Early Detection of Steel Rebar Corrosion by Acoustic Emission Monitoring

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ABSTRACT

Acoustic emission monitoring was performed in a unique way on concrete specimens containing reinforcing steel and the acoustic emission events correlated with the presence of rebar corrosion. Verification of rebar corrosion was done by galvanic current, half-cell potential, and electrochemical analysis. Results showing the early onset of rebar corrosion from acoustic emission are presented.

Keywords: reinforced concrete corrosion, rebar corrosion, acoustic emission

INTRODUCTION

The continuing deterioration of the nation's infrastructure, particularly the corrosion of its highway bridges, is a problem of great importance which has received intensive public and private attention in recent years. The Federal Highway Administration (1) estimates that 42 percent of the 575,000 bridges in the United States are structurally deficient and in need of repair; $20 billion worth of bridge repair is required on the interstate highway system alone. Forty percent of the total square footage of U.S. bridges falls into the 15 to 35 year-old category - prime candidates for major rehabilitation. As a consequence, in 1992, the U.S. Congress passed the ISTEA (Intermodal Surface Transportation Efficiency Act) mandate requiring implementation of a quantitative computerized bridge management system by 1996. The objective of the bridge management system is to provide state Department's of Transportation with the necessary tools to make more informed decisions on which bridges need immediate repair and rehabilitation. However, a prime need of such a system are quantitative bridge inspection methods to feed the correct information on the huge database of bridges.

A significant portion of the deterioration of highway bridges is due to corrosion of the reinforcing steel (rebar) in concrete bridge decks and substructure where the increased use of de-icing salts in the northern climates and attack from sea salt in coastal areas has exacerbated concrete rebar corrosion. Two commonly used bridge inspection methods for determining concrete rebar condition are visual observation and half-cell potential measurements. Visual observation uses direct or remote inspection to detect obvious signs of corrosion, such as physical damage in the form of spalling or cracking. Visual observation can range from cursory examination to detailed mapping of the surface. Core sampling is often performed if the visual observation suggests that further evidence is needed. However, visual observation is subjective and provides corrosion detection only after significant corrosion has occurred. Core sampling is destructive and requires repair of the concrete.

Half-cell potentiai measurements can be used to determine the probability of corrosion activity taking place at the time of the reading. Using ASTM Test Method C876-80, the corrosion potential of the rebar is measured using a grid pattern over the concrete surface. However, the interpretation of the potential mapping is often inconclusive because the measurements depend on the condition of the concrete. Moisture level and the amount of carbonation and salt concentration can effect the reading and give erroneous readings. In addition, half-cell potential measurements do not provide information on the rate of corrosion.

More advanced methods such as radiography and ultrasonics have been used to detect rebar corrosion. However, they have met with limited success due to the skill needed to analyze the data as well as the expense of the equipment. In addition, radiography uses X-ray or gamma rays and requires extensive safety precautions.

Acoustic emission (AE) monitoring of concrete has been used to detect rebar corrosion and has been shown to detect film cracking, gas evolution, and microcracking. Although attenuation of the AE signal in the concrete has been a concern in the past, unique placement of the AE transducers on the reinforcing steel and using the steel as the sound propagation medium should allow the onset of steel corrosion to be detected. In addition, it is also possible to use the AE signal to calculate the location where the steel corrosion is occurring, allowing bridge inspectors to determine the extent of corrosion damage. Thus, acoustic emission monitoring appears to be a promising technique that can be used as a bridge inspection method to quantify the condition of the steel-reinforced concrete, where corrosion is occurring, and where repair is needed. To this end, experiments were performed on steel-reinforced concrete specimens to determine the feasibility of using acoustic emission monitoring to detect corrosion of the steel reinforcement in concrete.

EXPERIMENTAL PROCEDURE

Three concrete rebar test specimens were exposed to a cyclic salt exposure for a period of two months to initiate corrosion of the top steel reinforcement. The specimens were subjected to a 15% sodium chloride electrolyte with a cycle of 3 days wet/ 4 days dry. This represents a modification to the test procedure in ASTM G109, but represents an accelerated test that better simulates wet/dry cycling of salt water on concrete bridge decks and substructures.

