتبرانهيار المنشآت الخرسانية سابقة الاجهاد بسبب التآكل احد المشاكل الهندسية التي لها تأثير اقتصادي سلبي وفي بعض الحالات تسبب ايضاً في خسائر بشرية. التنبؤ بحدوث التآكل واكتشافه في مراحله المبكرة كان دائماً من التحديات الهندسية لما له من قدرة على حماية المنشأة من مزيد من التدهور. مشروع النهر الصناعي في ليبيا الذي ينقل المياه من الصحراء الليبية إلى المناطق الساحلية هو مثال على التكلفة الباهظة لإهمال مراقبة صحة المنشأة (SHM) ، حيث عانى المشروع من عدة انهيارات كارثية في الانابيب نتيجة التآكل في الاسلاك سابقة الاجهاد. هذا البحث يقدم دراسة عملية حول فعالية استخدام طريقة الانبعاثات الصوتية (AE) كوسيلة لمراقبة صحة المنشأة لاكتشاف تآكل اسلاك الصلب في الخرسانة سابقة الاجهاد. تم في البحث تجهيز نموذج عملي يحاكي الانابيب المستخدمة في مشروع النهر الصناعي وإجراء مجموعة من التجارب على قدرة اجهزة التقاط الانبعاثات الصوتية على التقاط الانبعاثات الناتجة من تآكل الاسلاك والذي تم تسريعه باستخدام التيار المسلط. بينت النتائج العملية ان طريقة AE يمكن استخدامها بفاعلية في اكتشاف المراحل الأولى لتآكل الصلب في الخرسانة سابقة الاجهاد.

1. Introduction

Prestressed concrete is made by subjecting the steel wires to a permanent tension to compensate for the inadequate tensile strength of the concrete. The main advantages of prestressed concrete structural materials are that they are stronger, lighter and “crack free” (Singh 2000) and hence these materials are of use in various engineering structures such as dams, bridges, nuclear reactor shells, railway sleepers, pressure vessels and concrete pipes.

Prestressed Concrete Cylinder Pipe (PCCP) is one of the most durable pipe materials for large diameter pipes due to its high resistance to large inner pressure and external loading. PCCP is used to transport water and wastewater in several projects around the world such as the USA, China, Libya, Australia, Europe, the Middle East, and South America. The Man Made River (GMMR) in Libya and the South-to-North Water Diversion (SNWD) in China are major water transport projects which required extremely large diameter PCCP. (Elliott et al 2006, Travers 1997, Xiong et al. 2010).

These major projects require structural health monitoring to evaluate the health status of composite structures which is defined as all the information relating to the evolution of degradation modes within a composite structure. Corrosion is a major cause of structure degradation; its cost is estimated in billions of dollars every year. For example, the cost of repair of concrete structures damaged by corrosion in the UK is estimated about one billion dollars a year (Ann et al. 2009). Furthermore, failures due to corrosion may result in loss of life which cannot be compensate for.

The concrete provides the ideal environment to protect the steel wires which are embedded in it possibly for over 50 years (Bertolini et al. 2004). However, the life of a concrete structure becomes shorter due to steel corrosion which may occur by aggressive ion attack from products of chloride or carbonation (Ann et al. 2009). It is The main reason of failure of bridges and concrete pipes is due to corrosion during the short period after they were constructed.

An example of unexpected failure of prestressed concrete structure is the pipe failures due to corrosion occurred in the Man-Made River Project of Libya (MRA). The project is the one of the major civil engineering projects of the 20th century using almost 4000 km of prestressed concrete cylinder pipe (PCCP) networks as shown in Figure 1. (Kuwairi 2006, Essamin and . Holley 2004 , Ing et al. 2005, Hellier 2001, Carpinteri et al. 2007). The pipes are designed to take best advantage of the compressive strength and corrosion-inhibiting property of Portland cement concrete and mortar and the tensile strength of prestressing wire. A typical cross-section of the PCCP is shown in Figure 2.

