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Acoustic Emission for Civil Structures

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1. Introduction

“Acoustic emission” (AE) is the name given to the transient stress waves that are generated by crack growth and many other kinds of material degradation and deterioration. The phenomenon has been known intuitively since the beginnings of knowledge, and studied scientifically for at least a century. The cracking of ice and the snapping of twigs are commonplace examples. In recent decades, acoustic emission has been used as a nondestructive testing method. A substantial body of technique has developed to allow its application to the monitoring of bridges, pressure vessels, storage tanks, etc. These devices have an amazing sensitivity to high-frequency motion. At the frequencies most commonly used for AE testing, 100-300kHz, the AE sensor can give a detectable signal for surface movements of 10^{-13} m or less, a thousand times smaller than the size of an atom.

As a monitoring device for structural integrity, the acoustic emission sensor is effective over distances from a few inches to tens of feet. It can be compared to accelerometers that are often used to assess the condition of bridges, for example, through the techniques of modal analysis. Accelerometers are also piezoelectric devices, but they operate at much lower frequencies (typically tens or hundreds of Hz instead of hundreds of kHz). Both the AE sensor and the accelerometer are used to sense movements. However, the motion sensed by the accelerometer has a wavelength on the order of tens to hundreds of feet. It is thus measuring the movement of the structure as a whole and is not sensitive to small point disturbances. The AE sensor inspects a local part of the structure, and is very sensitive to point disturbances. Specifically, it can be used to sense damage processes at the moment they occur.

Acoustic emission has been used as a formalized structural evaluation method since the early 1980's. The formalized acoustic emission evaluation methods that are in place today are the result of a significant number of structural failures of fiber reinforced polymeric (FRP) vessels that took place in the preceding decade (Fowler and Gray, 1979; Fowler et al., 1989). Many of the failures could be attributed to manufacturing defects and/or inappropriate design procedures with a particular emphasis on the discontinuity regions of the vessels. Acoustic emission data was gathered on actual vessels and trends in the data were analyzed, resulting in a standardized loading and evaluation procedure (CARP, 1982). The concepts developed were later incorporated into the ASME Boiler and Pressure Vessel Code and are used today (ASME 2010a and 2010b). AE remains as the preferred method of evaluation for one-of-a-kind vessels prior to implementation and also for evaluation of in-service vessels.

For FRP vessels AE is used as a primary means of evaluation. It is generally not combined with strain gages or other sensing devices. This may be partially due to the nature of damage in FRP vessels and the resulting brittle failure modes. In these structures the localized damage can lead to catastrophic failure without visibly detected warning. One of the key advantages of acoustic emission in this industry is its ability to rate the significance of the damage. Once a damaged region has been located with AE, more localized follow-up methods are often used to further assess and map the damage. In contrast to evaluation of buildings and bridges, detailed calculations of the entire structure are generally not a part of the standardized loading and evaluation procedures.

Similar AE procedures have been developed for other polymeric devices such as manlifts (Ternowchek and Mitchell, 1992; Pollock and Ternowcheck, 1992); metallic railroad cars and other vessels (AAR, 1999; AAR, 2002; Fowler et al., 1989). AE has also been proposed for reinforced concrete structures (Ohtsu et al., 2002; JSNDI, 2000) and has been employed in the field (Golaski et al., 2000). Acoustic emission has been incorporated into the design process itself for FRP vessels as described in ASME Section X (ASME, 2010a; Ziehl and Fowler, 2003; ASTM, 2006) and has been related to fatigue behavior in FRP pipes (Ramirez et al., 2004). An overview of the AE method and its applications is given in Pollock (Pollock, 2008).

The use of AE as the primary method of evaluation in many industries differs from the evaluation of civil engineering structures. For civil evaluations calculations are generally combined with information gathered from strain gages and other sensing devices under applied or ambient loading conditions. An example of the calculation based approach is conventional load rating of existing bridges. With this approach the geometry and structural aspects of the bridge must be known (such as depth of girders, connections between girders and deck, reinforcing steel details, strength of reinforcing steel, etc.). With this information and assuming boundary and support conditions along with lateral load distribution characteristics, a beam-line analysis may then be conducted and load rating factors developed (AASTHO, 1994). This approach has inherent limitations, including its dependence on the assumptions made regarding materials and boundary conditions. The assumptions can be minimized through diagnostic load testing (Schulz, 1993; Goble et al., 1990 and 1992). This approach combines strain response under known loading conditions with numerical models of the bridge.

The differences between the evaluation approaches for civil structures and other structural systems discussed earlier are significant. For many non-civil structural systems, acoustic emission is used as a primary means of evaluation and the results are categorized ('minor damage', 'intermediate damage', 'severe damage') in the absence of detailed calculation procedures. For civil structures detailed calculations and numerical simulations are an integral part of the evaluation process and therefore in-depth knowledge of the structure is required. For civil structures AE has been sparingly used and is rarely, if ever, used as the primary means of evaluation. However, AE has recently seen an increase in the evaluation of civil structures and the sensitivity and non-invasive nature of the method are clear advantages for many civil applications (Ziehl, 2008).

This chapter describes recent work on the application of acoustic emission to civil structures. The applications are grouped according to the primary material type of interest including steel, reinforced concrete, and fiber reinforced polymers. The civil structures monitored or evaluated include both buildings and bridges. In some cases acoustic emission is used as a means of passive monitoring only and in other cases it is used to complement data collected and evaluated as part of a load testing procedure. One of the more recent and promising developments of AE for reinforced concrete structures is the in-situ monitoring of active corrosion and the results of preliminary research in this area are discussed.

2. Steel structures

A major threat to mechanical integrity of steel civil structures is cracking, in particular fatigue cracking. In-service steel bridges are reaching their design fatigue lives each year. There is a growing need to evaluate fatigue damage and predict remaining fatigue life. AE techniques have been extensively used in nondestructive testing and structural health monitoring (Gong et al., 1992; Martin et al., 1995; Chen and Choi, 2004). In the nature of fatigue cracks, energy arising from plastic deformation and fracture events is transmitted as stress waves that can be detected by remote sensors. The high sensitivity of AE techniques (Ghorbanpoor and Vannoy, 1988; Kohn et al., 1992; Bassim et al., 1994) offers demonstrated reliability for the detection of active cracks. For AE monitoring applications the cracking location does not need to be precisely known, sensors together with appropriate algorithms are capable of locating and quantifying active cracks. Correlation between AE and corresponding crack growth behavior is the basis for interpretation of acquired AE signals for the evaluation of fatigue damage and prediction of remaining fatigue life.