Figure 1 shows a schematic of the concrete rebar test specimens. The l-cubic-foot concrete blocks were formed using Portland cement and aggregate. Three, l-inch diameter, black steel reinforcement bars were placed in the concrete, one approximately 1-inch from the top surface and the other two 10 inches below the surface. The steel rebars were coated with an epoxy coating at the edges to prevent edge effects, but were left bare and exposed in the concrete environment. The two steel bars placed at the bottom of the concrete specimen were electrically connected to the top steel rebar by a shunt resistor. This allowed the galvanic current due to corrosion of the top rebar to be measured with exposure time. An acrylic tank was attached to the top of the concrete surface to allow electrolyte exposure to the concrete.

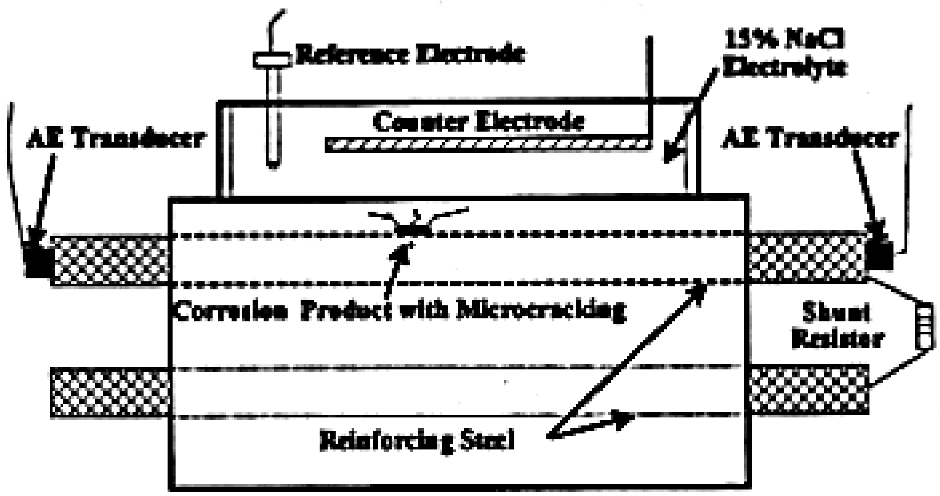

FIGURE 1 - Schematic of Rebar Test Specimen

Periodic galvanic current, electrochemical potential, electrochemical impedance spectroscopy (EIS) and linear polarization measurements were performed on the test specimens. In addition, acoustic emission monitoring was performed continuously on one of the specimens. The galvanic current, corrosion potential, EIS and linear measurements were performed weekly on the test specimens at the end of the 3-day wet cycle. The current was obtained by measuring the voltage over a 10-ohm shunt resistor between the top and bottom rebars. The corrosion potential measurements and EIS and linear polarization experiments were performed using the Model 398 Impedance System and SoftCorr* corrosion measurement system.

The AE signal was detected by placing AE transducers on the two ends of the top steel rebar as shown in

Figure 1. A Model 8013A** acoustic emission monitoring system was used to acquire the AE signals, and was controlled by software developed using the LabView*** software program. The acoustic signals detected were recorded in digital form and analyzed. The computer also tabulated the cumulative AE events occurring with exposure time. Figure 2a and Figure 2b show photographs of the test setup with the acoustic monitoring equipment attached to one of the test specimens. The following section gives a brief overview of the acoustic emission monitoring method.