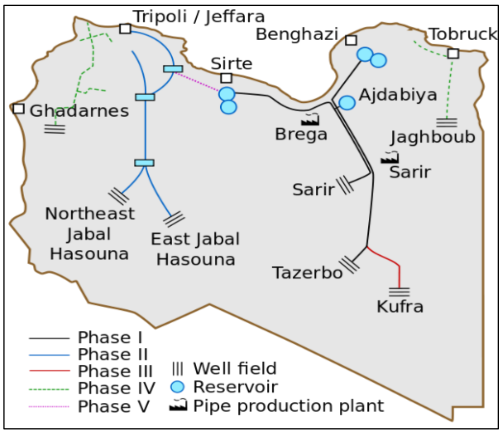


Figure 1 Layout of the Pipe Networks of MRA

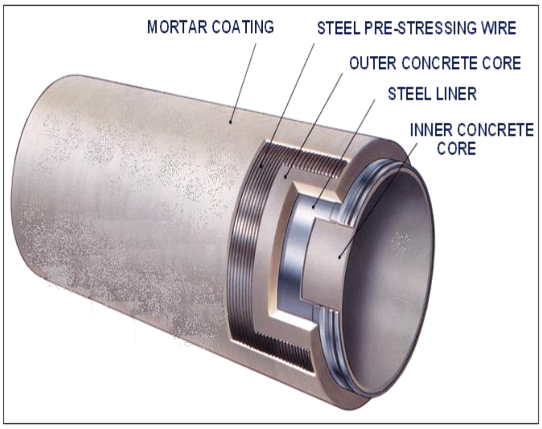


Figure 2 Typical Cross-Section of the PCCP

Five catastrophic pipe failures due to corrosion have occurred since their installation. Apart from future corrosion protection, engineers face the challenge of finding a way to detect the corrosion and prevent the pipes from deteriorating (Singh 2000). This highlights the importance of structure health monitoring in prestressed concrete structures.

This paper aims to evaluate the effectiveness of acoustic emission as a structure health monitoring tool and its ability to detect the early stages of corrosion prior to deterioration and eventual failure of the PCCP with application to the Man-Made Project of Libya.

1.1 Structural Health Monitoring

Structural Health Monitoring (SHM) can be defined as the process of implementing a damage detection technique for civil and mechanical structures. In this context, damage is defined as changes to the material and structure properties which adversely affect the system's performance (Sohn et al 2014). Among these damage detection techniques is acoustic emission (AE).

1.2 Acoustic Emission

Deformation due to fracture in a material releases stored strain energy, this is consumed by nucleating new external surfaces (cracks) and emitting elastic waves. The latter phenomenon is defined as acoustic emission (AE). It can also be defined as “the transient elastic waves which are generated by the rapid release of energy from localized sources within a material” (Miller 2005). All the frequencies of the concerned waves are in the ultrasonic range between 50 kHz and 1.5 MHz. The released waves, of different natures and frequencies, propagate in the material and may undergo modifications before reaching the surface of the studied sample. The surface vibration is generally detected by a piezoelectric sensor which translates it in the form of an electrical signal. This acoustic emission signal is then amplified and digitized by acquisition software, Figure 3. By analysing the resultant waveform in terms of feature data such as amplitude, energy and time of arrival, the severity and location of the AE source can be assessed.

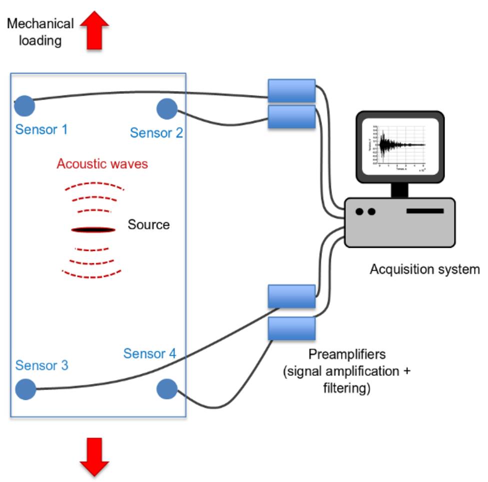


Figure 3 AE diagram of the acoustic emission sequence.