Two driving forces, maximum stress intensity K_{max} and stress intensity range ΔK, govern fatigue crack growth behavior (Sadananda and Vasudevan, 1997). For a specific material and set of test conditions, ΔK is equal to (1-R) K_{max} where R is the load ratio. The driving forces have their thresholds, K_{maxTH} and ΔK_{TH}. Fatigue cracks will not develop if K_{max} or ΔK in the actual structure is below the threshold. The fatigue lifetime is conventionally divided into three stages. In Stage I which lasts for most of the lifetime, the crack is initiating. In Stage II, the crack propagation rate depends strongly on ΔK and also to some extent on $K_{max.}$ Thus under constant-amplitude cyclic loads, the crack propagation rate increases as the crack advances. If K_{max} reaches the fracture toughness K_{IC}, the crack will come into the stage of unstable propagation (Stage III). Failure occurs after a relatively small number of cycles, and may be catastrophic or not, depending on the structural geometry.

Thus, in the area of interest to us, the first requirement is that K_{max} and ΔK are higher than their thresholds K_{maxTH} and ΔK_{TH}. Next, we are especially interested when K_{max} exceeds K_{IC} corresponding to the critical transition from Stage II (stable propagation) to Stage III (unstable propagation). The AE behavior takes a distinctive upturn at this transition, an example of which is shown in Figure 1 along with a compact tensile test specimen that was utilized to generate the fatigue crack (Yu et al., 2011).

In acoustic emission monitoring of ductile metals such as the structural steel for bridge construction, it would be nice if all acoustic emission events were simply related to rapid extension of the crack. However, this is not always the case and a good body of work exists that attempts to address the source of acoustic emission events. Mechanisms include crack extension, ‘fretting’ or ‘friction’ of the crack surfaces, yielding ahead of the plastic zone, the fracturing of brittle inclusions, separation of ligaments by internal necking, and others. Because acoustic emission is an in-situ method of evaluation, a one-to-one correlation between received data and actual internal mechanisms is not available and

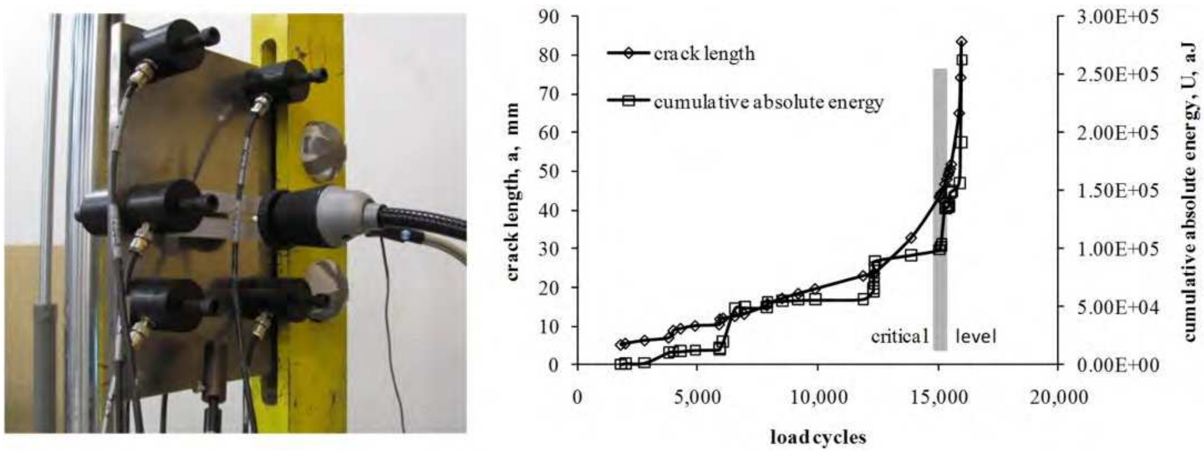


Fig. 1. CT Specimen with Five AE Sensors and Resulting Data

therefore the debate related to source mechanisms is an open topic. Guidance and further discussion may be found in Ohira and Pao, 1986; Han et al., 2011; Huang, 1998, and Ono, 2005.

Sison et al., 1996 includes a summary of the dozen earliest efforts to apply AE to steel bridges. By the mid 1990's sufficient knowledge had been gained to attempt transfer of the technology to the body of state highway inspectors. A project was undertaken, sponsored by the Federal Highway Administration, to define a focused technical approach and provide written guidelines for its application (Pollock and Carlyle, 1995). As always in AE inspection, there were strategic choices to be made about the monitoring approach. These choices included short-term versus long-term monitoring, controlled loading versus normal service loading, and wide area inspection versus local area monitoring. At the outset of this project, careful consideration was given to what kind of AE test could most likely find a useful place in the day-to-day operations of the state highway departments. It was recognized that evaluation of fatigue cracks in welded details in steel bridges is a substantial part of the integrity-related work of the state highway departments. The concept emerged that sometimes a state highway engineer, considering what to do about a known flaw, might want to get more information about it - and in this situation, it would be helpful to know whether it was acoustically active or not. Thus, a potentially useful kind of AE test would be to assess specific welded details, probably containing known cracks, as quickly and economically as possible and to return information promptly to the bridge owner's engineering staff.

In pursuit of this concept, a dozen flaws on four different bridges were inspected with AE and appropriate technology for an efficient inspection was developed. It was found that on the busy bridges selected for this study, monitoring for an hour would give a sufficiently representative sample of the flaw's AE activity. It is well known that heavy vehicles, much more than passenger car traffic, are responsible for fatigue damage in bridges. So the main criterion for choosing the monitoring period is that it should include a representative amount of heavy vehicle traffic. Also, of course, one must avoid adverse weather conditions such as rain, which produces unacceptable background noise.

The study included fatigue cracks in welded details, fatigue cracks in rolled sections, and several other conditions. An example is illustrated in Figure 2. This is a small crack in a floor beam flange adjacent to a rivet in the Brooklyn Bridge in New York City. The sensor is a 300 kHz resonant type (PAC µ30). A small sensor such as this is convenient for local area monitoring, and the relatively high frequency is good for reducing background noise. Background noise in bridge monitoring is produced by the passing traffic, not directly but indirectly. The traffic loading produces rubbing of structural members, generating acoustic emission at places that could be remote from the traffic but close enough to the inspection area to be detected. The study showed the effectiveness of guard sensor techniques for avoiding problems from this kind of noise.

Fig. 2. AE Sensor on Brooklyn Bridge Floor Beam

The guard sensor concept is to have a "data sensor" close to the flaw being monitored, then to surround that spot with several "guard sensors". If the flaw emits, the "data" channel will be hit first. If noise comes into the inspection area from outside, one of the "guard" channels will be hit first. On this basis the AE signal can be either accepted or rejected. Figure 3 shows a set of four guard sensors surrounding a data sensor on a welded detail. In the test shown in Figure 2 guard sensors were also installed but they were backside of the beam, unseen in the photograph.

Fig. 3. Data and Guard Sensors on I-10 Mississippi River Bridge (Baton Rouge, LA)

The effect of using guard sensors is illustrated in Figure 4. Here a flaw was monitored with two data sensors 8 inches apart in a linear location array, surrounded by several guard sensors. It was possible to record all hits on all sensors, then to examine the data post test, either using (left) or not using (right) the guards. Figure 4 shows how when guards are used, there is a very clear indication of the flaw, a spike in the location plot standing out clearly from the residual background noise (some noise still defeats the guards). However when the guards are not used, many more external noise events appear to locate between the sensors and there are even some peaks that are comparable in size with the peak from the flaw.

