Research Report
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ACOUSTIC EMISSION MONITORING OF IN-SERVICE BRIDGES

by

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16. Abstract

An experimental acoustic emission (AE) device, the GARD Acoustic Emission Weld Monitor (AEWM), has been field tested on six bridges during this study. In addition, the device was used to test three other bridges under separate contracts from state highway agencies. The device was evaluated to determine if it could detect fatigue-crack growth on in-service steel bridges.

The AEWM employs a proprietary three-step model (filter) to reject noise-related AE activity and detect and locate defects subject to varying stress conditions. The unit uses built-in microprocessors to compare incoming data to the model. If defect-related AE activity is detected, the AEWM will notify the operator and locate the defect in relation to AE sensors placed on the test specimen.

The device rejects high background noise rates typical of bridges and detects and locates AE activity from known defects such as cracks and subsurface flaws. The AEWM functioned properly in every field test situation to which it was applied.

The device has demonstrated capability to perform AE tests on in-service bridges. It may be used to detect hidden defects or to assist in making repair decisions concerning detected discontinuities. The AEWM and AE testing have the potential for low-cost inspection of critical bridge members.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

There is an increasing need to assure the structural integrity of steel bridges. As those bridges age, they are subjected to accumulative wear and damage by cyclic live-load applications. Those loads may create and propagate fatigue cracks through structural members, causing them to fracture. Many of those bridges contain structural members that lack load-path redundancy (i.e., fracture-critical members). If one of those members should fracture, the bridge would collapse.

Welded construction increases the potential for fatigue problems. Welding may induce crack-like defects into bridge members. Many weld details also create unanticipated stress concentrations. The interaction of welding defects and stress-concentrating details with cyclic live loading may lead to fatigue cracking and possibly catastrophic bridge collapse.

The main method of detecting cracks in steel bridges is visual inspection. Such inspections only detect large surface cracks. The quality of inspection depends on the ability and initiative of the inspector. Conventional nondestructive test (NDT) methods such as dye-penetrant or ultrasonic testing may be used to supplement visual inspections. Those methods are expensive and are subject to similar human-factor limitations that apply to visual inspections.

To conduct large-scale inspections of bridges, it would be best to first scan the bridge using an inexpensive NDT method. Thereafter, a second NDT method could be used to evaluate flaws detected by the initial testing to determine if they were actual defects. Most conventional NDT methods are cost effective for flaw evaluation but not for scanning. An inexpensive scanning method is desired for widespead nondestructive testing of bridges to be practical.

Acoustic emission (AE) testing has potential for the scanning phase. It offers several advantages to conventional NDT methods, including detecting only active defects, requiring less labor, reducing the need for inspector interpretation, eliminating the need for extensive test surface preparation, and minimizing test limitations imposed by structure geometry.

When a crack grows in a structural member, it releases energy into the material in the form of waves that radiate outward from the crack. Those waves are termed acoustic emissions. The energy in those waves is too weak to be heard. The waves may be detected by piezoelectric sensors (i.e., transducers) in the ultrasonic range from 100-1,000 kHz. The sensors are placed on the surface of the member and create weak electric signals when they detect the AE waves.

In normal AE monitoring, the signals are received by an electrical instrument that can measure AE signal parameters such as signal strength, frequency of occurrence, and location relative to the sensor array. Those parameters may be analyzed to determine if crack growth occurs.

There are a number of potential sources of AE activity on steel bridges including crack growth and mechanical noise (fretting). Several of those sources may occur at the same time. Spurious background mechanical noise may be more active than crack-related AE activity. Many mechanical noise parameters are similar to AE crack activity and AE instrumentaion should perform sophisticated signal processing to discriminate between AE sources.

Modern AE testing of bridges began in the 1970's. Most early tests were research-related, attempting to determine field AE characteristics of bridges and to develop or test new instrumentation. The Kentucky Transportation Research Program (KTRP) first performed AE tests on a bridge in 1973. From

1980-82, tests on tie chords of the I 471 bridge at Newport, Kentucky were conducted.

Most early AE tests were unsuccessful. The instrumentation employed in those tests could not differentiate between crack-related AE activity and background noise. Those problems indicated that more sophisticated noise-rejection/defect-detection AE instrumentation was required.

GARD, Inc. of Niles, Illinois developed proprietary three-step multi-parametric software to analyze AE data and select crack-related AE activity. The software has been incorporated into a microprocessor-based system, the Acoustic Emission Weld Monitor (AEWM).

The system is capable of processing large numbers of AE events occurring at rates too high for manual analysis. The AEWM determines when a crack is detected. It automatically informs the operator of crack occurrence in real time and locates it in relation to the AE sensor array on the test specimen. The system is capable of hard-copy output and data storage by floppy disks.

The AEWM was first tested prior to this study on the I 24 bridge over the Tennessee River. That bridge had cracks caused by out-of-plane bending in webs of floor beams at the end connections. Five crack locations were inspected for a minimum of two hours. The only stimulus for crack-related AE activity was normal service loads. Only one site produced AE activity determined to be crack-related (i.e., the defect-related AE activity was located at the crack site). The AEWM was able to reject a large amount of extraneous noise and identify only AE activity from the crack.

During this study, nine AE field tests were performed on six bridges. Additionally, KTRP and GARD performed three additional AEWM bridge tests under contract to states. Test results are summarized in Table 1. In some cases, the AEWM was used on girders with visible cracks or subsurface ultrasonic indications to monitor AE activity related to crack growth. Several other tests performed during this study were conducted to experiment with new arrays or test details. Activity was stimulated in all tests by normal service loads. On the I 310 bridge at Luling, Louisiana, the service loading was supplemented by proof-type loads consisting of semi-trailer vehicles. The AEWM was able to reject in every case large background noise levels typical on highway bridges.

Acoustic emission testing consists of four phases: 1) location of AE sensors, 2) calibration of the test equipment, 3) suitable loading of structural members, and 4) acquisition of data. Most steel bridge details may be inspected using simple arrays that require only two sensors. In some instances, additional guard sensors may be required to preclude noise problems. The system function and array location may be calibrated by injecting ultrasound at specific test points along the array. Acoustic emission activity from cracks are produced by loading the bridge. Normal service loads are preferred but proof loading may be useful in some instances. AE field data may be recorded and later correlated with strain-gage data to determine defect severity.

Recent tests by KTRP and GARD investigators have demonstrated that the AEWM may detect fatigue-crack AE activity in bridges. It is suspicioned that AE activity is a function of crack size and magnitude of the live loading. For bridge tests, the inspector must determine how long to monitor the structure to ensure sufficient loadings have been incurred to cause crack-related AE activity. That is complicated by the fact that not all live loads will produce AE activity.

AE test have provided experience on bridges. The GARD AEWM is able to detect fatigue crack-related AE activity on in-service bridges. The Federal Highway Administration (FHWA) has awarded GARD a contract to develop an

Highway Administration (FHWA) has awarded GARD a contract to develop an updated AEWM intended for bridge inspection (Contract No. DTFH61-86-C-00072). KTRP will evaluate the new AEWM when it is completed.

The AEWM has proven that AE testing is an ideal method for scanning bridges. The upgraded and reconfigured unit should permit cost effective nondestructive inspections of bridges. That should make periodic nondestructive inspection of high-risk bridges feasible.

INTRODUCTION

Many steel bridges are difficult to inspect because of their size and inaccessability. Their conditions are worsening because of increasing numbers of overloads, trucks, age, and poor details. Consequently, a method of early detection of fatigue cracks is desperately needed.

Periodic inspection should be performed on those bridges to insure their integrity, safety, and proper functioning. Repairs should be made in a cost-effective manner (i.e., unnecessary repair or replacement should be avoided). Effective inspection techniques are important to insure that repairs are properly executed and that additional flaws are not introduced.

The primary structural NDT method for bridges is visual inspection. It is often the only economically viable method. The primary weaknesses of visual inspection are dependency upon well-trained highly motivated inspectors and the lack of accessibility of many critical structural areas. Modern NDT methods offer many improvements; however, actual bridge inspections present many impediments to those methods.

Surface methods such as dye-penetrant and magnetic-particle testing require close structural access and are operator dependent. Volumetric methods such as radiography and ultrasound may detect subsurface flaws -- they are expensive, sometimes difficult to interpret, and suffer from accessibility problems.

A major weakness of all conventional NDT methods is they basically detect geometric discontinuities. Some discontinuities may be growing flaws that could lead to failure or impaired operation; however, many indications may be benign, stable, and never cause problems. The only way to separate growing from non-growing flaws through conventional NDT is to periodically re-inspect a flaw site to sense size changes. That approach may be ineffective and expensive.

The one NDT method that responds primarily to flaw growth is acoustic emission (AE). The excellent sound conducting properties of most structural steels means that large structures may be monitored with a few fixed sensors and less expensive operator costs (in terms of inspection time and operator skill). The method also has the potential for achieving cost-effective inspection of relatively inaccessible areas.

This study was primarily intended to investigate the use of nondestructive testing as a tool to minimize bridge failures due to fatigue cracking. A number of conventional NDT methods were investigated. That work will be reported in the final report. Due to success with AE testing, the emphasis of this study was placed on AE monitoring of in-service bridges as reported herein.

One objective of this study was to derive a suitable NDT method that could be used to scan steel bridges for defects. Scanning is a low-cost application of nondestructive testing aimed at identifying and locating, but not quantifying, flaws in large structures. It is the first portion of a two-phase approach to nondestructive testing. The second phase is flaw evaluation, a nondestructive procedure used to properly size or to determine the severity of a discontinuity or flaw in a structure. The use of two-phase nondestructive testing may be applied to economic advantage on a family of large complex structures such as a state's inventory of non-redundant steel bridges.

Many forms of nondestructive testing have proven promising or useful for flaw evaluation, but very few methods are viable for the scanning phase of the inspection process. This is due to several reasons: 1) many common forms of nondestructive testing are very expensive to apply over large areas of a structure, 2) those test methods may require a large amount of surface preparation such as grinding and paint removal, 3) most common forms of conventional nondestructive testing require considerable operator expertise and care, and 4) most common NOT methods are time consuming. Periodic nondestructive testing of large steel bridges would be impractical unless an economic method of nondestructive scanning could be developed.

AE monitoring has been advocated for years as a nondestructive scanning method for in-service metal bridges. AE monitoring has several advantages over other nondestructive test methods: 1) it will only detect defects that are fatigue-related (benign geometric discontinuities are not AE emitters, minimizing concerns about false defect indications); 2) it is a good method for detecting planar defects such as growing fatigue cracks that pose the greatest threat to structural integrity; 3) the method has the best potential for low-cost field inspection since it is not labor-intensive (i.e., the method has the potential for high testing productivity); 4) defect interpretation and location may be programmed into the AE test device; 5) the use of acoustic emission does not require large-scale paint removal or other extensive surface preparation; and 6) AE testing is not greatly affected by geometric variations of a structure.