2. Experimental Set-up

2.1. Sample preparation

A close simulation to real condition of the PCCP is essential to the accurate results of the current study. High strength steel wire samples are put under tension equal to 60 % of their UTS. The tension is maintained using a tension frame especially designed and fabricated. It is composed of two blocks (190mm x 45mm x 45mm) assembled via two threaded bars and two threaded steel bars with a diameter of 20 mm and a length of 500 mm. Four holes, two of 20 mm diameter and two 6mm diameter, are drilled in each block and eight nuts are used to tighten the two blocks. a schematic drawing for the tension holding frame is shown in Figure 4. The two working wire samples are passed through the 6 mm diameter holes in the steel blocks and then through two modified bolts and nuts (to control the tension load of each wire). Finally, a steel cylinder is threaded over the wire and then compressed in a loading machine. In this way the modified nut and bolt could be expanded between the clamped cylinder and the steel block and as a result tension could be introduced into the wire. Each wire was subjected to a tensile force of 20 kN by adjusting the bolts and nuts and monitored via strain gauges mounted on the wires.

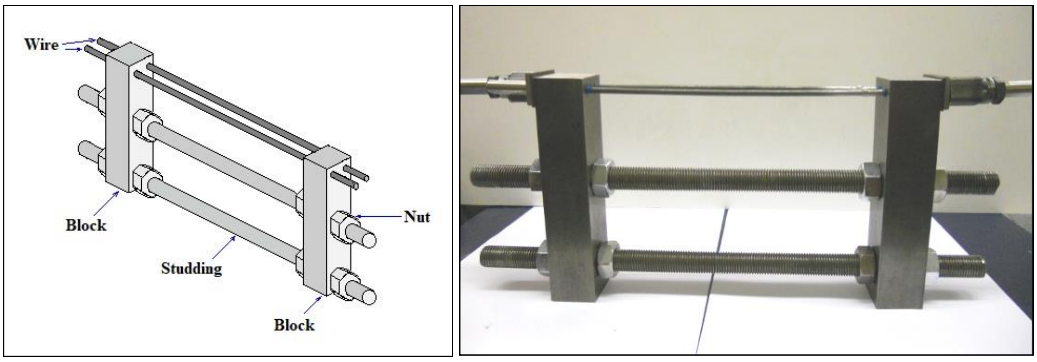
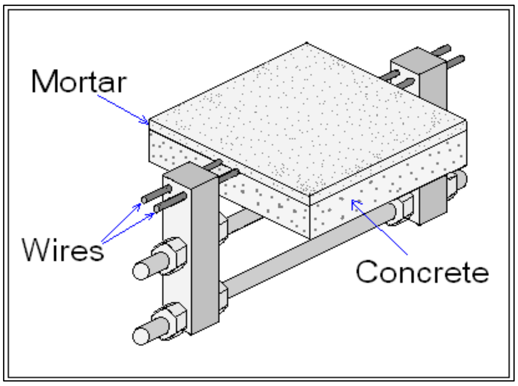


Figure 4 Holding frame with the wire samples mounted.

High strength steel wires samples similar to those used in GMRA PCCP are used in this experimental simulation. The steel wire has the following metallurgical composition and mechanical properties as certified by the wire manufactures: Carbon steel (carbon 0.8-0.84%, 0.85-1.00%Mn, 0.030 %Max S, 0.035% Max P, 0.20-0.35% Si). The tensile strength of the wires is almost 1738 MPa. supplied from GMRA PCCP manufacturing plant.