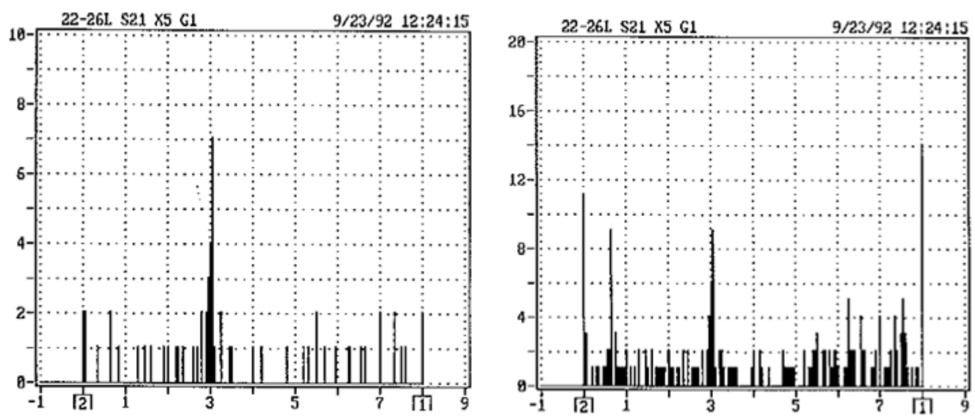


Fig. 4. Linear Location Plot with (left) and without (right) Guard Sensors, Bryte Bend Bridge, Portland, OR

Although these events originate outside the area of interest, their received waveforms are such that their Δt's place them apparently between the data sensors. It was concluded from this study that even though it required additional channels, the use of guard sensors was the most straightforward technique for discounting this kind of noise to permit valid data evaluation.

By the end of this project, a dozen flaws of several different kinds had been monitored on several different bridges, using essentially the same monitoring conditions and equipment setup. A table could be drawn up showing the activity recorded from these flaws, starting with the most active and working down to the least active in terms of located events per minute, during normal traffic loading. This table is shown below (Table 1).

These results were satisfying in that they showed AE activity ranging through more than three orders of magnitude, as the flaws went from code-rejectable inclusions and large cracks, to "nothing". The inclusions at the top of the list were characterized by ultrasonic testing; in general, inclusions can serve as starters for fatigue cracks. The activity of these inclusions is in very strong contrast to the minimal activity of previously discovered discontinuities in an electroslag weld, detailed at the bottom of the table. A "league table" of this kind puts AE activity into a meaningful context and can certainly help the bridge engineer to decide what to do about these flaws. The table also shows some results with repairs and retrofits. A retrofit, such as might be applied to reinforce a cracked area after drilling an arrester hole, is intended to hold the area tight so that it does not move and a new crack does not start from the repair. If the retrofit is not tight, it will not do its job and there may be further crack growth. A loose retrofit gives additional AE, as can be seen by comparing the 5th and 8th lines of Table 1. With further work along these lines, AE became recognized as a method for checking the effectiveness of repairs and retrofits.

A simple report form was developed so that the bridge engineer could get a summary of the test results on one page. Figure 5 shows the front side of this one-page form which carried standardized information; the back side would carry free-form test-specific information

Bridge**	Flaw	Time (min)	Total Events	Events/min
WW	Code reject able inclusion in web weld	60	1600	26.7
WW	17" crack in floor beam, intersection of top flange with web, more active end	60	800	13.3
WW	Code rejectable inclusion in bottom tensile flange	60	200	3.3
BB	0.03" crack discovered at web-to-stiffener weld	30	57	1.9
MS	13" crack growing at floor beam / truss panel joint - retrofit removed	92	90	1
BB	Crack at web-to-stiffener weld	30	25	0.8
WW	17" crack in floor beam, intersection of top flange with web, less active end	60	20	0.3
MS	13" crack arrested at floor beam / truss panel joint - retrofit operational	61	18	0.3
BB	No cracks, stiffener/web/top flange/floor beam area	30	1	0.03
WR	4" ultrasonic indication in electroslag weld	120	0	<0.01
WR	13" ultrasonic indication in electroslag weld	120	0	<0.01

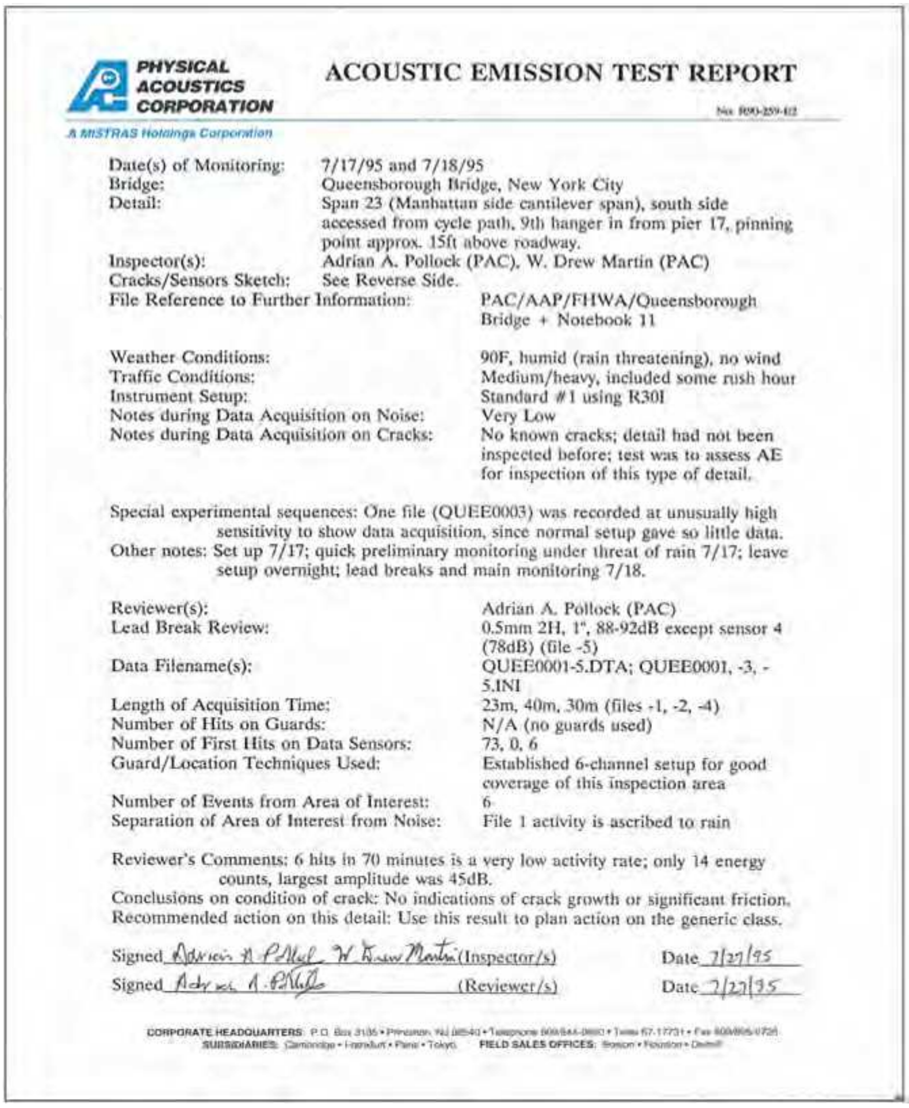
** WW = Woodrow Wilson (DC), BB = Bryte Bend (Sacramento), MS = Mississippi R. (I10 Baton Rouge), WR = Willamette R. (Portland OR)