THE ACOUSTIC EMISSION PHENOMENON

In a body undergoing stress, some potential energy due to elastic deformation will be released when the body either plastically deforms or fractures. A portion of this energy will be released in the form of stress waves that propagate at the speed of sound. Those stress waves are usually referred to as acoustic emission. A commonly experienced example in the audible frequency range of this phenomenon is the noise produced by a dry stick fracturing as it is bent.

Submicroscopic and microscopic processes that occur during plastic deformation, as well as the growth of macroscopic cracks, may act as sources of acoustic emission. Solid-state metal phase transformations, such as the formation of martensite in steel, also may produce AE activity. A crack produces acoustic emission either by actually growing in size or by creating fretting noises that result from the opening and closure of mating crack faces. The plastic zone existing just in front of an advancing crack tip may be a significant AE source in some materials such as steel. Detection of fatigue-crack growth by AE monitoring in the laboratory has been reported by many researchers (1-4).

ACOUSTIC EMISSION WAVE TRANSMISSION

Acoustic emissions released from defects such as cracks may be considered to be emitted from a small localized source (Figure 1). The AE (body) wave packet released from a slowly growing crack propagates through the material as an expanding sphere. When the wave contacts a bounded surface, the wave mode changes from a body wave to a surface wave (i.e., a Raleigh wave or plate wave). Those waves expand on the bounded surface as concentric circles radiating from the epicenter of the AE source.

Surface waves may be detected by sensors (transducers) placed on the surface of the test specimen. Those sensors contain piezoelectric crystals that create an alternating voltage when vibrated by the AE waves. The voltage output from the sensor may be processed by electronic instrumentation that provides information about source events. In most cases, the magnitude and duration of the AE waves are proportional to the signal voltage amplitude and duration from the sensor. Typical defects in steel bridges emit AE activity that is too weak to be detected at audible frequencies. Therefore, most AE transducers and monitors operate in the ultrasonic region (100 to 1,000 kHz). Usually, sensors output higher signal voltages for wave stimulations at a certain wave frequency, which is termed the resonant frequency of the transducer.

Body waves may propogate through the material at a higher velocity than surface waves, but are more readily attenuated than surface waves. The velocity of surface waves in steel is approximately that of shear waves (1.3×10^5 inches per second). Due to the greater attenuation (i.e., loss of sonic energy as a wave transmits through a material) of body waves, surface waves are usually more important in AE monitoring of steel plate structures.

Only a small quantity (approximately five percent) of the energy released in crack growth is available for acoustic emissions. While measurements of that AE energy might provide insights about the source process, the AE signal is affected by 1) rate of energy release at the source, 2) properties of the material adjacent to the AE source, 3) distance of the source from the AE sensor, and 4) shape of the structural member. The resulting wave also must undergo other changes when being converted from a mechanical wave to an electrical signal at the sensor.

Considering a source of acoustic emissions as a point, waves propagate through an infinite body as a series of expanding spherical surface waves. There are several factors -- scattering, true absorption, true attenuation, and retransmission through a different material -- that weaken the sound pressure from an AE source as it propagates through the material to the AE sensor.

Scattering occurs because transmission through a body is affected by inhomogeneities in steel, such as, inclusions, pores, and grain boundaries. True absorption is loss of sonic pressure due to the conversion of mechanical energy (wave oscillations) to heat. This process is called damping. True attenuation is caused by the spherical wave spreading as it travels away from the AE source. Higher frequencies are subject to greater attenuation than lower frequencies. The wave will be reflected when a sound wave hits a boundary, when the surface is smooth. The wave will be partially reflected and partially scattered when the surface is rough. Transmission of AE waves through a coupling medium (i.e., a material which affixes the sensor to a test member) also distorts the AE source event. Both shear and transverse waves may be detected when a solid coupling such as a paste or glue is employed. When fluid couplings are used, the transmission of shear waves will be dampened.

The distance of the transducer from the epicenter of the event affects the type of wave measured. Waves arriving at the sensors usually bear good resemblance to the source event in a semi-infinite source. When the distance between an AE source and a sensor is large, the surface wave form dominates. In a bounded material such as a structural steel plate, AE waves reaching the sensors may have undergone multiple reflections, interferences, and mode conversions. AE plate waves may bear less resemblance to the wave form generated by the source and possibly more to the effects of specimen geometry.

There have been a number of attempts to relate AE source properties to AE wave forms in bounded specimens. There is some doubt about the practical application of those methods. All of the aforementioned AE wave distortions reflect the difficulties in relating the results from small laboratory test specimens to semi-infinite situations encountered in bridge structures.

SIGNAL PROCESSING

The signal voltage output from the sensor is usually in the form of a damped sinusoidally decaying alternating voltage (Figure 2). The signal may be rectified so that the negative voltage components are added to the positive voltages. That signal is called a ringdown wave. One AE excitation will generally produce one ringdown signal. Its magnitude and duration are related in part to the magnitude of the AE wave. Higher energy AE events will produce longer duration high-amplitude (voltage) AE signals from the AE sensor.

The most common means of processing AE signals are 1) ringdown counting, 2) energy analysis, 3) amplitude analysis, and 4) frequency analysis.

Counting is a technique whereby the number of times the alternating wave of a ringdown signal amplitude (the accumulative ringdown count), or its time derivative (the ringdown count rate), exceeds a predetermined threshold value. That number is recorded by the monitoring device connected to the sensor. This method has been the most common means of displaying AE results. A less common type of counting records only the number of AE events (i.e., individual ringdown signals) by eliminating the succeeding alternating ringdown waves with a time delay, preventing the following threshold exceeding signals from being counted. This method provides the least information about an AE event. It is the easiest method, especially when limited data storage capacity is available in the AE instrumentation. Standard ringdown-count data are strongly influenced by test variables including the test specimen, the signal detection threshold, and monitoring equipment variables. It is difficult to relate those data to an AE source event, especially when measuring only total ringdown counts.

Acoustic emission energy is assumed to be proportional to the integral of the square of the transducer output voltage. The commonly measured root-mean-square (RMS voltage) is closely related to energy rate or AE power. Energy is usually measured after amplification of 80 to 100 dB over a band width of about 1 MHz. It is difficult to relate measured energy to AE wave energy for several reasons. One is the uncertainty of the mode of sensor operation and the partial coverage of the source band width by the detection system. The advantage of RMS voltage counting is that it provides for continuous measurement of a parameter that may be standardized and used for comparative experiments.

For amplitude analysis, amplitudes of voltage signals from the sensor are plotted in a distribution and compared. By examining the relative number of events at various amplitudes, useful information may be obtained for distinguishing between different AE source events.

Frequency analysis has the potential to yield information on the AE source rise time and fracture type; however, the required signal processing is extremely complex. This usually is accomplished by passing the amplified wave through a transient recorder to digitize and process the wave using fourier transform routines in a small digital computer. This limits the upper bounds of frequencies analyzed to 50 MHz. Most experimental frequency analyses have been done with an upper limit of about 5 MHz. Characteristics of AE signals are then analyzed in terms of power spectra, frequency band width, and phase data.

SPATIAL AE SOURCE LOCATION AND ISOLATION

Ideally, nondestructive scanning also must be able to locate or isolate flaws. Several techniques are applicable when attempting to monitor acoustic emissions from a known source. One method uses a single channel of a multichannel system to monitor only emissions from the flaw site. The sensor of the one channel dedicated to monitoring the flaw is mounted on the test specimen adjacent to the flaw. Several sensors attached to other channels of the AE system serve as guards to acoustically isolate the channel monitoring the flaw. Sensors for those channels would be placed on the test specimen more distant from the flaw in a pattern that encloses the active sensor. Flaw-generated accoustic emissions would be expected to strike the active sensor first. If one of the guard sensors were activated first, that would indicate that the AE events detected were extraneous noise. Such signals are not analyzed since the AE system circuitry is designed to ignore AE signals from the active sensor for that time period. A second method is related to planar flaw location and will be discussed later.

Another method of AE source location involves an AE source at an unknown location between two AE sensors. The sensors are positioned at a known spacing along the test specimen. This is termed linear flaw location. A clock in the AE system is started when one sensor is struck by an AE burst. The clock is stopped when the second sensor is struck by that burst. The difference in the times of arrival of the AE wave at the two sensors may be used to locate the defect in relation to their positions. If the two AE sensors lie on a plane (steel plate surface), the loci along which all possible sources lie which have the same time of arrival difference would be a pair of hyperbolas symmetrical to the bisector of a line drawn between the two sensors (Figure 3). The hyperbola containing the AE source would be the one closest to the sensor that first received the AE event. AE activity from sources located outside the array away from either sensor will produce AE activity having unacceptable times of arrival for the array sensor spacing. That activity is easily recognized by the AE system and is rejected. Two or more guard sensors may be employed to eliminate AE sources that are not on the line between the two active sensors. If a guard sensor is struck first by AE waves from sources transverse to the active array, subsequent signals from the active sensors will not be processed by the AE system.

The two-sensor linear array may be positioned adjacent to it and any AE sources in the region may be detected and located accurately when the AE region is narrow, as in a weld or a row of fasteners. Small structural details also may be monitored with a linear array. If acoustic emission sources lie over a widely extended area, it is necessary to have at least one additional sensor to create another array. That array would be used to determine a third hyperbola. The imaginary line connecting sensors of the second array is usually normal to that of the first array. The AE source will then lie at the point created by the intersection of the two arrays of the time-of-arrival hyperbolae.

ACOUSTIC EMISSION SOURCES

The user of AE methodology faces many problems due to the environment, and complexity, and size of bridges. The uncertainty of internal defect excitation places even further limitations on the AE technique. The main disadvantage with present AE technology has been the inability to relate AE signals to specific source events.

Possible sources of detectable AE activity on steel bridges include crack initiation, crack growth, crack closure, plastic deformation, elastic deformation, loose paint and oxide fracture, rubbing noises, and electrical noises.

It is unlikely that AE monitoring would detect the initiation of fatigue cracks. Early Stage I fatigue-crack growth in steel involves microscopic low-energy processes that are probably too weak to be detected by field-type AE systems. Stage II fatigue-crack growth may be detected by AE monitoring. The material-related source of AE activity for Stage II fatigue cracks is the propagation of the plastic damage zone that precedes the tip of the growing cracks. Fatigue cracks that are of concern are fairly large and should be adequate sources of AE activity.