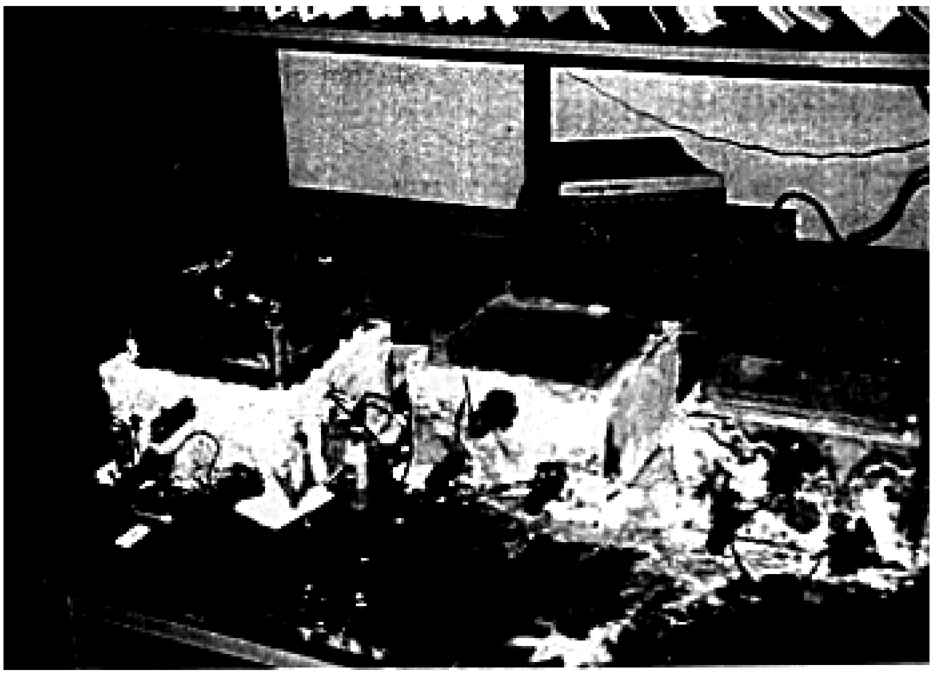

FIGURE 2a - Overall Set Up (AE equipment in background)

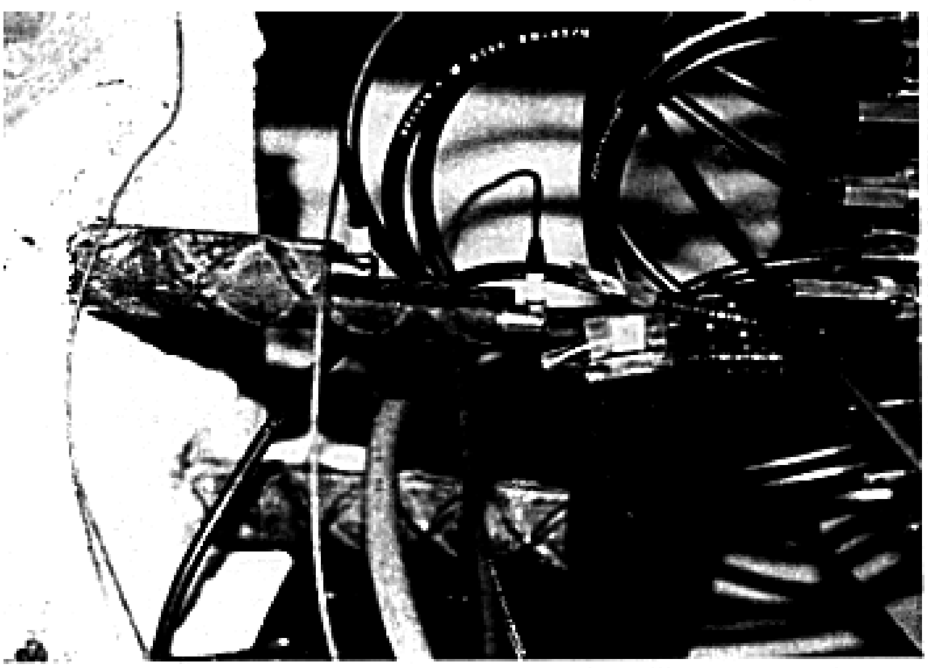

FIGURE 2b - Detail of Set Up Showing AE Transducers

Acoustic Emission Monitoring

Acoustic emission is a passive NDE technique that makes use of the high-frequency acoustic energy emitted by an object that is undergoing stress, such as when corrosion products formed on a corroding rebar push out on the concrete surrounding it. The primary advantage AE offers over more conventional NDE techniques is that it results directly from the process of flaw growth. Slow crack growth in ductile materials produce few AE events, whereas rapid crack growth in brittle materials produces large quantities of high amplitude AE events. Corrosion product buildup and subsequent microcracking of the concrete represents the latter phenomenon.

A typical AE monitoring system uses piezoelectric sensors acoustically coupled to the test object with a suitable acoustic coupling medium, (grease or adhesive). The output of the sensors is amplified and filtered by pre-amplifiers and then fed to the monitor via shielded coaxial cables. The monitor further filters and amplifies the AE signals, processes the data, and displays the results. Both results and raw data are typically recorded for archival purposes or for post-test analysis, for instance to determine location of the AE signal.