Table 1. Flaws on Steel Bridges and their Respective Levels of AE Activity

such as photographs and any AE data graphs of particular interest. The simplicity of this form would help to keep the cost of the test down, as well as expediting communication of the results. A table such as Table 1 would be used on site to explain the test to bridge owner personnel. This approach became a useful starting point for test services to inspect limited areas of interest.

A feature of this approach was that to keep it simple, one did not get into the difficult question of whether the emissions were coming from friction (crack face interference) or actual crack growth. In fact, the great majority of detected AE is likely coming from friction. In arguing that this relates to the severity of the flaw, the position can be taken that any local movement is bad because it implies changing strains and stresses, which are likely to be driving crack growth. This position: "a quiet piece of structure is a good piece of structure, any AE is bad" may be simplistic, but it has much to commend it in terms of practicality. On the next level of technological sophistication, more advanced AE analysis attempts to tell the difference between frictional AE and actual crack growth events. This kind of advanced analysis will lead to more precise diagnostic and prognostic capabilities in the future.

Fatigue cracking is a threat to railway bridges as well as to highway bridges. Significant work on the integration of AE into the qualification processes for railway bridges has been reported by (Gong et al., 1992). In Gong's program, the severity of cracks (and the level of urgency assigned to their further inspection and eventual repair) is based on an engineering assessment of the range of stress intensity factor, ΔK, to which they are exposed in service. ΔK is the important factor to consider because it is this that governs the crack growth rate. Correlations were established between AE and ΔK, thus allowing AE to be used in the evaluation of the severity of the crack and its subsequent disposition.



PHYSICAL ACOUSTICS CORPORATION
A MISTRAS Holdings Corporation

ACOUSTIC EMISSION TEST REPORT

Date(s) of Monitoring: 7/17/95 and 7/18/95
Bridge: Queensborough Bridge, New York City
Detail: Span 23 (Manhattan side cantilever span), south side accessed from cycle path, 9th hanger in from pier 17, pinning point approx. 15ft above roadway.
Inspector(s): Adrian A. Pollock (PAC), W. Drew Martin (PAC)
Cracks/Sensors Sketch: See Reverse Side.
File Reference to Further Information: PAC/AAP/FHWA/Queensborough Bridge + Notebook 11

Weather Conditions: 90F, humid (rain threatening), no wind
Traffic Conditions: Medium/heavy, included some rush hour
Instrument Setup: Standard #1 using R30I
Notes during Data Acquisition on Noise: Very Low
Notes during Data Acquisition on Cracks: No known cracks; detail had not been inspected before; test was to assess AE for inspection of this type of detail.

Special experimental sequences: One file (QUEE0003) was recorded at unusually high sensitivity to show data acquisition, since normal setup gave so little data.
Other notes: Set up 7/17; quick preliminary monitoring under threat of rain 7/17; leave setup overnight; lead breaks and main monitoring 7/18.

Reviewer(s): Adrian A. Pollock (PAC)
Lead Break Review: 0.5mm 2H, 1", 88-92dB except sensor 4 (78dB) (file -5)
Data Filename(s): QUEE0001-5.DTA; QUEE0001, -3, -5.INI
Length of Acquisition Time: 23m, 40m, 30m (files -1, -2, -4)
Number of Hits on Guards: N/A (no guards used)
Number of First Hits on Data Sensors: 73, 0, 6
Guard/Location Techniques Used: Established 6-channel setup for good coverage of this inspection area
Number of Events from Area of Interest: 6
Separation of Area of Interest from Noise: File 1 activity is ascribed to rain

Reviewer's Comments: 6 hits in 70 minutes is a very low activity rate; only 14 energy counts, largest amplitude was 45dB.
Conclusions on condition of crack: No indications of crack growth or significant friction.
Recommended action on this detail: Use this result to plan action on the generic class.

Signed (Inspector/s) Date 7/27/95
Signed (Reviewer/s) Date 7/27/95

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Fig. 5. A Simple Form for Reporting AE Tests on Welded Details

Before leaving the topic of fatigue cracks, it should be mentioned that in all such work on bridges, a crucial consideration is whether or not the crack is in a "critical member". Depending on the geometry of the load-bearing structure in the neighborhood of the crack, the growth of a crack can end in either of two ways. Some fatigue cracks follow a path that has them accelerating towards a catastrophic failure of major structure. Other cracks follow a path such that the load is redistributed to other members that manage to carry it, while the crack finds its way to a low-stress region and practically stops propagating. An understanding of the bridge structure and load paths is needed to tell the crucial difference between these cases.

A second major threat to mechanical integrity of steel civil structures is corrosion. A leading example of this is the slow deterioration of the cables of suspension bridges and cable stay bridges. Corrosion of the inner strands of the cables leads to a slow reduction of its strength. This is a real concern in old bridges where procedures for maintaining a good chemical environment for the cable strands (oil injection, etc.) have been neglected and water ingress has occurred during many decades of service. Diagnosis and prognosis of structural health are very important for long term planning of the maintenance, and ultimately the replacement of these slowly deteriorating structures.

A role that AE can play in addressing this problem is the detection of individual wires breaking in the corroded parts of the cable. A main cable may contain upwards of ten thousand bundled wires so a few breaks do not amount to much, but over a period of time it is the cumulative breaking of many wires that would lead to the failure of the cable. Systems for monitoring wire breaks with AE have been in place for a number of years on some well known bridges. The main challenges are installation (Figure 6), maintenance and data interpretation (discrimination of wire breaks from background noise). Special algorithms have been developed for recognizing wire breaks, using an economically viable number of sensors, even in the presence of major background noise sources such as trains passing over the bridge.