The wire samples are immersed in concrete to simulate the real conditions. A concrete block (200*200*50mm), representing the inner pipe is prepared according to the technical specification for PCCP Manufacturing used in the GMRA in accordance with AWWA C301-92 (Singh 2000). Finally, the mortar 200*200mm and 20 mm thickness consisting of one part cement to not more than three parts fine aggregate by weight was coated on the upper surface of the concrete. The construction is shown in Figure 5.



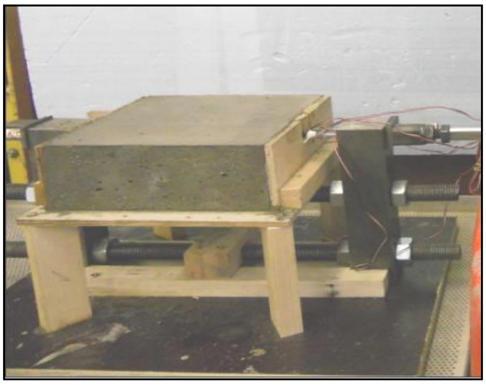


Figure 5 Concrete and mortar specimen

2.2. Setup of AE instruments

Four Physical Acoustic Limited (PAL) AE sensors (R3I – resonance 30 kHz, R6D – resonance 60 kHz) are mounted to the top surface of mortar in the four corners of the rectangular specimen as shown in Figure 6. The four AE sensors were mounted using silicon sealant as an acoustic couplet and were fixed on the upper surface of mortar with a U shaped plate attached with screws holding the sensors and to ensure a good coupling. The threshold level for AE data acquisition is set up at 40 dB. The sensitivity of the AE system was checked using the Hsu-Neilson source (Hsu and Breckenridge 1981).

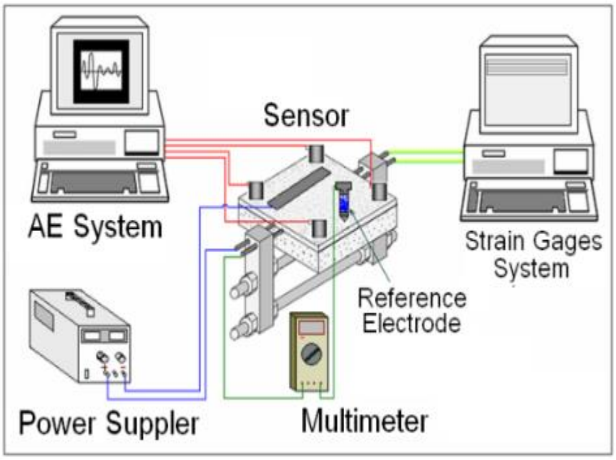


Figure 6 Schematic Diagram and Photo of Experimental set up

3. Results and Discussion

Figure 7 shows the cumulative acoustic energy as detected by all sensors for almost nine days of continuous monitoring. The detected energy is attributed to active corrosion and mortar cracking. The graph demonstrates the behaviour of the energy emission in three regions of time. Each period of time marked represent three days of monitoring.