Acoustic emission has been applied to concrete by many researchers, the earliest account being in 1942 (2). A significant work was also published in 1970 (3). Concrete cylinders of varying composition were tested according to standard ASTM test procedures. A pre-stressed concrete pressure vessel was also tested to failure. Results showed significant AE signals and proved that AE is a good indicator of failure processes in concrete. Since this work, considerable effort has been applied by a number of researchers, which has produced a basic understanding of the acoustic emission properties of concrete. However, limited results have been obtained on using AE to detect corrosion of steel rebar in concrete or the microcracking in the concrete to the buildup of corrosion products.

RESULTS

The AE data indicates that numerous AE events are obtained when corrosion of the steel rebar is initiated. Figure 3a shows the number of AE events recorded on a concrete rebar specimen as a function of cyclic exposure time. There is an increase in AE events at about 20 days into the exposure which is most likely due to microcracking due to corrosion product buildup on the rebar. Figure 3b shows one AE event as recorded by the three tranducers placed on the ends of the rebar. The AE signal is of a high frequency, as expected for rapid crack growth, and is shifted by ~ 10 microseconds between the transducers. Such a shift in the AE signals is due to the acoustic signal traversing down the rebar and should allow source location of the AE event and rebar corrosion to be calculated.

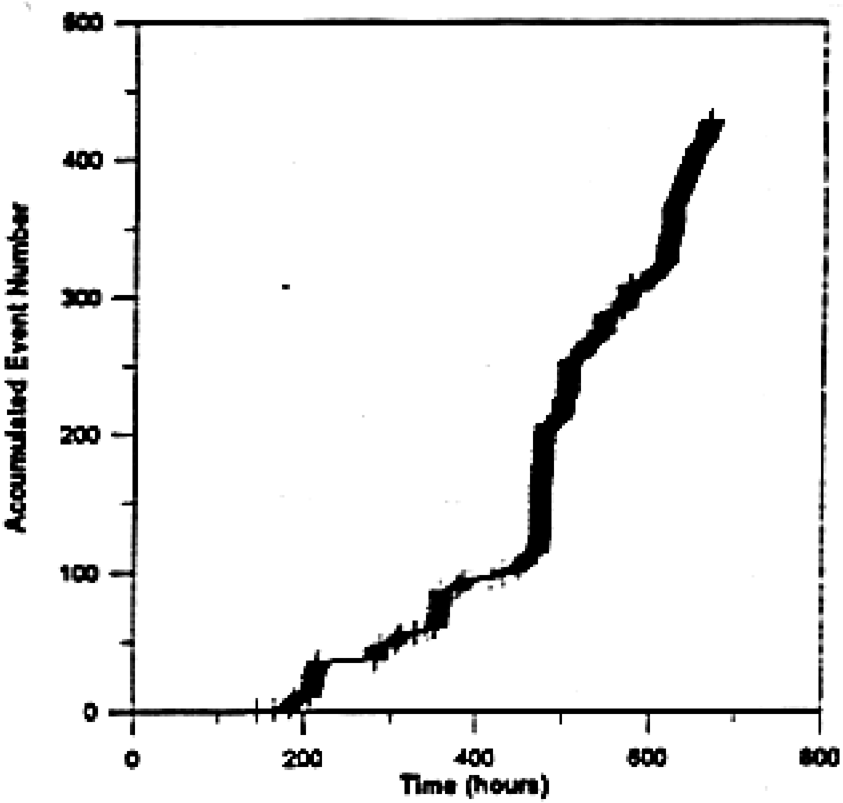

FIGURE 3a - Cumulative AE Events versus Exposure Time

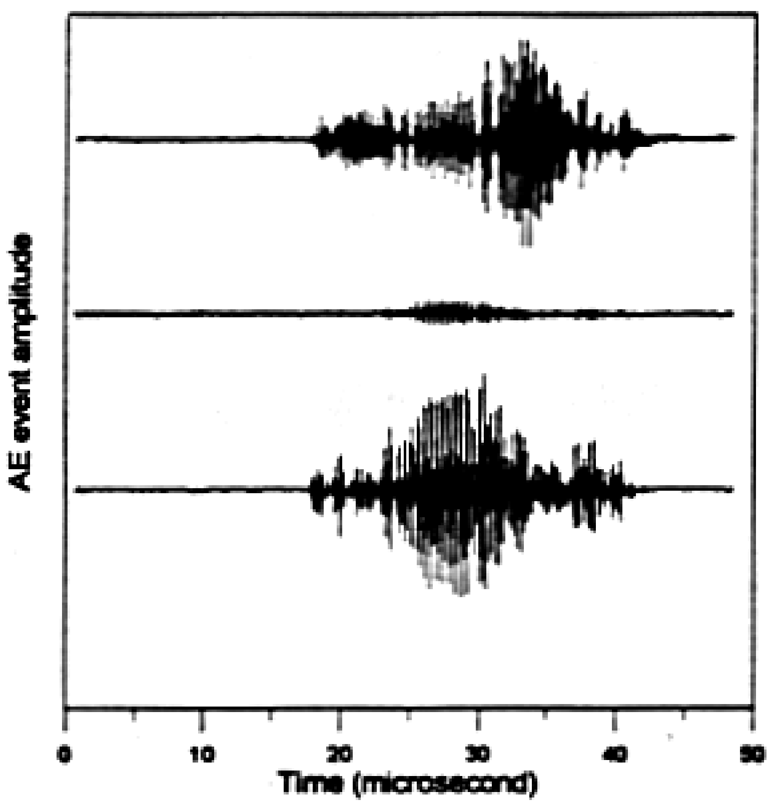

FIGURE 3b - AE Signal at the Three Transducers for a Single AE Event

The AE results were corroborated by galvanic current measurements and half-cell potential measurements taken between two steel rebars in the concrete, in accordance with ASTM Test Method

G109 and ASTM Test Method C876, and electrochemical impedance spectroscopy (EIS) measurements. A sudden increase in galvanic current indicates that corrosion is occurring on the top steel rebar that has been exposed to the salt solution. Figure 4a shows the galvanic current as a function of time for the concrete rebar specimen, showing a sudden increase in current at approximately 32 days exposure time. Also, the half-cell potential measurements became more negative to about -420 mV $(Cu/CuSO_4)$ in the same time. According to ASTM C876, a potential that is more negative that -350 mV $(Cu/CuSO_4)$ indicates that there is a 90 percent probability that active corrosion is taking place. Figure 4b shows a Nyquist impedance plot from the EIS measurements. The EIS semi-circle has decreased after 21 days of cyclic exposure and indicates that the corrosion rate of the rebar has increased during this time. The data from these three measurements verifies that active corrosion of the top steel rebar is most likely taking place.