Fig. 6. Installing Sensors for Long Term Monitoring of a Suspension Bridge Cable

To understand better the mechanisms of cable deterioration, a specially fabricated cable was installed in a test cell (Figure 7) at Columbia University (New York City), in a joint project with MISTRAS Group and Parsons, the well known bridge engineering company. This cable had 50 implanted sensors for measuring environmental conditions (temperature, humidity, pH) as well as corrosion vulnerability using several different kinds of corrosion sensor. The sensors were deployed in normal regions and in regions where the normal protective layers were disrupted. The cable could be pulled in tension, heated and cooled, sprayed with simulated acid rain and so forth. The purpose of this study was to understand the intra-cable environment and the dependence of corrosion on external challenges and maintenance variables. Information was collected for input to predictive models that could tell the degradation of a cable's strength over long periods of time as a function of environment and cable condition. The design of the monitoring system emphasized data fusion. While it included AE detection of wire breaks, this was not the only purpose of the system, not even its main purpose. More to the point in today's system design is the recording of the many assorted variables that are pertinent to structural integrity, whether they be challenges, responses or measures of condition. This kind of fusion of data from many sources has become a theme in the emerging technology of structural health monitoring.

The practical utilization of AE on civil structures has been substantially assisted by the development of wireless systems during the first decade of the 21^{st} century, and this development will yield even greater benefits as wireless techniques continue to improve.

Fig. 7. Suspension Bridge Cable Test Cell with Multiple Sensor Types

Traditionally, the running of long cables between the sensor/preamplifier and the main AE instrument has always been a major part of the effort involved in any AE field test. And in any consideration of permanent installations, the cost of professional conduiting of the cables would typically be several times greater than the cost of the AE electronics.

Replacement of these cables with wireless systems is a longstanding dream that has become a growing reality in recent years, thanks to the burgeoning of digital communications infrastructure in our society in general. Wireless hardware for AE first took the form of a node for sending parametric information (i.e. slowly varying quantities, not needing significant bandwidth). Next came a node with onboard signal measurement capabilities that could transmit the measured signal features to a receiving station near the central computer. By 2011, a four-channel node (Figure 8) was introduced that could also transmit the full AE waveforms; source location also became possible, with the four channels associated with a single clock for good measurement of the arrival time differences.

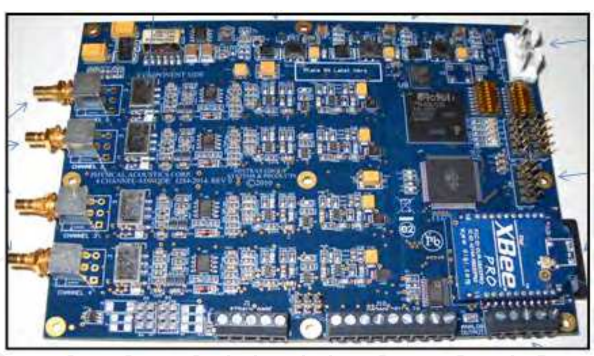

Fig. 8. Low-Power, Four-Channel Wireless Node with Feature Extraction, Full Waveform Transmission, and Inputs for Strain Guages and Six Parametrics

An associated costs-cutting development is the introduction of self powered (energy harvesting) AE systems (Karami et al., 2012). With wireless, you don't have to run so many cables; with self-power, you can leave the system there permanently. At first sight this may seem like an indulgence, but when all the costs of lane closure are taken into account it becomes clear that it is cheaper to leave the equipment in place than to close the lane to go and remove it. For these reasons self powered, wireless systems are expected to bring about a major improvement in the practical applicability of AE technology to both steel and concrete structures.

3. Reinforced concrete

Genuine source mechanisms for acoustic emission in concrete structures are numerous and include cracking of the concrete (crack extension), rubbing of crack surfaces during crack closure, debonding of the reinforcing steel from the surrounding concrete, and localized cracking in the vicinity of the reinforcement due to doweling action. Sources of non-genuine AE in concrete bridges and structures are not as severe as in steel bridges due to the attenuating nature of the concrete itself. Nonetheless, non-genuine sources do exist and need to be taken into account. These sources include movement of supports including bearings and the customary environmental noise sources such as wind-borne debris and rain.

The safe load carrying capacity of reinforced concrete structures can come into question for a number of reasons including a change in use or occupancy, questions regarding details of construction such as missing or misplaced steel reinforcement, and in some cases the use of newer materials and systems that may not be addressed in existing codes and standards. A variety of load test methods exist for both buildings and bridges. For buildings, the cyclic load test (CLT), as described in Appendix A of ACI 437R-03 (ACI 437, 2003), is a recently introduced in-situ evaluation method. This method has the potential to reduce the time of the load test in comparison to the 24-hour load (24-h LT) test method described in chapter 20 of ACI 318-08 (ACI 318, 2008) while simultaneously providing improved insight to the response of the structure. The typical instrumentation utilized for load testing of buildings and bridges consists of displacement and rotation gages and in some cases these may be supplemented with strain gages. These devices lack the sensitivity of acoustic emission. Because many of the damage mechanisms that are present in reinforced concrete manifest themselves as cracking of the concrete prior to structural collapse, AE would seem to be an ideal method for the evaluation of reinforced concrete structures during load testing. Additionally, the loading pattern that is specified for the CLT method (Figure 9) is serendipitously reminiscent of loading patterns that have been used for many decades for the evaluation of fiber reinforced polymeric pressure vessels and tanks (ASME, 2010a and 2010b).

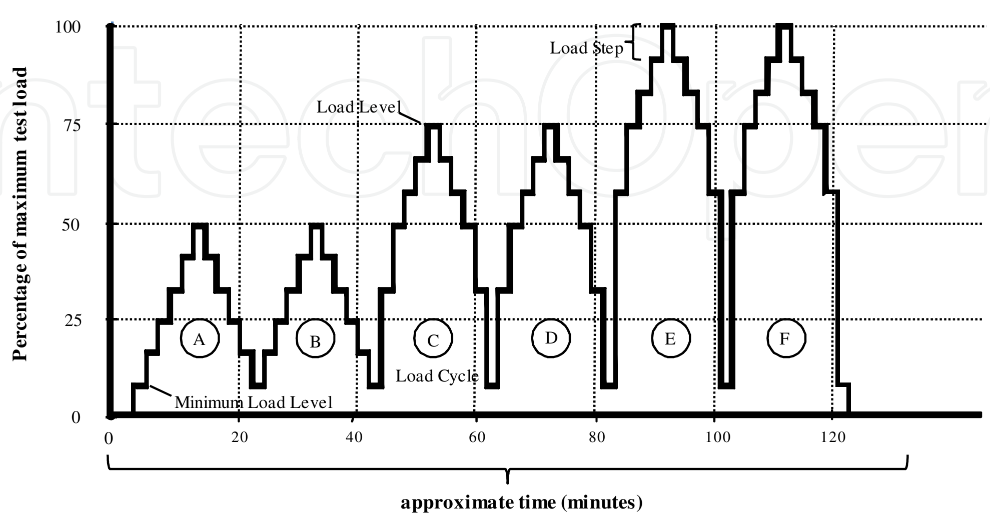

Fig. 9. Loading and Unloading Protocol associated with the Cyclic Load Test (after ACI 437R-03, Appendix A)

For prestressed and post-tensioned concrete flexural elements, cracking of the component under service level loads can be considered as a failure of the serviceability criteria. In such cases acoustic emission can be useful to minimize damage to the element during the load test itself. Another area in which acoustic emission can provide significant advantages over rotation, displacement, and strain gages is in the assessment of shear-dominated failure mechanisms. In such cases the current load testing approaches may not be useful until very significant damage has been done to the web and/or the bond of the reinforcing bars or strands near the ends of the girders (Figure 10).