Crack closure is a valid AE location mechanism. Stress reversal or complete relief of tensile stresses are not required during a load cycle to provide effective crack closure. The mating faces of cracks on bridges usually corrode. The corrosion product expands and fills the crack opening. Forces acting to open and close the crack will cause the corroded crack faces to rub together, creating detectable AE noise.

Plastic deformation processes normally are not encountered on bridges except during the applications of heavy loads. Those may be encountered at specific sites on some bridges; however, it may be difficult to explain these emissions. AE events also may be expected from elastic strains; however, those may occur randomly along the stressed structural member as with most plastic-strain emissions.

Paint decohesion and surface-oxide fractures are possible sources of acoustic activity, especially when high stresses are imposed on structural members. Those activities also are likely when AE monitoring is conducted at temperature extremes. Most of this activity may be anticipated on older structures with built-up, cracked or spalled paint, and general corrosion.

Rubbing or fretting noises on bridges present the greatest problem when performing AE monitoring. Bridges have a number of mechanical-noise sources including bolt and rivet fretting, expansion-joint/vehicle wheel impacts, concrete deck-to-stringer fretting, rubbing of faying plates, and pin fretting. Mechanical noise is a drawback because areas of highest concern are at or near joints between structural members. Joints are usually the noisiest areas. It is extremely difficult to use wide-band spectrum analysis or flaw location methods at joints. Low-pass filtering and use of high-frequency transducers may eliminate low-frequency (audible) noise. High-frequency noise must be eliminated by more complex signal-processing techniques.

Electrical noise problems may severely affect the performance of an AE detection system. Electrical noises on bridges are usually related to the electrical systems of vehicles passing over the structure. Problems with electrical noise may be handled in several ways. Differential (anticoincident) transducers may eliminate some electrical noises. Electrical isolation of the transducer and signal cables from the structure is also necessary. High-pass filtration for eliminating signals having frequencies greater than 1 MHz in the main AE system is another effective step. Electrical noises tend to exist in the form of voltage spikes of short durations. Introduction of instrumentation acceptance criteria requiring valid AE signals to have a predetermined duration and/or minimum frequency (high-pass filtering) will eliminate consideration of voltage spikes.

ACOUSTIC EMISSION SENSORS AND INSTRUMENTATION

The ideal transducer would measure both horizontal and vertical displacement (for velocity) and convert those linearly into electrical signals over a band width up to 100 MHz. AE signals may be expected to be generated in steel in frequencies up to and exceeding 10 MHz. Unfortunately, most existing wide-band transducers do not have the sensitivity to measure small amplitude displacements below 1×10^{-11} meter. Some capacitative transducers exist that are displacement sensitive over a frequency range from 0 to 50 MHz. Those are less sensitive to surface displacements than the narrow-band piezoelectric transducers widely used in AE tests. Piezoelectric transducers are capable of measuring displacements in the order of 1×10^{-15} meter. Their response is over a narrow band about the resonant frequency which usually gives a response range of 50 to 1,000 kHz. That type of transducer will not cover the full spectrum of monitorable AE waves, but it is good for detecting and locating the positions of weak emission sources. Piezoelectric transducers have been employed in amplitude and energy distribution analyses; however, the transducers may only sample emissions from a small spectrum of frequencies.

Acoustic emission instruments used for structural monitoring are commonly multi-channel systems capable of linear and/or planar flaw location, source isolation, or noise rejection. Acoustic emission instrumentation ranges from simple battery-powered units to complex systems capable of monitoring many locations simultaneously. Some complex AE systems are mounted in vans.

Many structural monitoring systems are capable of detecting AE activity in the 100-500 kHz range. They usually store analog or digitized test data for record keeping or post-test processing. A few AE systems are capable of real-time defect detection and location.

Some newer AE systems use pattern-recognition data processing to distinguish between defect-related AE activity and noise. Typical parameters analyzed by the AE instrumentation include ringdown counts, AE amplitude, signal rise time, AE event rates, AE location data, AE frequency content, and external load or strain data. Usually, relevant parameters are front-end filtered or extracted in digital form and stored on floppy discs. This greatly reduces data storage requirements compared to storing recordings of raw AE signals. Some AE systems may be used to post-process digitized data. This allows selection of AE defect-activity criteria and scanning of stored digitized data to see if AE activity meeting the preselected defect criteria are satisfied.

HISTORY OF ACOUSTIC EMISSION TESTING OF STEEL BRIDGES

In 1939, a suspension bridge at Portsmouth, Ohio experienced corrosion cracking of the main cable wires at anchorage points located at each end of the bridge. Watchmen were placed in the anchor chambers where the fractures had been detected. Subsequently, they reported hearing sounds of further wire breakage on quiet nights (5). When this was reported, a decision was made to recable the bridge. That was one of the earliest documented instances of the use of the AE phenomenon in a structural application.

In 1971, AE tests were conducted on a portable military bridge being proof loaded by the British Army (6). During the proof test, one bridge girder was instrumented with seven transducers including several two-sensor linear arrays used for linear flaw location. Analysis of AE ringdown counts was conducted online during load periods, during load-maintenance periods, and during repeat tests. Subsequent data analyses yielded further information on AE amplitude distributions and source locations. AE sources were attributed to locations where plastic deformation had occurred.

In 1972, Dunegan/Endevco Corp performed AE tests on eight cables of the Dunbarton lift bridge near San Francisco, California (7). The old bridge showed wear on the cables and connectors. To prevent high sound attenuation, radiator hose clamps were placed around the wire ropes to consolidate the strands. The 150-kHz transducers used in the test were coupled to the radiator clamps. The cables were proof loaded by providing a transverse load with a hand winch. The load was applied and held for 10 minutes. Transducers also were placed on wire-rope connectors for a continuous 24-hour monitoring period.

Several cables showed more continuous AE activity than others. The AE proof-load test did not indicate signs of serious deterioration. Additional cable repairs were not recommended since the bridge was to be demolished in a few years.

KTRP personnel performed an AE monitoring test on a continuous eyebar truss bridge in 1973 (8). A single-channel AE device was used for that study. The test was conducted using a 140-kHz resonant transducer having a system gain of 80 dB. The test revealed that mechanical noise was a serious problem for AE testing of bridges. Also, the test indicated there was good sound transmission between pinned eyebars.

The next notable AE testing on steel bridges was performed by Battelle Northwest for the Federal Highway Administration. It consisted of developing and demonstrating an AE system for inspection of in-service bridges. Initially, work was directed toward determining the acoustic spectrum of bridges and developing an AE system for centralized AE signature analyses (9, 10).

After initial AE tests on three bridges in the Washington state area, plans for development of a centralized AE signature analysis were abandoned and Battelle concentrated on developing a small field-portable AE-flaw monitor. The new system was battery powered and was capable of untended AE monitoring for an extended time in the field. It contained erasable programmable read-only memory (EPROM) chips on which AE field data were recorded. The chips could be removed and taken to a laboratory. There, they could be read and subsequently erased for reuse. The portable, self-contained AE system possessed a three-transducer, two linear-array flaw isolation system. It used adjustable time-accept limits for each linear array to define a set of hyperbolas. AE data outside the set of hyperbolas were rejected. Only data that met the time of arrival of the two hyperbola sets were accepted. That created an accept zone determined by the area bounded by the overlapping hyperbola.

The revised portable AE device was tested on floor beams of several bridges in the Washington state area and also on shop welds at a fabrication plant.

Field tests on bridges revealed that data inside the accept zone of the portable Battelle AE system ranged from 0.5 to 3 percent of the total acoustic emissions generated and detected. The Battelle test identified several sites on bridges that were more acoustically active and produced more valid data than on other bridges.

From August 1980 to July 1982, KTRP investigators conducted AE tests on the I-471 bridge over the Ohio River in Newport, Kentucky, using the Battelle device to monitor a tie-chord butt weld that contained an indication of ultrasonic defect (Figure 4). The unit was stored in the tie-chord box and the EPROM's were replaced and read on regular intervals over a 1-1/2 year period.

Those tests indicated that high amounts of AE activity could be detected during peak traffic hours over the bridge. Rainfall also produced high amounts of AE activity. Comparative AE tests between the test area and a similar weld location containing no ultrasonic indications of flaws proved inconclusive.

From March 1982 to January 1983, the West Virginia Department of Highways (WVDOH) monitored AE activity on the I-64 Dunbar Bridge over the Kanahwa River near Charleston, West Virginia (11). The Dunegan Corporation placed an AE system on a pier under the bridge. Eight weld locations that contained subsurface ultrasonic defect indications were instrumented and monitored. Resulting data were transmitted to WVDOH offices by telephone and placed on a digital tape. Planar source location was subsequently performed by Dunegan using copies of the data tapes.

Transducer arrays employed in those tests were of interest. Special angle-beam, 500-kHz resonant transducers developed by Dunegan were placed along weld lines. Those transducers were 20 dB more sensitive to signals from AE activity travelling along the angle beam (weld line) than from sources approaching from the sides. Conventional guard transducers were placed offset of the midpoints of the weld lines. The transducers were cemented to the steel girders.

The planar flaw-location system required at least three transducers to be struck for an AE event to be considered valid. One array produced 12,560 such events. This was almost 1,000 times greater than the least active array (14 valid planar events) and about 10 times more active than the second most active location (1,461 valid planar events).

During the period between 1982 and 1984, United Technologies Corporation developed a broad-banded piezoelectric transducer for the Federal Highway Administration (12). The transducer was of the point-contact type with a conical piezoelectric element. Laboratory tests indicated the transducers had flat, continuous wave response between 100 kHz and 1 MHz. The transducer was intended for use with broad-band instrumentation and signal processing to provide signal characterization as a means of differentiating between noise and AE activity from cracks on steel bridges.

INSPECTING STEEL BRIDGES WITH THE ACOUSTIC EMISSION WELD MONITOR

Many attempts have been made to apply AE monitoring to in-service inspection of various major structure types including aircraft, nuclear reactors, and highway bridges. Until recently, very little success had been achieved. The primary reason for that poor record has been a failure to deal with the overwhelming problems of background noise. The inability to separate significant (flaw-related) AE from mimicking, unrelated, irrelevant AE background noise has severely hindered acceptance of the method. A typical detail such as a bolted splice between a floor beam and the girder of a tied-arch bridge may produce 1,000 AE events per hour under moderate traffic. A double-cantilevered box-beam pier cap supporting a portion of a heavily travelled interstate highway having high-density traffic may produce over 15,000 AE events per hour.

The task of manually examining and sifting through massive volumes of AE data typically produced from bridge monitoring would be an impossible task.