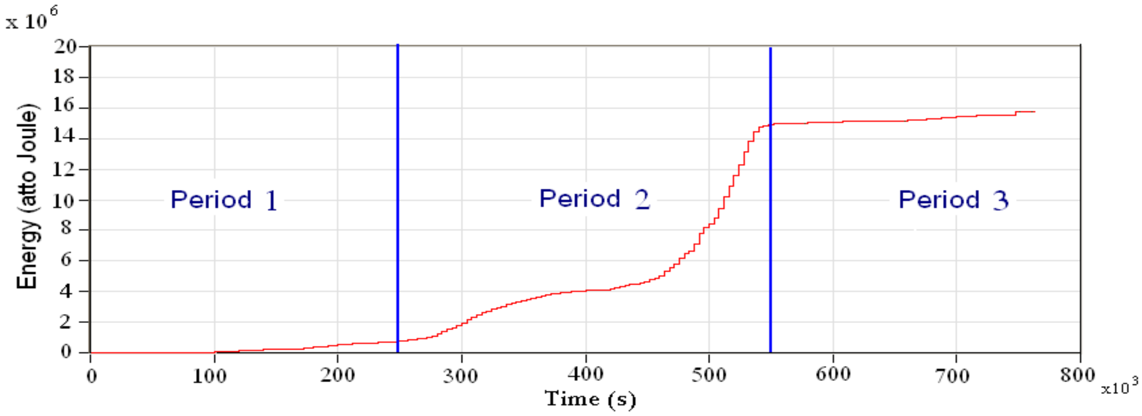


Figure 7 Energy vs. time

Figure 8 shows source location of sample before supplying current (no corrosion) for about 20 hours. It can be seen that there is a low level of events prior to the onset of corrosion. A colour key that indicates the number of signals detected at a position is also provided.

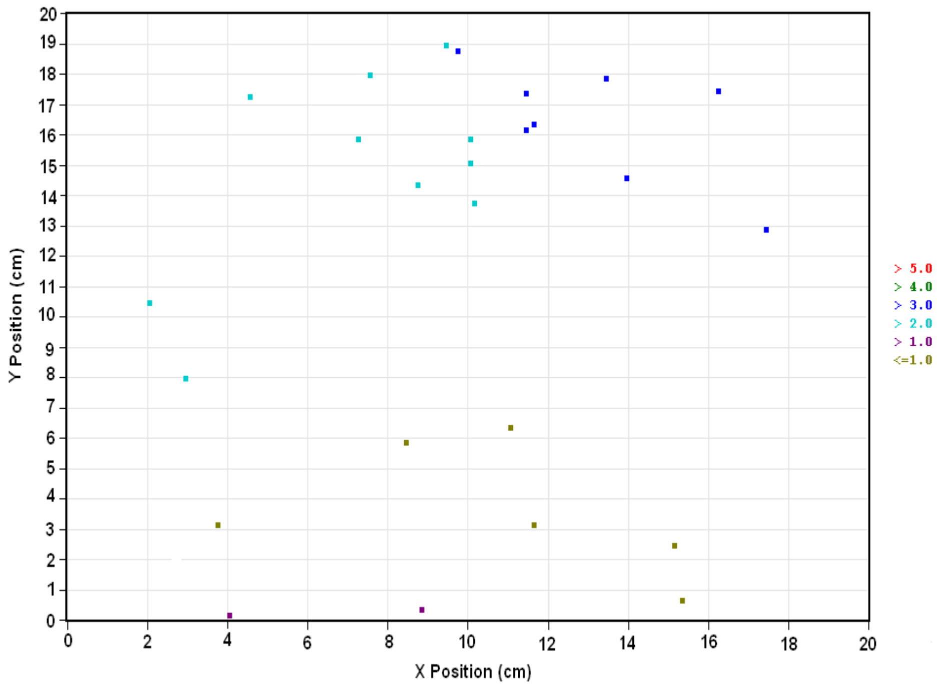


Figure 8 Source locations before supplying current (no corrosion)

The period of test is divided to three different stages as shown in Figures 7 and 8. The first stage, which is first three days, is named period 1. The energy emitted is attributed to constant corrosion activity, a small visible crack and the separation of mortar from the concrete.

Furthermore, Figure 9 shows the source location of signals within this period 1. It can be seen that the highest hits concentration appears in the region of corrosion reaction, where the stainless steel plate (cathodic reaction) and wire (anodic reaction) are placed.