Fig. 10. Shear-Tensile Failure in Prestressed Girder Specimen (after Xu, 2008)

For acoustic emission evaluation, several investigators have reported correlation of AE parameters to damage levels of reinforced concrete structures. One of the most widely implemented damage assessment methods is the correlation of calm ratio and load ratio (also referred to as Felicity ratio) (Yuyama et al., 1999; Ohtsu et al., 2002; JSNDI, 2000). Another approach makes use of severity versus historic index, known as 'Intensity Analysis', as a measure of deterioration for concrete bridges (Golaski et al., 2002). This method is directly related to assessment of fiber reinforced polymeric vessels. "Relaxation ratio" has likewise been used to quantify the residual strength of reinforced concrete beams (Colombo et al., 2005).

While the AE method is clearly useful for detection of cracking in reinforced concrete, the AE method of structural evaluation for reinforced concrete alone is not likely to be accepted at this time. This is due to a lack of widespread implementation combined with the inescapable fact that data interpretation methods are conducted on a case by case basis without the benefit of a governing code or standard for basic settings such as test and evaluation thresholds and noise rejection methodologies. Therefore, much of the effort to date has been placed on a combined inspection approach, wherein the acoustic emission data is used in combination with data gathered through more conventional instrumentation such as displacement gages. (Galati et al., 2008; Ziehl et al., 2008).

While the application of controlled loading such as that shown in Figure 9 is possible and even customary for building applications, this is not commonly the case for highway structures. For highway structures it is much more common and practical to use loading trucks with known wheel weights. In many applications a determination of the load carrying capacity is of interest whereas in others the interest is simply in the detection of active cracking, or lack thereof, under particular loading scenarios. One such application is the determination of locations of active cracking in a prestressed girder system in the shear region of prestressed girders. In this particular case a combination of factors resulted in severe cracking at the support region. AE sensors were arranged in an array of six in the web region of each girder and loading trucks were positioned to maximize the shear in the girders. A sensor array and a related plot of acoustic emission activity related to active crack growth are shown in Figure 11.

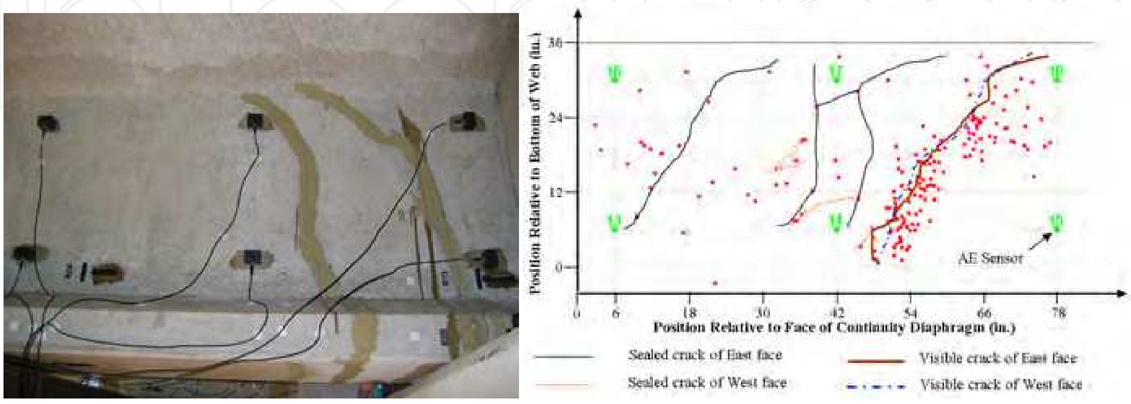

Fig. 11. AE for Detection of Active Cracking in Prestressed Girder (after Xu, 2008)

Due to the extreme sensitivity of AE, the monitoring of the passage of superloads presents another common and informative application (Grimson et al., 2008). In most cases the permitting process involves the development of computer models of the bridges to assure that damage is not done during the passage of the superload. Due to the many simplifying assumptions made in the development of computer models, such as simple supports, lateral load distributions factors, degree of composite action between the girders and the deck, and the longitudinal distribution of the superload itself, the actual response of the bridge may differ from the computer models. One of the largest superloads in the state of Louisiana crossed the Bonnet Carre' bridge (Figure 12). This superload passage resulted in acoustic emission activity that was significantly increased in comparison to the AE activity during the passage of normal traffic (Figure 13).

Fig. 12. Superload Crossing of Bonnet Carre' Bridge (after Grimson et al., 2008)

In addition to the use of acoustic emission for the evaluation of load carrying capacity and serviceability, AE has more recently been used to directly assess the presence of corrosion in both reinforced and prestressed concrete structures. It is intellectually clear that the crack growth activity generated by the expansive products associated with corrosion will produce acoustic emission. The use of AE is particularly attractive for the detection and monitoring of corrosion rates because the existing electro-chemical methods are invasive by nature and are generally limited to the evaluation of corrosion at a particular point within the structure. The fact that AE sensors can be applied as a global network combined with the inherent ease of installation is appealing.

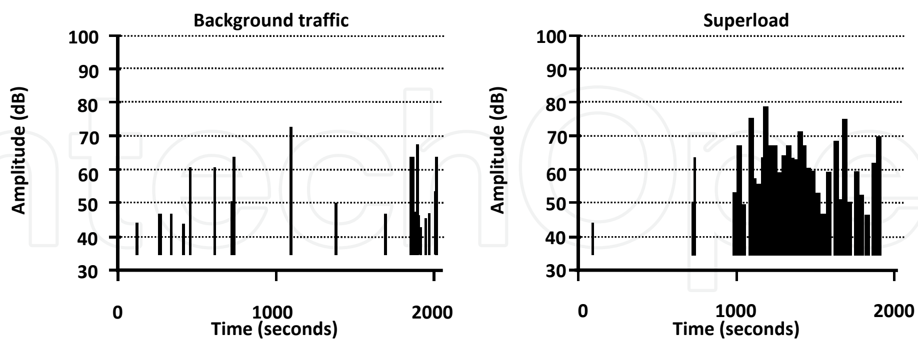

Fig. 13. AE Data related to Superload Crossing (after Grimson et al., 2008)

While much of the focus for acoustic emission has been placed on passively reinforced concrete, prestressed concrete construction represents a large portion of bridge construction and surpasses traditional reinforced concrete (NBI, 2011). The use of prestressed concrete in parking garages and buildings is also prevalent. Prestressing is generally selected due to its low initial cost, minimum downtime for on-site construction, and long life expectancy. In spite of the good overall performance record of prestressed concrete elements, it has been reported that approximately 30,000 prestressed bridges have some sort of deficiency (NBI, 2011). Furthermore, many bridges are rapidly approaching their design lives.