From both the technical and economic standpoints, such an approach would be far more impractical than bridge inspection methods presently in use.

Elimination of background noise requires a sophisticated AE-signal processing approach. Early attempts to use a single AE-signal parameter (single-stage filter) such as AE-signal amplitude or energy to filter and look for clusters or groups of events at a given location did not work. Other approaches involved use of source location to isolate acceptance zones to the area of interest. This approach proved unsuccessful because the locational resolution limits imposed by practical operational constraints did not allow an AE system to clearly separate regions of potential crack growth from adjacent bolt and rivet holes which are significant noise sources. The successful, practical AE system for in-service bridge inspections must be considerably more effective in eliminating background noise than the single-stage filtering approaches.

PATTERN-RECOGNITION NOISE DISCRIMINATION

To allow crack-growth related sources to be separated from the overwhelming number of irrelevant background events, attempts must be made to determine a menu of source characteristics that separate the flaw growth from the background noise. To be practical for in-service bridge inspection as a flaw detector and locator, the AE system must be capable of using sensor spacings of at least the order of magnitude of typical bridge connections (i.e., from 1 foot to 10 feet). The event-based approach to signal processing coupled with narrow-band high-sensitivity transducers has proven effective in a number of applications, including in-service bridge inspection.

A method to intelligently choose the key event features for comparison is desired. The selection method should be one that provides a very high probability that the chosen events are either crack-growth related or at least generated by some feature of a crack. The properties of such a selector or filter may be deduced by simply considering some characteristics of a crack and how they may relate to acoustic emission. Rejection of events by a filter may be increased by chaining or cascading tests.

The first filter element relies on the fact that a crack is a relatively localized phenomenon. Thus, all crack-related AE signals should come from a single source or from a narrow band of sources.

Source location is not a sufficient filter for crack-related activity. Attempts to detect cracks growing in welds or in fastener holes by plotting the number of AE events versus location usually fail to indicate the crack. The problem is that other sources such as slag popping in a weld or fastener fretting in a structure may produce just as many AE events (and probably more) over long periods than a slowly growing fatigue crack.

An excellent example of the inability of source location/ringdown counting to eliminate noise is readily apparent in a recent study. In that effort performed over a 1-year period on several electroslag welds in a major highway bridge, directional sensors and guards were employed to aid in isolating monitored areas. Locationally filtered data showed large accumulations of events at several sites which gave no clear vertification of the ultrasonically detected weld discontinuities. The only supportable conclusion from that effort was that some similar locations have higher noise backgrounds than others.

The second key element in the crack filter is the rate of occurrence of AE events. It has been determined experimentally that cracks, whether they are propagating or simply opening and closing, will tend to produce AE events at high rates. Those rates usually greatly exceed those produced by any competing source. This phenomenon may be due to the crack front advancing in a series of short rapid jumps between small imperfections that act as crack arresters. Also, that could be the effect of many small pits and valleys in the crack face making and breaking contact due to relative motion of the crack faces as the crack opens or closes, or could be multiple microcrack formation and growth in the plastic zone.

To be an effective filter, a third element is required. It is necessary to establish a reasonable detection threshold or lower-energy limit. In general, both the number and rate of AE events in a test tend to increase for decreasing event energy. Part of this may be due to thousands of microscopic events occurring in a particular experiment or simply to the effects of electronic noise. In any case, if one looks at smaller (lower-energy) AE events by continually increasing the sensitivity of the monitoring system (i.e., by raising the signal amplification), eventually a situation is reached where only continuous emission is detected. This threshold may be based on a ringdown-count (RDC) limit, since ringdown counts are related to event energy. Together, the above three elements provide a complete three-part filter that should select crack-related AE events. Events emanating from a crack should have a higher probability of passing this filter than events that are not crack related.

The GARD Division of Chamberlain Manufacturing Company of Niles, Illinois, has developed and patented such a three-element computer-based filter and software. In real time, it requires AE events to first pass a ringdown-count limit test, followed by a maximum rate of occurrence test, and finally a locational proximity test that requires all events passing the first two tests to originate from the same location. The algorithm assumes that crack-growth related AE events will have some parameters that tend to separate them from other types of sources. A group of AE events must pass each test in succession to indicate crack-growth detection. The basic assumption in this empirically derived algorithm is that crack-related AE will possess a high rate of occurrence from a well defined location. The use of upper and lower ringdown-count windows provides additional immunity to large mechanically induced noises (such as bolt fretting) and low-level noises that achieve occurrence rates approaching those of cracks.

While the justification for this algorithm may not be completely explained in a theoretical manner, it has been shown to work effectively in a large range of cases.

The algorithm was developed and proven effective on over 20,000 linear feet of in-process weld monitoring. The same algorithm allowed detection of slow-growing fatigue cracks on highway bridges under normal traffic loading conditions. Those successes were achieved even though the subject cracks were immediately adjacent to rows of bolt holes, splices, and cover plates. Results of a laboratory experiment performed on a small rivited box beam undergoing cyclic fatigue loading indicated the GARD algorithm allowed a fatigue crack to be detected as it grew out of a fastener hole even though many other fasteners were creating considerable background AE noises. In that test, over 99 percent of the AE activity generated was rejected by the algorithm.

ACOUSTIC EMISSION WELD MONITOR FUNCTION

The algorithm has been incorporated into a microprocessor-based AE system known as the GARD Acoustic Emission Weld Monitor (AEWM). That device uses conventional analog electronics to acquire and process AE activity (Figure 5). That includes the use of analog signal amplification and band-pass filtering of signals from standard resonant transducers. Also, conventional time-of-arrival linear flaw location is employed using two active transducers. The unique portion of the AEWM is its microprocessor-based multi-parametric filtering program previously discussed. The program analyzes the AE data, rejects noise-related activity, and locates and characterizes flaws in real time.

Consecutive AE events are subjected to the three-step sequential test or AE pattern-recognition filtering program (Figure 6). First, the analog circuitry computes the ringdown count and time of arrival. Then, the microprocessor portion of the system tests the collected analog information for each event. As the first step in the filtering program, the ringdown count must lie within fixed limits. When this is satisfied, the second filtering step is imposed wherein the AE event must occur within a predetermined minimum event rate with other AE events preceding or following it (which also have passed the ringdown test). A third step determines whether all the events passing the first two filtering tests were located by time of arrival from within a tight locational tolerance (plus or minus 1 inch). AE event data that fail to pass any one of the tests are discarded. Additionally, the frequency content of each AE event is analyzed using a comb filter. Valid AE events having high-frequency biases are classified as cracks. Other data that satisfy the model are characterized by the AEWM as unclassified defects.

The AEWM can continuously process large numbers of AE events occurring at rates too fast for an operator to analyze. The microprocessor circuitry also determines when valid flaw activity occurs. The operator is informed of flaw-related events in real time by an indicating lamp on the AEWM and by a LED panel, which displays the relative location of the flaw between the two active transducers. The unit also is capable of data storage on floppy disks and direct hard-copy output subsequent to a test.

To conduct AE monitoring, two resonant-frequency transducers are affixed to the test specimen bracketing the feature of interest such as a weld line. Transducers are wired to preamplifiers, which in turn are connected by coaxial cables to analog signal-processing modules mounted in the AEWM. The transducers are affixed to the test specimen by magnets. A lubricant is used to acoustically couple transducers to the test specimen.

The AEWM usually is operated in the stand-alone mode. Push-button controls on the face of the device are used to input transducer spacing (for flaw location) and to control the AEWM operation. The stand-alone operation requires that the AEWM operator adjust the system gain (signal amplification) on the two active analog modules of the device and prepare the microprocessors to accept and process AE activity. The calibrated signal amplification (i.e., gain) adjustment is provided by switches on the faces of the AEWM analog modules. The gain on each of the two active transducers/preamplifier/analog monitor channels is set independently to accommodate for variations in component response and in transducer to test piece coupling efficiency. The gain or signal amplification is based on previous experimental results. Programming and preparation of the system microprocessors requires the AEWM operator to conduct a four-step operation, performed by sequentially suppressing three or four push buttons mounted on the face of the AEWM in each of the steps.

Once the gain is properly set, it does not need to be readjusted until monitoring is completed and the transducers are moved to another test site.

Likewise, most of the microprocessor preprogramming does not need to be repeated until the test is completed.

A video terminal may be used to visually display test results and operational sequence. The system gain is set between 60 and 80 dB, depending on transducer spacing on the test specimen. During the course of this work, it took 10 to 20 minutes to place the transducers and prepare the AEWM to monitor in the stand-alone mode.

To insure proper functioning of the AEWM, the operator observes the calibration indicating lights on the face of the AEWM analog modules. The lowest red lights on the face of the analog front panels indicate that low-level AE activity is being received. The upper red light indicates that the high-level AE activity is being received. The intermediate green light indicates that AE activity of defect-level intensity is being detected.

During bridge monitoring, all three of the indicating lights on the analog module will normally flicker intermittently as a result of AE activity generated by normal traffic or proof loads on the bridge.

If for some reason one analog module does not function or is not receiving a signal from a transducer, the indicating lights on the module will not function. If signal amplification set on the face of the analog modules is too low, no intermediate or high-level AE activity will be shown by the indicating lamps. If amplification is too high, the upper limit indicating light will be the only one that flashes.

The presence of flaw-related AE activity is denoted by a red indicating lamp located on the front panel of the AEWM. The light is activated when the AEWM operator initiates the monitoring process. If the lamp extinguishes during monitoring, the AEWM has detected AE flaw activity. The face of the AEWM panel also contains a 16-character alphanumeric LED display lamp. When flaws are detected during thesting, their number and approximate location will be shown on the LED display. The operator may interrogate the AEWM using push buttons on the face of the panel to determine whether the flaw is crack related or unclassified. A post-monitoring display on the video terminal shows the transducer spacing and the location of any flaw activity between the transducers within a 1-inch tolerance (Figure 7).

In the data-recording mode of operation, the AEWM may store AE test data on a floppy disk. Data may be recalled and manipulated using a number of processing programs contained in the AEWM microprocessor memory. The operator may reprocess the prerecorded data to 1) change the flaw models used by the AEWM, 2) reprocess weld data using revised flaw models, 3) simulate changes in signal gain, 4) analyze AE activity from specific locations, and 5) perform various statistical analyses. Also, a serial printer may be used to obtain hard-copy printouts of flaw indications, file dumps (display of raw recorded data), and data manipulations.

Operating the AEWM using the data-recording mode is more complex than the stand-alone operation. Ten commands ranging from three to 16 characters must be entered using the video terminal keyboard. Use of floppy disks requires constant operator attention to several switches and indicating lamps.