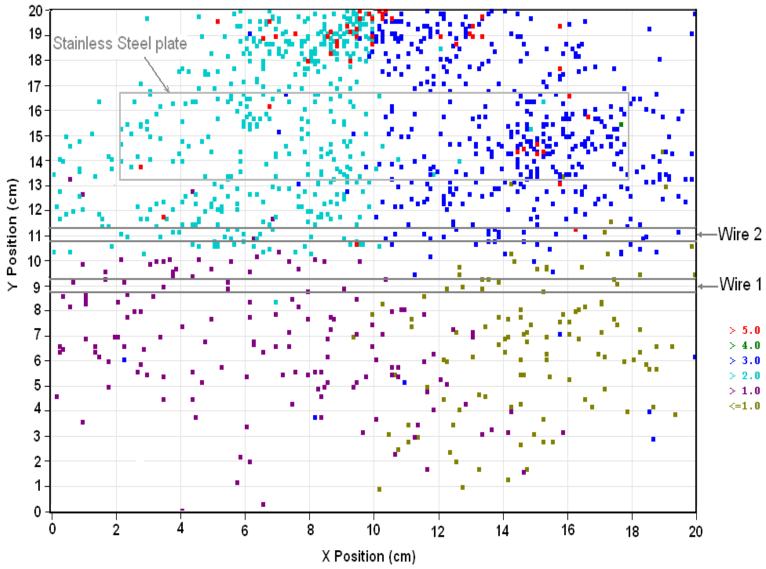


Figure 9 Source location for first three days (Period 1)

The second stage is between the fourth day and sixth day which is named period 2. In this stage, it can be seen that the emission energy increases significantly as shown in Figure 7. Furthermore, it can be seen that in Figure 10 the locations considerably increase due to the growth of the crack and split of mortar from concrete. Also, a high concentration of hits in the area of corrosion reactions can be observed.

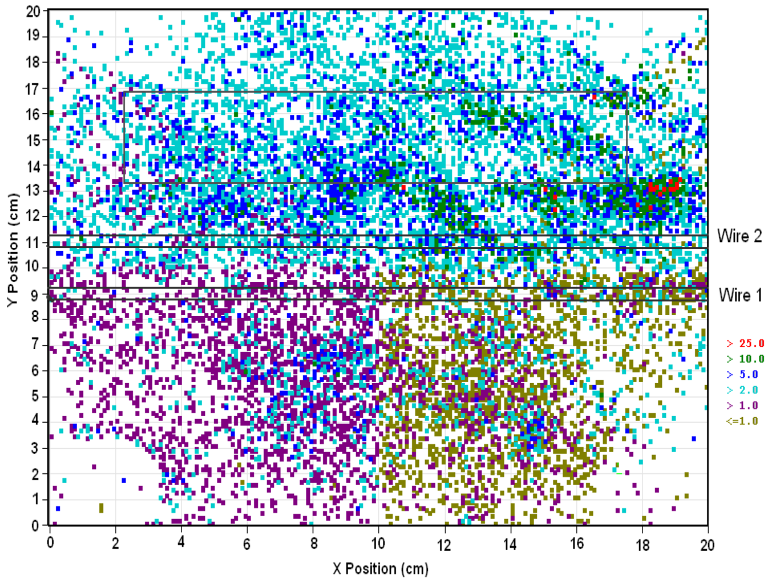


Figure 10 Source location for middle three days (Period 2)

During the final three days (period 3 in Figure 7) it can be noted that the energy decreases due to decrease of corrosion rate. In addition, Figure 11 shows source location on the mortar surface. It can be seen that the number of hits is decreased from period two.