Corrosion of steel reinforcement is a primary contributor to deterioration and is of particular concern in marine environments and where deicing salts are used. The annual cost of bridge corrosion is $13.3 billion and life-cycle analysis estimates indirect costs at more than 10 times the direct cost (Hart et al., 2004; Koch et al., 2006). For prestressed construction the cracking is in many cases not allowed by the governing design codes under service level loading. However, cracks occur nonetheless due to temperature effects during the initial stages of curing, during transportation and erection, and due to overloading. Cracks in prestressed concrete can increase the rate of water penetration. Corrosion is particularly common at midspan of highway bridges where a collision has occurred and the concrete has been patched. It is also common at the support region of the girders where the beneficial effect of prestressing is not fully developed (Klieger and Lamond, 1994) and the steel strands are sometimes exposed. In prestressed concrete piling, corrosion is pervasive in the tidal zone where wet-dry cycling takes place.

Electrochemical methods have been developed to assess the degree of corrosion. While these techniques are useful for mapping the general areas of corrosion, they generally have the drawbacks of being intrusive and time consuming. Furthermore, in many cases they require the use of on-site experts for operation of the equipment (Baboian, 2005; ICRI 1996). In contrast to this acoustic emission monitoring makes use of the fact that the expansive nature of the corrosion process initiates micro-cracking of the surrounding concrete and this micro-cracking is readily detectable with AE sensors. A prime benefit of AE monitoring is that the sensors can be simply affixed to the surface of the concrete member without a need to access the embedded reinforcing steel. This can be accomplished in either a localized or more global array, depending upon the scale of the structural component and the suspected extent of corrosion. The sensors themselves can be used for assessment over a particular period of time and then moved to another structure for monitoring, which is particularly important for the assessment of a large inventory of structures as is typical for bridge owners. This stands in contrast to other methods of corrosion monitoring wherein sacrificial anodes are used and the probe containing the anodes must be in close proximity to the steel reinforcement, thereby requiring drilling of the element to be monitored.

From a structural point of view, changes in failure and serviceability mechanisms such as cracking, debonding, and strand rupture due to corrosion have been investigated with acoustic emission (Yoon et al., 2000; Austin et al., 2004). For the direct monitoring of corrosion activity in the absence of load the AE method has proven to be more sensitive than electro-chemical methods and therefore holds promise for the quantification of corrosion rate, and this information can then be incorporated into projections for the remaining serviceability of components or systems.

Due to the promise of the AE method for detection of corrosion in steel strands, recent detailed studies have been conducted under accelerated corrosion with the express purpose of verifying the potential for detecting the onset of corrosion and the rate of corrosion. To this end the primary sources of acoustic emission activity during the onset and progression of corrosion were located and the results in terms of acoustic emission activity compared to electrochemical methods. Both the AE and electro-chemical results were verified with visual inspection.

The investigations to this point have focused primarily on relatively small specimens, 4.5 × 4.5 × 20 in. (114 × 114 × 508 mm), Figure 14. Two inches of cover was provided for the specimens as this is generally representative of field construction. Each specimen was cast with a single 270 ksi (1.9 GPa), ½ inch (13 mm) diameter seven-wire low relaxation prestressing strand. All specimens were cast using concrete with a design compressive strength of 6 ksi (41 MPa) at 28-days with a maximum coarse aggregate size of ½ inch (13 mm).

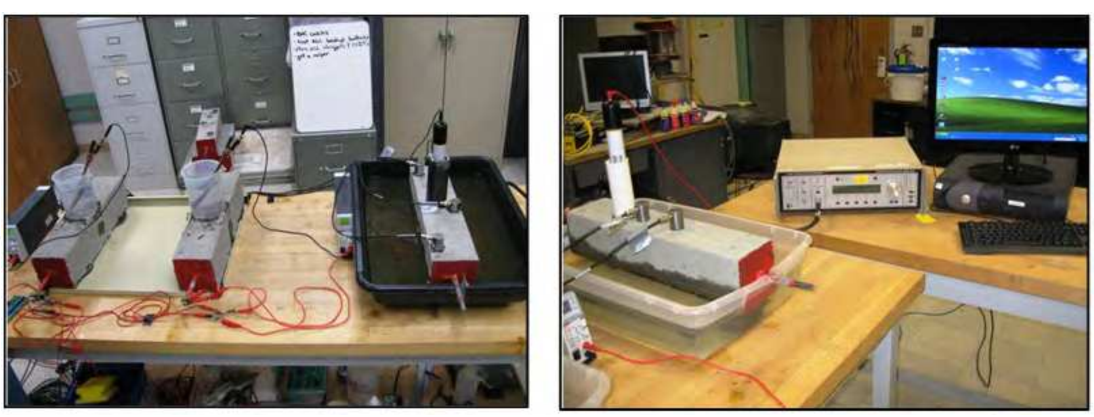

Fig. 14. Test Setup for Accelerated Corrosion of Prestressed Concrete Specimens (after Mangual et al., 2011)

The presence or absence of cracking is a critical parameter in acoustic emission monitoring in general, and this is particularly the case of corrosion monitoring due to the relatively low energy sources involved at the corrosion initiation stage. Cracking has two significant effects on the received data; a) the cracks form an additional reflective surface that can complicate the AE data interpretation, and b) the cracks provide a means of energy release for the expansive product itself. The second item tends to reduce the energy of the recorded signals in cracked concrete structures. All specimens discussed were intentionally cracked to account for this condition which may well be present in actual field structures. The crack was kept to a reasonable size of 0.016 in. (0.4 mm), which is above the threshold value from which rapid chloride can permeate and depassivate the reinforcing steel (Tutti, 1982).

Specimens were placed in a container filled with 3% NaCl to a level 0.25 in. (7 mm) below the level of the strand. An electrochemical cell was formed with a copper plate brought into contact with the steel strand. A constant potential was applied with a current range dependent on the resistivity due to the concrete and pore solution.

Potential measurements were taken in the vicinity of the initial crack. The applied voltage lowered the potential of the steel below -350 mV and depassivation took place after approximately five hours of testing. Values more negative than -350 mV are considered indicative of a 90% probability of corrosion in the area interrogated (ASTM, C876).

While broadly applied in field applications, half-cell potential measurements are not intended to quantify corrosion or corrosion rate. Therefore while this method provides quantitative readings the interpretation of the data is limited and is not particularly helpful for predicting the remaining service life of a structure. In contrast to the 'corrosion/no corrosion' information obtained from half-cell potential readings, acoustic emission can provide equal or better sensitivity combined with the ability to monitor the rate of the corrosion process. A plot of representative data is shown in Figure 15.