FIELD TESTS WITH THE AEWM

Field tests were conducted to determine the suitability of the AEWM for inspecting bridges. Initial tests were conducted under an earlier study. GARD performed AE tests on two bridges for the Wisconsin Department of Transportation. The Kentucky Transportation Research Program performed AE tests on the I-310 cable-stayed bridge at Luling, Louisiana, under contract with the Louisiana Department of Transportation. The entire series of tests is included in this report to summarize test efforts with the AEWM.

INITIAL AEWM BRIDGE TEST

The first test using the AEWM was on the I 24 twin-arch structure over the Tennessee River near Paducah, Kentucky. The test was performed by KTRP and GARD personnel in December 1982. That work was done under study KYP-79-94, "Special Problems of Metal Bridges".

The Kentucky Transportation Cabinet had previously detected out-of-plane bending cracks on those structures near the end connections of floor beams. Cracks were present in the vicinity of coped flanges where the floor beams were framed into the tie chords. That type of cracking is caused by design problems and is somewhat generic for tied-arch bridges. The cracks were fatigue-related and not due to fabrication defects.

Several crack sites were located in the end floor beams over the piers during an inspection performed just prior to the AE monitoring tests. Cracks were present at the termini of the upper flanges usually at the toes of the web-to-flange fillet weld. A typical crack is shown in Figure 8. Surface rust highlighted the cracks, in some cases.

Crack sites chosen for AE testing were located near bolted angle-splice plates that connected the floor beams to tie-chord girders. It was assumed those locations would be difficult to monitor because of the large amounts of fretting noise resulting from the bolted connections. That assumption was confirmed during the tests. Typically, over 1,000 AE events occurred per hour. All of that activity was associated with the passage of traffic over the portion of the bridge being tested.

Two sensors were mounted in a linear array 64 inches apart along the edge of the angle splice plate that connected the floor beam to the tie girder (Figure 9). They were acoustically coupled to the floor-beam web. The upper flange (which is the side of the crack) was located about 16 inches below the upper-mounted AE sensor. A third sensor was attached as near as practical to the crack. That third sensor was driven by a high-powered pulser and was periodically pulsed, injecting a simulated AE burst into the web to check the AE system's performance. Coaxial signal cables were placed across the pier and up to the bridge deck where the AE equipment was mounted in a motor home that acted as a mobile laboratory. Figure 10 shows the vehicle parked on the curb lane of the bridge.

Five locations were monitored during a 3-day period. Three of those locations had visible cracks. One location produced AE indications. Those indications were repeated on two consecutive days and were located in the known crack site.

The first two locations tested were over the west pier on the eastbound span. The first test area had a 1-1/2 inch long crack at the flange termination. Considerable AE activity was detected during the 2-hour test. The activity occurred in conjunction with traffic and the highest amounts of AE activity correlated with semi-trailer traffic. None of the resulting activity produced any valid AE indications. This test constituted monitoring a small crack under normal, but fairly infrequent, loading conditions. The sensors were moved after two hours to the passing lane side of the bridge in an attempt to get higher loading on a flaw. Because of the presence of the motor home in the curb lane, most of the traffic shifted to the passing lane and the loading over that end of the floor beam was greater. This location had two 1-inch cracks visible in a location similar to the first. No valid indications resulted during a 2-hour test at that site. A relaxation of flaw-detection criteria by lowering the activity rate from four to two events per second produced some clustering of AE activity from the crack site along with some widely scattered background activity during a post-test playback of the data.

The next site tested was located on the downstream side of the westbound span (under the passing lane). This was the most severe crack site tested. There was a 2-inch long crack at the toe of the web-to-flange fillet weld in addition to a second crack about 3 inches long eminating from under the angle splice plate directly above the same region. That flaw was subjected to greater AE excitation than the other lane since it experienced more truck traffic during the test. Figure 11 shows results of two separate tests performed at this site during two successive days. Each test was 2-1/2 hours in duration. The model used for flaw detection had the following limits: ring-down count -- 16 to 4,000, rate -- four events in 1 second, location -- 1 inch tolerance.

The total number of AE events received is shown in the upper right-hand corner of the printout. Totals were 2,130 AE events for the first 2-1/2 hour monitoring period and 818 AE events for the second period. The difference reflects the relative amounts of traffic for the monitoring periods. The AEWM display prints sets of rectangular brackets to represent the two sensor positions with Channel 1 at the left and Channel 2 at the right. Flaw indications are shown at any location where the detection criteria are met. The edge of the angle splice runs along the line between the two sensors. The character, C, 0, in the upper display indicates that at this location the flaw-detection criteria were satisfied. The characterization model decided the AE activity was crack related. The 0 following the comma is the truncated average of ringdown counts for the four or more events that satisfied the detection model. In this case, 0 signifies the average ringdown count was between 0 and 99. Additional groups of events that satisfied the model are represented below the C, 0. Time of occurrence proceeds in a downward direction. The S: indication is produced by the calibration pulser located adjacent to the bottom edge of the flange. The cracks extended around the end of the flange and above the end of the flange toward the angle splice plate. The S, 3 indication occurs at the end of the flange (S signifies non-crack related). One additional S indication occurs near the midpoint of the monitoring region. No flaw was detected in that region. It was later determined that the indication was noise related (as will be explained).

The lower display was the result of another 2-1/2 hour monitoring period during the day. There was considerably less traffic during that period which is reflected in the lower AE event count (818). One indication S, 3 occurs from the lower edge region of the flange. The photograph below the printout shows the sensors in place. The actual orientation was vertical. The picture was rotated 90 degrees counterclockwise to place the significant features in approximately the same orientation as the printouts.

The sensors were positioned on an adjacent plate having the same fasterner pattern, but no flaws to further test the reliability of the AEWM to discriminate between fastener noise and crack-related AE activity. A 2-1/2 hour monitoring period at this site produced 700 AE events and no flaw indications. The final site tested contained a filet weld having a longitudinal 4-inch long crack (Location 4). That crack was evidently a product of the fabrication shop and produced no AE activity since no crack growth was occurring.

All tests were performed in the AEWM data-recording mode. The data were stored on floppy disks and taken to the GARD laboratory for subsequent replay and analysis. Field data from one test where the AEWM detected a flaw were replayed several times through an oscilloscope with the AE sources (i.e., from cracks and noise-generating details as determined by the AEWM linear array) from the bridge displayed as light points acting along the abcissa as they would along the linear sensor array (Figure 12). Each component of the AEWM three-step model was inactivated successively. Those replays revealed additional AE indications running along the bolt line between the active transducers. Those new indications were false (i.e., background noise) and masked AE activity from the crack. This shows that the three-step model is valid and necessary to identify AE indications from cracks in high mechanical-noise environments such as bolted or riveted joints.

The AEWM test indicated the unit was able to detect fatigue crack growth successfully on a bridge. That test generated interest for further evaluation of the AEWM and the AE phenomenon on bridges.

AEWM BRIDGE TESTS CONDUCTED DURING THIS STUDY

I 24 Bridge over the Tennessee River

In September, 1983 KTRP acquired an AEWM on loan from GARD to perform field tests on bridges. The unit was used to retest the I-24 twin structures over the Tennessee River. That selection was due, in part, to the presence of stable growing cracks which could be monitored occasionally over an extended time period. Sufficient traffic was present to anticipate detecting several valid AE events per day from the most active location (on the eastmost floor beam of the westbound structure).

Four follow-up AE tests were conducted on the bridge during a 13-month period beginning in October 1983. Tests revealed a diminished amount of valid AE activity with time. The crack-growth rate was measured and determined to have decreased with time. The last test, conducted in November 1984, included a 48-hour continuous monitoring of the worst crack sites; no valid AE flaw activity was identified. Out-of-plane bending cracks at those locations are typically auto-extinguishing. Crack-growth measurements and the follow-up AE monitoring support that conclusion.

An attempt was made to monitor the bridge from a point 1,000 feet from the actual defect site. The equipment vehicle was located off the approach span in the median between the two bridges. The cable was placed along the edge of the curb lane and lowered to the pier to the test site. The small coaxial cable (RG 174) used in that test was not adequate due to high electrical resistance. Field tests using larger coaxial cable (RG 58) have not been attempted. A laboratory test using a 1,000-foot run of the larger cable indicated it would function satisfactorily. Another test revealed that steel-plate members are very good conductors of sound. Testing at floor-beam locations indicated that sound waves from fretting noise generated at one end of a floor beam could easily travel 20 to 30 feet across the floor beam and strike a transducer array mounted at the other end with very little reduction in the strength of the sound waves by attenuation.

I 75 Bridge over the Ohio River

The second bridge monitored was the I 75 bridge over the Ohio River at Covington, Kentucky. The areas of interest on that bridge were welded cover plates on the lower flanges of longitudinal stringers in the northbound approach span on the Kentucky bank. The cover plates were welded on the lower flanges of rolled beams to increase their load-carrying capacity. Welded cover plate termini have a history of being fatigue-prone. Previous strain-gage tests of those sites conducted by KTRP personnel measured stress ranges in excess of AASHTO recommended limits. Painters had discovered cracked paint along the toes of the cover-plate termini fillet welds prompting the AE inspection. It was decided to evaluate cover-plate termini with AE monitoring. Figure 13 shows the sensor array in place on the bottom face of the lower flange of a girder. Three sensors are visible in the figure, the two active sensors of the linear array are located on either side of the inspection detail. The center sensor, located at the termination of the cover plate, was used as a pulser to provide AE-system integrity checks.

The cover-plate terminations appeared to be ideal for AE testing, since there were no bolted connections near the monitored area. Flaw indications were detected by the AEWM located at the midpoint of the linear array within the first 15 minutes of monitoring with the AEWM. Shifting the array sensors 18 inches offset along the bottom flange of the girders produced the same results (i.e., the AEWM flaw indications were centered again at the midpoint of the transducer array).

The AE indications were assumed to be false since the indications remained at a constant location in reference to the positions of the sensors rather than to the fixed physical location of the cover plate termination and since there were no visible AE sources in the monitored structure at the midpoint of either array. The source of the signals was suspicioned to be fretting noise between the concrete deck and upper flange of the stringers. If the sensors were located on the upper flange, the fretting noise would have been rejected by the rate/location test in the AEWM software filter because the AE event rate from any one location would be below the acceptance level for flaw indications. However, with the array on the lower flange, AE sources (fretting noise) located on the upper flange could be mapped improperly by the array.