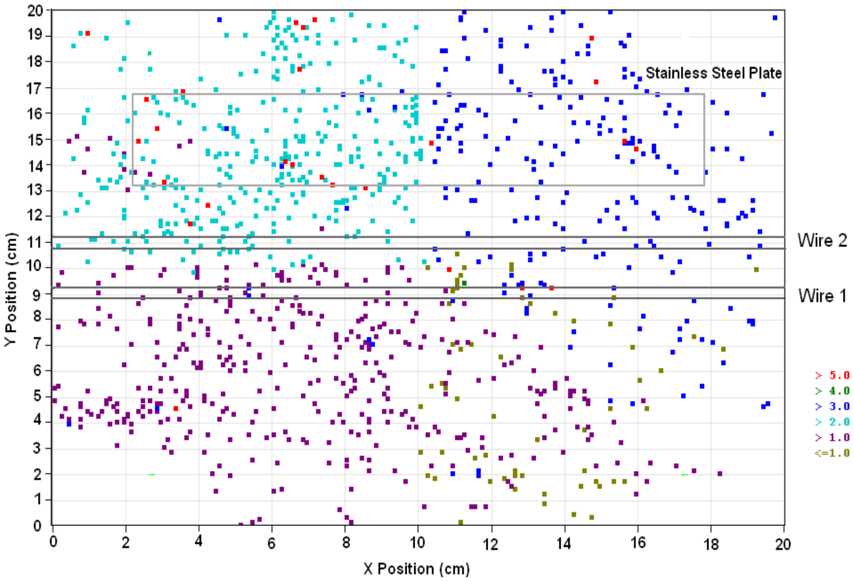


Figure 11 Source location for last three days (Period 3)

Figure 12 shows the distribution of hits with minimum amplitude 40dB for whole test (three periods) while Figure 13 shows hits distribution with amplitude greater than 47dB for whole period of the test. It can be noted that the highest hits concentration and highest energy in region coincide with maximum wire corrosion which was visibly observed post test.