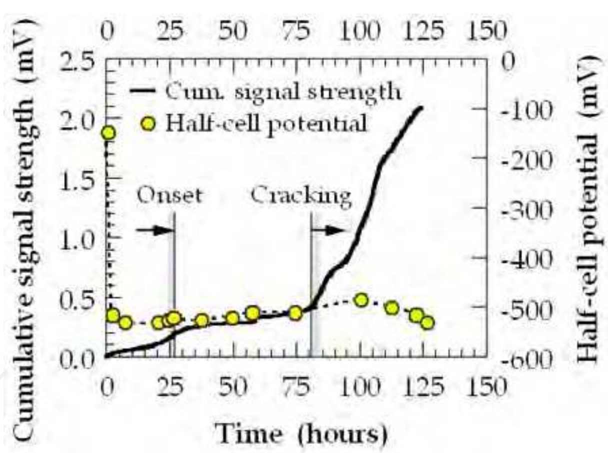

Fig. 15. Comparison of AE and Half-Cell Potential Data vs. Time (after Mangual et al., 2011)

4. Fiber reinforced polymers

Fiber reinforced polymers offer promise for civil engineering structures due to their inherent lack of susceptibility to corrosion and high strength. Acoustic emission is well-established for FRP materials and, as discussed above, has its roots in the FRP vessel industry (Fowler and Gray, 1979). Damage mechanisms in FRP structures include fiber breakage, matrix cracking, delamination, and fiber-matrix debonding. Of these mechanisms fiber breakage is relatively easily discriminated from the others due to the high energy of this source mechanism and this is particularly the case for breakage of carbon fiber bundles.

In some FRP structures, the material degradation mechanisms are of secondary importance to the connections between disparate systems. Such is the case for FRP honeycomb (FRPH) structures such as those used for panel type bridge construction and AE has been successfully implemented to evaluate fatigue damage for such a system prior to implementation (Cole et al., 2006). A similar investigative approach but with focus on degradation and/or manufacturing defects (such as internal delamination between plies) has recently been undertaken as part of a quality assurance program for two hybrid FRP/reinforced concrete bridges constructed near Corpus Christi, Texas. In both cases AE sensors were affixed to a pre-determined number of bridge beams for evaluation prior to implementation. Specialized loading procedures for the girders were developed in general conformance with those implemented for FRP vessels when evaluating against pre-determined acoustic emission evaluation criteria (Ulloa et al., 2004; Ramirez et al., 2009; Chen et al., 2009). In one case AE evaluation indicated potential intra-ply delamination in a girder and the location of the indication was later followed up with ultrasonic inspection. A photograph of FRP girders in place at one of the two bridge sites prior to placement of the concrete deck is shown in Figure 16 (Ramirez et al., 2009).

Fig. 16. Hybrid FRP/Reinforced Concrete Bridge Girders Evaluated with Acoustic Emission (after Ramirez et al., 2009)

Because FRP is a relatively new material for civil construction, it is sometimes prudent to utilize the sensitivity of acoustic emission for field evaluation after the structure has been opened to traffic. For one of the FRP/reinforced concrete bridges mentioned above, load testing was performed with AE each six months over a two year time span (Ziehl et al., 2009). In such cases it is very important to carefully weigh the axles of the loading trucks prior to evaluating the resulting AE data. This is because even a slight overload in relation to a previous loading can result in copious amounts of AE data in fiber reinforced polymeric systems due the Kaiser effect. However, much of the resulting data in such cases is of little consequence. Another factor to carefully consider for field applications in general is the potential effect of wind-borne debris (such as sand) on the AE data and how best to discriminate between such debris and actual AE data. For such cases the use of broadband sensors may be useful for clustering of noise versus genuine data based on frequency content.

Another aspect that is rarely considered, but should be in certain applications, is the effect of temperature on the AE evaluation criteria (Chen et al., 2007). This is not an issue in most environments, but may be important in very hot or very cold climates. In general the effect of an increase in temperature is to decrease the acoustic emission activity, and this may result in the inappropriate passing of evaluation criteria if those criteria were developed for ambient conditions. This effect is due to the viscous nature of the matrices commonly used for FRP construction.

5. Conclusions

Acoustic emission is a useful method of evaluation for many different materials used for civil construction including steel, reinforced concrete, and fiber reinforced polymers. Each of these materials offers certain advantages and challenges from the standpoint of acoustic emission monitoring.

Steel construction is typically achieved with highly ductile materials and the source mechanism itself is not well understood at this time. This challenge is combined with the low attenuation characteristics of the material which leads to a good deal of emission due to fretting of the crack surface. A primary challenge for the assessment of crack growth in steel structures therefore is how best to discriminate between fretting and other emission, such as that associated with crack extension.

Reinforced, prestressed and post-tensioned concrete have a different body of opportunities and challenges. Concrete is one of the least studied materials from the standpoint of acoustic emission. This material is characterized by high attenuation coupled with large amounts of emission due to its brittle nature. In terms of evaluation criteria reinforced concrete behaves very differently than prestressed or post-tensioned concrete due to the active nature of the reinforcement in the latter cases, which leads to significant friction in the cracks during unloading. One of the newer and more promising developments for reinforced and prestressed concrete is the use of AE for detection and monitoring of active corrosion.

Fiber reinforced polymers are perhaps the most widely studied of the three materials from the standpoint of acoustic emission. This is due to the large body of work that was conducted during the 1980's on FRP tanks and vessels. Because the materials used in tanks and vessels are generally reinforced with glass fibers many of the evaluation criteria and loading protocols bear a close relation to those for glass fiber reinforced girders and bridge decks.

An increase in temperature may result in non-conservative evaluations for structures fabricated with fiber-reinforced polymers. Further study is warranted for steel, reinforced concrete, and FRP structures with respect to the effect of temperature on acoustic emission evaluation criteria.

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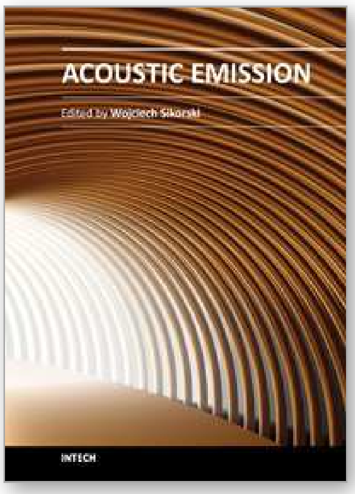

Acoustic Emission

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Acoustic emission (AE) is one of the most important non-destructive testing (NDT) methods for materials, constructions and machines. Acoustic emission is defined as the transient elastic energy that is spontaneously released when materials undergo deformation, fracture, or both. This interdisciplinary book consists of 17 chapters, which widely discuss the most important applications of AE method as machinery and civil structures condition assessment, fatigue and fracture materials research, detection of material defects and deformations, diagnostics of cutting tools and machine cutting process, monitoring of stress and ageing in materials, research, chemical reactions and phase transitions research, and earthquake prediction.