A simple solution to the problem was the addition of two guard sensors located closer to the interfering sources than to the active array as shown in Figure 14. The guard sensors and one extra software test in the signal processing program eliminated false AE indications. The additional software test looks at the order of receipt of the AE activity from the sensors. If the guard sensor receives the signal first, the source is closer to the guard sensor and the event is rejected. Those modifications were made and tested at 12 locations on the I 75 bridge. False AE indications were eliminated. No other AE indications were detected and subsequent dye-penetrant tests of selected sites revealed no defects. No repairs were recommended and it was decided to periodically reinspect selected cover-plate terminations.

The use of the linear location array having guard channels was subsequently employed on the I 24 Tennessee River bridge in one of the later tests on that structure.

I-24 Bridge over the Ohio River

KTRP personnel subsequently performed AE monitoring tests (in conjunction with GARD) on the I 24 Ohio River bridge near Paducah, Kentucky. A total of three sites were monitored. Two sites were butt welds in the tie girders of the arch on the Kentucky side (Figure 15). The welds in the tie girder had produced ultrasonic defect indications, but there were no visible cracks. The welds had been retrofitted with bolted cover plates since the tie girders were fracture-critical members. One site produced four AE crack indications over approximately four hours of monitoring. The sources were located in the areas where ultrasonic defect indications were detected. The other test site did not produce AE indications. Figure 16 shows the AEWM printout of this test.

The third site was a floor-beam stiffener in the arch. It had a visible crack due to out-of-plane bending. A check hole had been drilled through the member to stop the crack, but it reinitiated and continued to grow at least 2-1/2 inches beyond the hole for a total overall length of about 5 inches. This site produced the highest AE flaw-indication rate observed on any bridge. Typically, one or two flaw indications from the crack were detected every 15 to 20 minutes during the monitoring period. The AE indications corresponded to the passage of heavily loaded trucks over the bridge. That compared to the rate of one indication every 2 hours on the I 24 Tennessee River bridge for a similar crack.

I 471 Bridge over the Ohio River

In June 1985, KTRP investigators conducted AE monitoring tests on the tie chords of the I 471 twin tied-arch bridges at Newport, Kentucky. Those were large bridges having 720-foot clear main spans. The bridges contained plate-thickness transition butt welds in the tie chords similar to those on the I 24 Ohio River bridge at Paducah. A new AE monitoring technique was employed. Instead of monitoring flange or web welds individually, the continuous weld lines around the peripheries of the tie chords were monitored using an active 42-inch transducer array spacing (Figure 17). The flange and web splice welds were offset from each other by approximately 14 inches. The transducers were located halfway between an imaginary line equally spaced between the two weld lines. The array locational accuracy was measured in a series of tests by injecting sound into both web and flange areas. The location of those test pulses was determined in relation to the position of the two sensors mounted on the tie chord. Calibration tests were performed using a portable AE pulser (Figure 18). Tests revealed that very little locational error resulted due to the offset of the transducers in respect to the web or flange weld lines.

Tests on the I 471 bridge were conducted during a 3-day period. No defect indications were detected. The tests revealed that the peripheral AE test method worked satisfactorily. Low AE rates were encountered at the tie-chord welds (typically 50-100 events per hour) despite heavy traffic.

US 25 Bridge over the Rockcastle River

The fifth bridge inspected was the US 25 bridge over the Rockcastle River, near Corbin, Kentucky. It was a riveted twin-girder structure. No defects were anticipated on the bridge. The linear sensor array was placed on the web adjacent to the lower flange of the girder. A 44-inch transducer spacing was employed (Figure 19). Traffic on the bridge was sparse. Trucks using the bridge were predominantly empty coal trucks. Truck traffic over the bridge produced multiple AE events for each passage of a vehicle. The AEWM rejected those events as being noise-related. The AEWM flaw-detection model proved capable of dealing with fretting noise from mechanical fasteners.

I 64 Bridge over the Ohio River

The sixth structure tested under this study was the I 64 bridge over the Ohio River at Louisville, Kentucky. Cracks had been detected in stringers where flanges had been coped to allow the stringers to be framed into floor beams. A transducer array of 18 inches was placed on the web of a stringer that had the largest crack (Figure 20). The tip of the crack was positioned between the two active sensors of the linear array. Guard sensors were not used. That location was monitored for 4 hours. No AE flaws were detected. The stringer was heavily loaded by westbound traffic on the top deck of the structure. During that period, some 2,000 noise events were detected.

Cracks had been visually monitored for several years, with no sign of significant crack growth. Either the crack that was monitored was benign or its growth was too intermittent for the AE monitoring period provided or the crack growth per load cycle was too small to be detected.

I 94 AEWM BRIDGE TESTS PERFORMED UNDER CONTRACT

I 94 Overpass in Milwakee

In November 1984, GARD contracted with the Wisconsin Department of Transportation (WiDOT) to test the support structure of the southbound I 94 overpass near the Holt Exit in south Milwaukee. The structure was a double-cantilever box beam extending outward from a center pier. That portion of I 94 is elevated over a railroad yard and there are several similar structures in the vicinity. Figure 21 shows an overall view of the area and the vehicle that housed the AEWM.

Previous visual and ultrasonic inspection by WiDOT confirmed the presence of several transverse cracks in flange-to-web welds. Cracks appeared to be weld related (probably hydrogen-induced cold cracks). Cracks in the upper or tension welds generally appeared to be larger than cracks in compression areas. WiDOT inspectors were concerned that cracks were growing under fatigue loadings.

GARD monitored a 7-foot long upper web-to-flange weld for two days. The test weld was terminated in vertical bolted splices. The concrete bridge deck also rested on the upper flange. Both of those details provided very high background AE noise. A total of six AE sensors were used with the AEWM. The array used two active and four guard sensors. Figure 22 shows one end of the array. The top sensor was active and the bottom one was a guard.

The test weld had two visible cracks. During the 2-day monitoring period, one AE indication was detected from the larger crack. The test location was a very active AE site. Typical event rates averaged over 3,000 events in a 20-minute period and no false indications were triggered. It was concluded that the larger crack was growing by fatigue quite slowly.

A reproduction of the AEWM printout from that test is shown in Figure 23. The AE source was located 60 inches from the Number 1 sensor and is the site of the larger of the two cracks.

US 18 Bridge over the Mississippi River

GARD also tested the US 18 bridge over the Mississippi River near Prairie du Chien, Wisconsin under contract to WiDOT. Those tests were requested to evaluate existing flaws in a structure. Third-party AWS-Code ultrasonic testing had detected several code-rejectable subsurface indications in electroslag welds on both the upper and lower flanges of fracture-critical girders. GARD personnel monitored two of the larger indications over a 2-day period and detected no valid AE activity at either site. Due to the low traffic volumes on the bridge, low AE background rates were encountered (100 to 200 events per hour).

I 310 Bridge over the Mississippi River

The last AE test with the AEWM to date was conducted by KTRP investigators under contract to the Louisiana Department of Transportation. The test was performed on the I 310 cable-stayed bridge over the Mississippi River at Luling, Louisiana in November 1986. A preliminary visual examination was performed on portions of the bridge containing cracks. Those cracks emanated from small transverse box girders that pierced the larger longitudinal trapezoidal boxes of the main span. Transverse boxes were used to mount the stay cables and to support the deck (Figure 24).

The pierced-box detail had resulted in some initial cracks that were detected at the time of construction. A question was posed as to whether further crack growth had occurred during service. The bridge was both strain gaged and AE monitored. The strain gaging was performed by personnel from Lehigh University. Monitoring was begun in Box A under the southbound lanes of the bridge at the fourth stay-cable cross girder on the main span near the south tower of the structure. The first test site was at Web 2. That web contained the largest known crack which had been capped by a check hole about 3 inches in diameter (Figure 25). The crack ran up the box web from under a splice plate between the check hole and a crescent-shaped detail in the web. It was estimated to be about 14 inches long. The AEWM was initially used to determine whether any new cracks were being created about the upper periphery of the check hole.

The AEWM was housed in a car parked in the curb lane adjacent to the cross girder. Coaxial cables used to connect the AEWM to the remote sensors were placed through an opening at deck level in the main span wind screen and then through the cross girder to the trapezoidal box at an opening near the test site.

The two transducers of the linear array were placed 18 inches apart. The linear array had to be positioned so that any valid AE activity would emanate from the upper side of the check hole and not from the crack that terminated at the lower portion of the hole. Once the array was properly located and calibrated using a portable ultrasonic pulser, it was set to monitor the crack area with a system gain of about 70 dB.

Inspection personnel waited for suitable truck traffic to activate any potential crack in the upper surface of the hole and create crack-related AE activity. A few heavy trucks passed over the southbound lanes. The AE indicating lights on the analog panels of the AEWM revealed that very few AE signals of any type were being produced by trucks. That corresponded to low strains measured by Lehigh personnel monitoring strain gages mounted adjacent to the hole at the same location.

No AEWM flaw indications and very little AE signal activity was observed during 3 hours of continuous monitoring. Very low strains were detected by the Lehigh personnel. Louisiana highway personnel drove two 80,000-pound, HS20-type trucks over the bridge, once in each lane. Those trucks did not produce any AE flaw indications.

The two HS20-type vehicles were driven over the bridge together the second day of testing. The trucks first transversed the bridge abreast on the southbound lanes. The test was repeated in the northbound lanes. The tests were repeated with the trucks in tandem (Figure 26).

The loading produced a small amount of AE signal activity, but did not trip the AEWM flaw-detection system in each proof test of the southbound lanes. Past experience indicated high crack-related AE activity depended not only on heavy vehicle weights, but also upon high vehicle speeds. Trucks were unable to achieve speeds approaching the posted limit due to the steep grades at both ends of the bridge. The truck loads on the northbound lanes over Box B produced less activity than the southbound test since AE monitoring was being conducted in Box A. It would be expected that loads in the opposite box would produce lower AE activity even though the boxes were tied together through the deck and the cross boxes.

The test sensors were moved after ten proof loadings of the bridge. During 8 hours of AE monitoring at that location, not only had no AE crack activity been detected, but the test site was the most acoustically inactive KTRP personnel had ever monitored on a bridge. The sporadic, weak AE signal activity may be explained by the low strains recorded throughout the bridge loading tests.

The AE sensors were moved to the second location on the other side of the cross girder. The new test site was at the end of a horizontal stiffener where two check holes had been placed to stop a similar crack. The crack had not completely penetrated the web.

The two-sensor linear array was placed horizontally at a spacing of 36 inches (Figure 27). The array was separated by a vertical stiffener welded to the web. Eight heavy truck proof tests of the northbound and southbound lanes were monitored. There were no AE crack indications and very little detectable AE activity. Acoustic emission signal activity was slightly weaker from the AE sensor mounted away from the hole. The stiffener was located in the sound path between the hole and one sensor. That indicated a problem with sound transmission across the stiffener and the need to relocate the array.