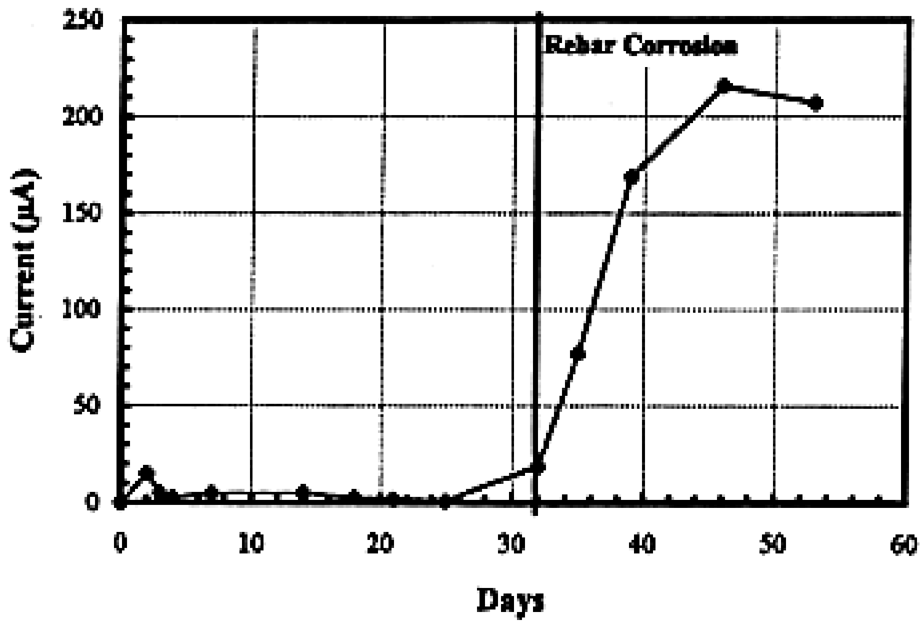

FIGURE 4a - Galvanic Current versus Exposure Time

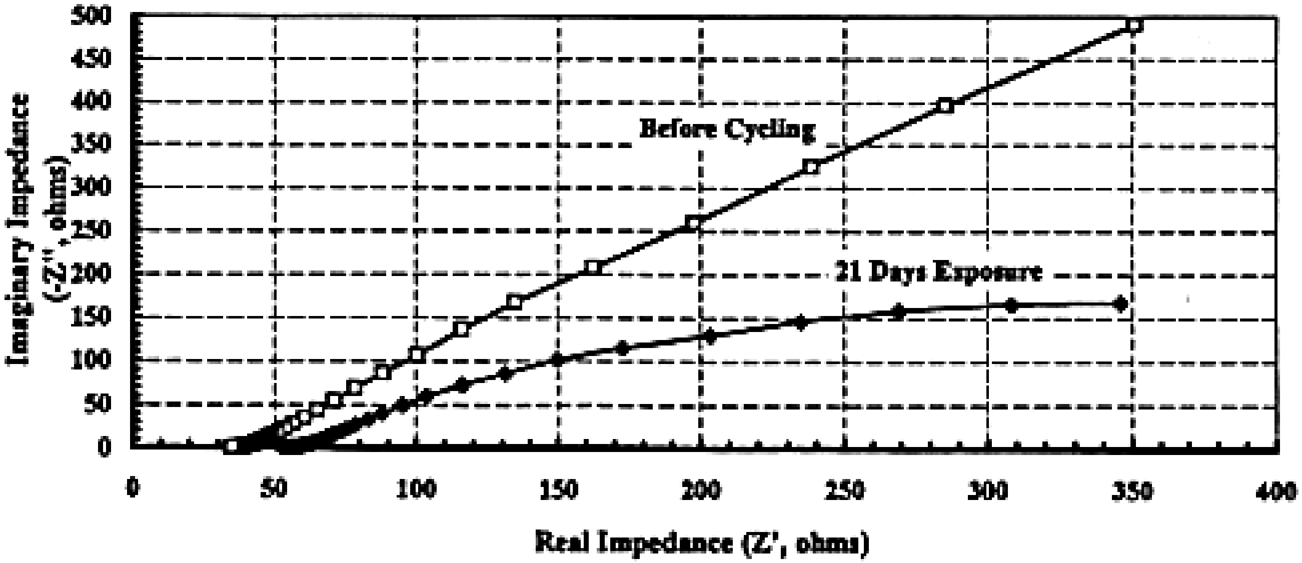

Figure 4b - EIS Nyquist Plot

The results from these preliminary experiments suggest that the unique placement of the AE transducers on the steel rebar provides an excellent sound propagation medium to monitor rebar corrosion. When corrosion occurs, the AE signals appears to correlate with the rebar corrosion. In addition, AE monitoring detects corrosion earlier than the galvanic current and the half-cell potential measurements. Most likely the AE signal is due to microcracking of the concrete as the corrosion products build up on the reinforcing steel. However, further research is needed to quantify the relationship between the AE signal and concrete rebar corrosion. More frequent, higher frequency events may be produced initially when the concrete begins cracking, whereas the AE signal may change once microcracking has occurred and larger cracks begin to form. Quantifying the characteristic AE signal will be important when using AE in the field where the rebar may be in various states of deterioration. In addition, more work is needed to determine whether AE can be used as a source location for rebar corrosion. The experiments suggest that source location is possible, but further verification is needed.

CONCLUSIONS

Acoustic emission monitoring was performed on steel reinforced concrete specimens by using the steel rebar as the waveguide. The experiments indicated that AE monitoring can detect the onset of rebar corrosion earlier than other methods such as galvanic current and half-cell potential measurements. Further experimentation is proceeding to determine whether source location of the corrosion/ corrosion products is also possible using AE.

ACKNOWLEDGMENTS

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NOTES

* Model 398 is a trade name and Softcorr is a registered trademark of EG&G Princeton Applied Research.
** Model 8013A is a trade name of the LeCroy Corporation.
*** LabView is a trade name of National Instruments Corporation.

SUBJECT INDEX TERMS

1. Acoustic emission testing
2. Bridges, Steel
3. Bridge corrosion
4. Non-destructive techniques