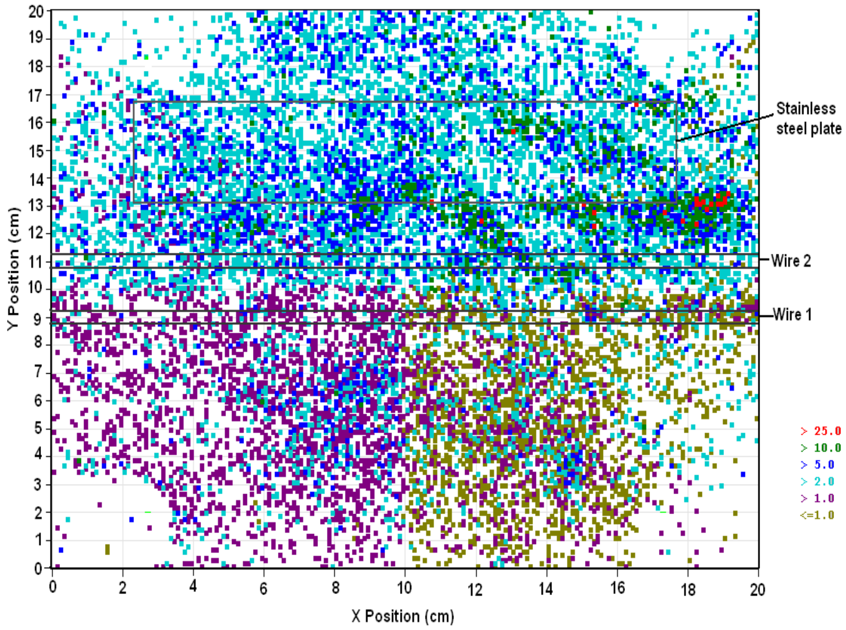


Figure 12 Source locations for 9 days

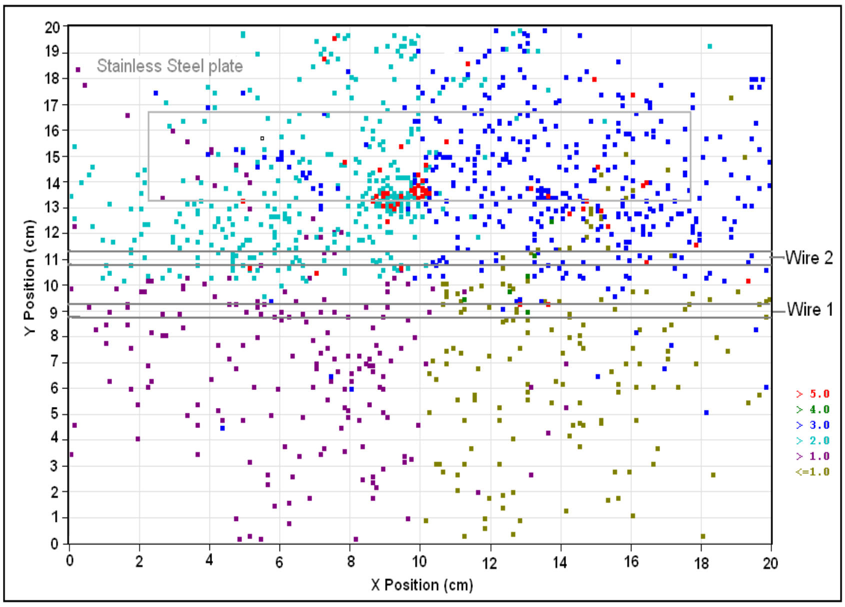
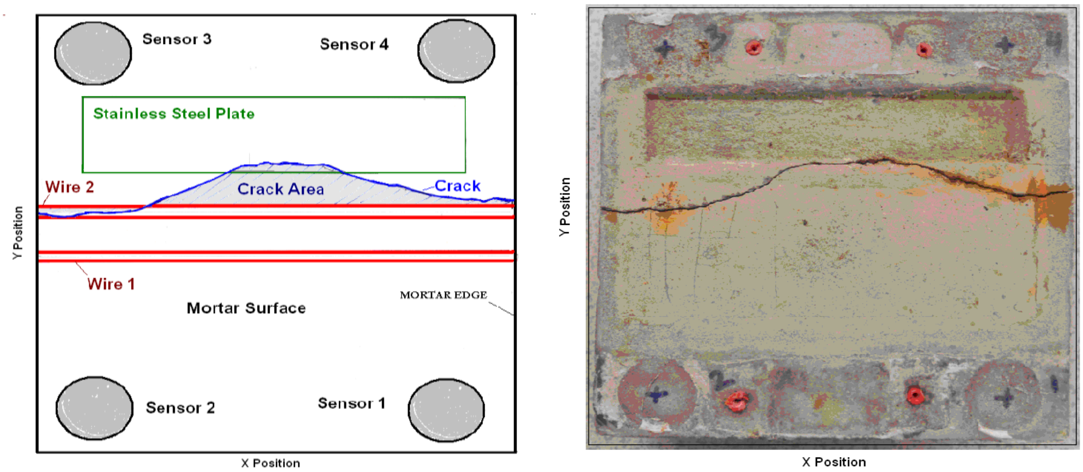


Figure 13 Source locations for whole test with amplitudes greater than 47dB

Figure 14(a) is a schematic diagram of the specimen after testing. The figure shows the sensors mounted on mortar surface, wires, stain steel plate and crack shape. Figure 14b is a photograph of the top mortar surface after finish the test, again showing the crack shape. Comparing the two figures with previous locations reinforces that the AE was detecting the concrete cracking as a result of wire corrosion within the specimen.



(a) (b)

Figure 14 Schematic Diagram and photo of top mortar surface

The corrosion wires and corrosion product once the mortar had been removed is shown in Figure 15. It is evident that significant corrosion occurred in the upper wire and it was in this location that a large majority of AE signals were detected and located. The results offer encouragement to the use of the AE technique to detect early corrosion in pipe structures, however for full validation considerable larger specimens will have to be considered.

A further series of investigations are planned that will utilize environmental chambers to assess temperature effects and geometric effects with the ultimate aim of producing a guide to detecting early corrosion in pipe structures using AE.

Figure 15 Photo of upper concrete surface and wires

4. Conclusions

This paper investigates the effectiveness of AE technique as SHM tool. The results show that AE can be used efficiently to monitor the corrosion activity and can detect the onset of corrosion in steel wire in the interface between prestressed concrete and mortar. Furthermore, this technique is found to be able to locate approximately the corrosion activity on small prestressed concrete samples.

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