The array was relocated with both AE sensors adjacent to the hole and without any intervening stiffener. The new array performed satisfactorily as verified by tapping the check-hole sidewall with a screwdriver and subsequently checking the AEWM for location of mechanically induced indications. An array spacing of 32 inches was used. The location was monitored for a period of about 5 hours over a 2-day period. None of the proof-type loads were imposed on the following day.

The AE monitor was shifted to a location on the outside web of the northbound trapezoidal box on the last day of tests. A crack which terminated at a check hole cut in the web was present. The crack had penetrated about 1-1/2 inches through the 2-1/2 inch thick web. That location was monitored to determine if AE activity could be detected in the uncracked portion of the ligament similar to the previous test site. The two-sensor array was placed adjacent to the check hole at a spacing of 24 inches. The location was monitored for 4 hours while the bridge was loaded by normal traffic. No AE defect indications were detected.

A summary of results for all bridges tested is shown in Table 1. The value of AEWM data for aiding repair decisions is illustrated.

ACOUSTIC EMISSION BRIDGE TESTING PROCEDURES

The first step in AE testing of bridges is to examine the design and details of structural members to determine what locations should be subjected to AE monitoring. The AE practitioner should consider all factors related to the test location to determine how to best perform testing. AE testing of bridges is not well specified by existing codes.

Acoustic emission testing consists of our distinct phases: 1) location of AE sensors, 2) calibration of test equipment, 3) application of a suitable loading of the structural member, and 4) acquisition of data.

SENSOR PLACEMENT

Many structural elements of bridges appear to be complex and very difficult if not impossible to test upon initial inspection. Upon closer inspection, it becomes apparent that most test sites may be simplified to a few critical linear elements that may be tested with the simple two-transducer linear array. Typical examples of this situation are a row of rivets or weld line. It is desirable to avoid planar arrays that entail the use of three or more transducers. Tests by GARD and KTRP personnel on a variety of bridge structural details have never required planar flaw location. Most typical steel structural elements consist of sections of some plate-type detail. The intersections of those details are straight lines. Those intersections are usually the locations where testing is desired and the tests may be adequately performed using a linear two-sensor array. Localized details may be tested by simply bracketing the detail with the linear array. The linear array is simple and does not require much time to place sensors.

In placing a test array, it is desirable to locate the transducers as close as possible to any potential noise sources such as a row of bolt holes. This is a special feature of the AEWM. the sensors would be placed to isolate the test zone from areas where fretting noises might be generated using most conventional AE systems. The array may be located near noise sources and the three-step filter in the unit would reject fretting noises introduced by bolts or interfaces between concrete and steel. Potential noise sources that are distant and normal to the linear two-sensor array may present a problem when a clear sound path exists between the potential noise source and the array. Those distant noise sources generally are located normal to the linear array. In such cases, use of guard transducers is sometimes necessary. A bridge subjected to traffic is analogous to a situation where several widely separated sites (connections and/or welds) become active more or less simultaneously. This results in activation of AE sources that may be considerably removed from the two-transducer array.

Referring to Figure 3, the signal from an off-axis source in linear location array is an error in source location that increases as the distance between the source and the array increases. The error is equivalent to a shift of the source toward the midpoint of the linear array (due to hyperbolic loci of constant time-of-arrival differences). At some distance normal to and sufficiently removed from the location line, widely separated sources will be located at the same point when detected by a linear sensor array. The resulting AE activity may trip the AEWM flaw model if those AE sources act concurrently. Increasing the separation of the array sensors will sometimes minimize that problem. Use of off-axis positioned guard sensors may prevent erroneous detection of off-axis AE sources.

The AEWM processor evaluates the order of receipt of the acoustic burst at the various sensors. A signal is rejected and no source location is computed if a guard sensor receives a signal first. Two possible guard configurations determined effective for in-service bridge inspections are shown in Figure 28. The boundary between accept and reject regions for AE sources is defined by the perpendicular bisectors of the lines joining a guard sensor with active locator sensors. The reject-accept boundary is shown in the upper half of the figure for a single guard located along the perpendicular bisector of the locational line. When two guards are used with the active sensors, the accept-reject boundary is as shown in the lower half of the figure. The particular guard configuration used depends upon the bridge detail being monitored with the reject zone positioned to exclude any off-axis AE sources. It is sufficient to use a single guard transducer when the potential noise source is located a considerable distance from the active transducer array. It is more desirable to use two-guard sensors when a nominal distance is encountered between the potential noise source and active transducer array, as encountered in the stringer beams on the approach span of the I 75 bridge at Covington.

In placing the two active transducers to test a linear region such as a weld line, the transducers may be offset slightly (6 to 9 inches) without seriously affecting the locational ability of the AEWM. As the hyperbolas used for location become more curved for AE sources closer to the active transducers, the transducers may be offset from the ends of the plates and still have the ability to look around the transducers and detect defects that apparently would be located outside of the transducer array. AE sources located on the weld line outside the array would not produce valid AE indications if a transducer array were placed on part of a weld line connecting the lower flange and web of a large plate girder. This provides additional discrimination for an AE test. The transducers usually are placed about 2 inches from any edges at the ends of the test line. The possibility would exist for detecting unwanted noise reflecting from the ends of the plate if transducers were placed exactly at the edges of the plates being inspected.

Paint on the test surface should be cleaned and checked to see that it is tightly adherent prior to placing transducers. It would be necessary to remove loose or thick paint and expose the primer or bare metal. A small area about 1-inch square must be cleaned for attachment of the transducers. Debris may affect coupling efficiency and impair a test. A sensor should have a small quantity of silicone-grease couplant placed on its contact face prior to attachment to the test site. Silicone grease aids in transmission of sound between the test specimen and the sensor.

It is necessary to use some type of hold-down device to firmly affix the sensor to the test specimen. In tests performed on most bridges, a special magnetic hold-down device developed by GARD was employed. The device applies approximately 20 pounds of normal force on a sensor.

A short coaxial lead wire connects a sensor to a preamplifier. Electrical quick-connect couplings are attached to both ends of the lead wire and the coaxial wires used to connect the preamplifier to the AEWM. LEMO or BNC connectors are used. Coaxial RG 58 or RG 174 type wires were used for the bridge tests. RG 58 wire is preferred for long runs. RG 174 is suitable for runs are less than 100 feet. RG 174 wire is much smaller in diameter and may be obtained in bundles having up to eight separate coaxial wires in a common sheath. The diameter of that assembly is about 1/2 inch. The eight-wire bundle may be easily handled in that configuration. Most testing requiring guard sensors has employed the RG 174 wire bundle for ease of handling. Each wire is numbered at both ends near the connectors to insure that the AEWM is connected to the proper sensor.

When longer runs are required, it is necessary to use RG 58 coaxial cable which has individual wires approximately 3/16 inch in diameter. For long runs of RG 58 coaxial cables, it is best to determine the length of cable required. Long runs of RG 58 wire may be assembled from wire segments that are 20 to 50 feet long. Short runs may be spliced using BNC-type couplers. Once the runs of a proper length are made, multiple wire assembles may be made by taping the separate wires together on 10-foot intervals. The ends of those assemblies may be splayed to allow sensor placement at the test site.

Couplers on the ends of both types of coaxial cables are prone to damage. It is best to perform conductivity tests on the cable and connector assemblies prior to field installation. It is often difficult to determine simple causes of signal failures once AE testing has started. Coaxial assemblies should be wound loosely for transmittal to the test site. Care should be exercised to prevent pinching or knotting individual cables.

One major problem encountered on bridges is routing signal wires that connect the preamplifiers to the AEWM. It is often necessary to place the equipment vehicle on the structure and to attempt monitoring structural elements on the other side of the bridge deck. It is not safe to place coaxial cables across the deck. In those instances, it is necessary to route cables under the bridge and bring them up to the other side. It is also desirable to tie the cables off at approximately 20-foot intervals if they are to be suspended. Care should be exercised at the end near the transducer array to tie off the cable and ensure that there is no force pulling against the mounted sensors. That may cause the sensors to slide laterally and loose their coupling with the test specimen. A preamplifier which is not rigidly connected to the transducer hold-down assembly should be taped or otherwise mounted to the test specimen to prevent the unit from pulling against the sensor. A rough test surface or very thick paint may reduce the force of the magnetic hold-down units. Additional magnets or other clamping should be used to affix sensors in those cases.

Sensors employed in those tests are typically resonant piezoelectric transducers having centering frequencies of about 150 kHz. Acoustic Emission Technology 175L resonsant transducers have been used with GARD 0-dB preamplifiers in most tests. Those transducers are very responsive to small excitations and are well matched to the performance characteristics of the GARD preamplifiers.

Physical Acoustic Corporation Model 15I integral preamplifier transducers have been utilized on a trial basis. Those transducers are slightly larger than the normal piezoelectric sensor and have built-in preamplifier circuits that provide 40 dB gain. The AEWM operates at a lower line voltage than Physical Acoustic Corporation units; therefore, less gain is achieved. The advantage of that type of transducer is it does not require a separate preamplifier compared to the conventional type of sensor. That permits a more convenient mounting package and reduces the connections required to install transducers on a bridge. The units worked satisfactorily during the field test on the I-471 bridge, even though one of the internal preamplifier transducers eventually displayed a tendency to oscillate. That could cause the AEWM to become inoperable in a manner that would not be readily apparent.

It was elected to discontinue use of those transducers until the problem could be resolved.

CALIBRATION OF TEST EQUIPMENT

The system should be calibratedafter the sensors are placed and the signal cables are connected to the AEWM. Calibration usually, is a simple process whereby the AEWM operator sets a specific gain on the equipment, also entering the active transducer spacing, and then proceeds to test the array with a pulser. The Acoustic Emission International Model 851-PBH portable battery-powered pulser was used for field calibration of the field tests.

For calibration, the pulser transducer is placed along the test line between the two active sensors and the pulser is run at a pulse repetition rate that exceeds that of the flaw model used in the AEWM. The activated pulser sends ultrasonic-frequency sound waves into the test material and trips the AEWM detection model by exciting the two active transducers. The operator determines whether the flaw model is tripped and if the calibration test properly located where the pulsing transducer was placed between the two active transducers in the array. The equipment is ready for testing once that step is complete.

It is oftentimes easier for a technician to perform the pulse calibration check at the test site and for a separate AE operator to concurrently observe the function of the AEWM in the test vehicle. It is useful for both parties to have two-way radios to communicate with each other. A comprehensive series of pulse checks is sometimes desirable to test the function and location of the active transducer array and also to check the function of any guard transducers being used.

Initial calibration tests should be conducted to insure that the guard(s) will prevent noise outside the array from giving spurious AE defect indications. A test should be performed with the pulsing unit transducer placed away from the guard transducer(s) and array to perform that task. It is also necessary to insure that the guard transducer(s) will not inhibit any AE activity that is occurring in the test region of interest. To perform this test, it is necessary to conduct pulse checks at locations near the midpoint of the active array and offset slightly towards the guard transducer. The test setup is functioning correctly and problems should not be encountered if the pulse test is recorded by the AEWM. The operator in the vehicle should observe the indication lights on the analog panels for each channel of the unit when pulsing is performed. Minor amplification adjustments sometimes may be necessary for the various channels of the AEWM. This is necessary to insure equal AE data-reception characteristics from each of the AE channels. That adjustment is required due to unaccountable differences in the characteristics of the transducers and also due to differences in coupling efficiency between various portions of the test specimen.

LOADING OF STRUCTURE

Acoustic emission structural monitoring requires activation of flaw-related AE sources. A flaw must be activated by an imposed load or stress. There are two principle types of AE field tests -- proof-testing and service monitoring. Heavily loaded trucks travel over the structure while AE instruments listen for activity to proof-test monitor a bridge. To conduct service monitoring, AE instruments listen for AE activity while a bridge is subjected to normal traffic-induced stresses. Each method has certain advantages and disadvantages.

Proof testing requires that a structure or structural element to be stressed to a level near or above the maximum anticipated service stress, but usually lower than the yield stress. Proof testing has several advantages over service monitoring. Application of a high stress increases the chances of AE source activation. Weak sources of AE activity may be more readily detected when proof stressed. Large flaws not subject to subcritical crack growth also may be detected. Acoustic emission monitoring by this method may be performed in real time, eliminating some cause-effect questions. The test may be completed in a shorter time than required for service monitoring. It may be desirable when a structure is subject to intermittent loads.

Proof testing has some disadvantages compared to service monitoring. Proof tests require several personnel. Special techniques and equipment must be developed to proof test large structures. Multiple-channel/multiple-AE detection devices must be employed to test complex structures. Proof testing will activate many AE sources, making data analysis more difficult. Those tests must be performed at relatively warm ambient temperatures to insure maximum material toughness. Also, some structures may not be adaptable to proof-testing techniques due to inherent design limitations.

Service monitoring has several advantages over proof testing. Those tests may be performed using relatively simple AE monitoring devices. A test may be set up and portable AE equipment left unattended during the monitoring period, requiring less labor. Tests may be conducted over a long time period to provide an idea of the activity rate. Few coincidental AE source mechanisms will be activated, simplifying data analysis. Some structures are routinely stressed to significant levels due to design. Those bridges may not require proof testing. Service monitoring may be performed over a wide range of temperatures. It also may be safely performed on all members of a structure.

Another factor that must be considered is the test duration, especially when service loads are required. Testing should encompass a sufficient time period to insure that a bridge has been subjected to loads capable of activating flaw-related AE sources. Bridge loads may vary greatly throughout a day or a week. It is advantageous to determine when the maximum loadings or heavy volume of truck traffic will be on a bridge. Truck volumes and weights would be site specific. Strain-gage data may be useful for determining whether a bridge has been subjected to sufficiently heavy loadings to activate deleterious AE sources.

Service monitoring has several limitations. There may be times in the growth of a subcritical flaw when no AE sources are active. If they are active, the sources may be very weak. Stresses on bridge components being monitored are generally not measured in relation to AE activity during service monitoring, making it difficult to relate AE activity to source events. Service monitoring should be performed over extended time periods. That ties up equipment and makes it difficult to relate AE activity to events in the structure. Long-duration tests may necessitate leaving equipment unattended and exposing it to vandalism. That danger may be minimized if the system is compact and could be stored in a remote location near a test site. The data-processing capabilities of a compact AE monitor will be limited, especially if battery power is used.

Proof testing may be a more desirable method for testing newer structures of limited size that may be monitored with a reasonable number of AE sensors. Service monitoring may be more appropriate on larger and more complex bridges.

Traffic volumes and load spectra are quantities that have definite affects upon initiation and propagation of fatigue cracks. Several days of AE monitoring should be sufficient for most bridges to produce sufficient local stresses to drive existing fatigue cracks in test areas and produce AE defect activity. On bridges having extremely heavy loadings, several hours of AE monitoring may be sufficient.

KTRP-GARD personnel experience indicates that short-term monitoring under normal traffic loading is sufficient to obtain valid data. Bridges subject to fatigue cracking are normally heavily and frequently loaded. Short-term tests (4 or 5 days) should be sufficient to detect active fatigue cracks.

In most cases, a bridge will be loaded by some form of traffic (routine or heavy proof loads). AE equipment capable of testing bridges is usually housed in a vehicle such as a mobile van or car. It is desirable to have short signal-cable runs and the equipment vehicle is normally parked on the bridge. Most larger bridges have curb lanes to accommodate equipment-housing vehicles. The lack of curb lanes in some cases will require long wire runs to prevent closure of a lane for the equipment vehicle. The vehicle parked on the bridge deck, even in the curb lane, can interact with traffic entering onto the bridge and affect the loading of the bridge. The effect of a vehicle parked in the curb lane is to divert traffic into the passing lane. If it is desirable to test bridge members supporting the traffic lane, the diversion of traffic will reduce the loading on those members and decrease the possibility of defect-related AE excitation. In those cases, it is more desirable to park the vehicle in the curb lane of the opposite direction roadway and route the wires under the structure to prevent an unfavorable interaction with traffic that would stress the member to be monitored.

DATA ACQUISITION

It is helpful to use strain-gage data to correlate stresses in a structure with AE activity. It is often difficult to determine whether or not a truck passing over a bridge is heavily loaded from its external appearance. Strain-gage data will quickly reveal whether the member has been heavily stressed due to the presence of one or more trucks on the bridge. That information may also be used to anticipate whether an existing crack is subject to fatigue-crack growth and also to estimate how active any detected crack growth may be. Strain-gage information may also be useful for prioritizing repairs on a particular structure.

Strain-gage data are not necessary in all cases, but provide additional information that may help explain AE results obtained while monitoring a structure. Strain gaging may also be performed prior to AE monitoring. It is currently not possible to concurrently store strain-gage and AE data from the AEWM. It would be desirable to do so. In the case of Low loading amplitudes on the structural members contributed to the dearth of AE activity at the test sites on the I 310 bridge at Luling, Louisiana. It would have been difficult to understand the low amount of AE activity on that bridge without the strain-gage data.

One test on the Luling Bridge with strain gages revealed a very rapid impulse-type load of about 6 ksi. Because of its short duration, that particular load was believed to be due to wind acting on the structure. Such loadings are generally unanticipated, yet, contribute to crack growth and may cause unforeseen AE activity. That is another reason to apply strain gages either to the test member or to the local test site.

The red indicating lamp on the face of the AEWM panel will extinguish when a crack is detected during the monitoring process. When the monitoring period is to be terminated, it is possible to interrogate the AEWM and determine the exact location and nature of the defect detected by the device. Data also may be recorded in hard-copy form directly from the AEWM onto a serial printer or may be stored on a floppy disk when the data-recording mode is employed. All AE test parameters measured during monitoring are stored on a floppy disk in that mode of operation. Data may be reprocessed and examined upon completion of testing, concentrating specifically on sites where visible cracks or other potential defects are known to exist. That information may be useful for determining whether very low-level crack AE activity was emitted from a crack site. Sufficient indication of flaw-related AE activity is obtained by simply operating the AEWM in the stand-alone mode. Test data analyzed by the AEWM will not be recorded in that mode. Only the flaw indications will be recorded; they may be routed to a printer for a hard-copy record. Calibration information also may be recorded on hard copy prior to the test for subsequent reporting purposes.

When testing reveals an AE flaw indication, it is desirable to shift the sensors in relation to the flaw position and re-monitor the test site until another flaw indication is detected. This will preclude the possibility that AE noise from some distant source has infiltrated the array and produced spurious AE indications. It is a safeguard to perform this step when operating in a portion of a bridge where the geometrics of various structural elements join in a complex pattern. When the test area contains an active flaw, the location of the AE indication will shift with the repositioning of the sensors. Repositioning of the transducer array will not shift the location of subsequent indications when the flaw indication is noise-related. Those safeguards are considered necessary to insure the integrity of AEWM findings. AE data may be returned to the laboratory or office and subsequently correlated with other information, including strain-gage test results and fracture-mechanics calculations to determine the severity of any potential defects in the structure. That information may be used to make plans for repairs or to prioritize repairs among a number of different structural elements.

PROPOSED ACOUSTIC EMISSION TEST MODEL

Figure 29 is a theoretical "Limit of AE Detection Curve" for a particular steel, AE gain, and transducer spacing. For any minimum crack size (i.e., length), a_m, no live-load stress will stimulate detectable AE activity. For any live-load stress less than σ_m, no crack of any size will produce detectable AE activity. No crack size/live-load stress combinations representing points under Curve AB will provide detectable AE activity. Once Curve AB has been obtained experimentally and the live-load stresses have been measured on a structural member, the minimum crack size for reliable AE detection could be determined.

Using the frequency of loading data obtained from strain-gage tests, the test duration necessary to reliably detect a fatigue crack might also be determined. Curve AB may represent a special fracture-mechanics value K_{AE}, the cyclic stress intensity increment required to produce AE activity having a 90-percent probability of detection.

Figure 30 shows a hypothetical stress distribution histogram for a typical bridge member. Stress intensity ranges under 1 ksi are not considered significant and are not tabulated. Various stresses encountered in the histogram are due to different individual vehicle or combinations of vehicle loadings on the structure over a specific time period (24 hours in this example).

The chart represents the statistical probability that a 24-hour strain-gage test would detect 15 stress cycles in the range of 3 to 4 ksi and five stress cycles in a range of 4 to 5 ksi.

Figures 29 and 30 can be used to determine the necessary AE monitoring period when a bridge has a growing fatigue crack that is larger than the minimum crack size a_m necessary to produce detectable AE activity. The structural member shown in Figure 30 will probably experience 18-20 AE producing stress cycles over 24-hours when the subcritical crack is large enough to produce AE activity for live load stresses greater than 3 ksi (as determined from Figure 29). That monitoring period should be sufficient to detect any AE activity related to fatigue crack growth. Conversely, when the structural member contains no known crack, and it is monitored for 24 hours without an AE indication, one may assume that if a crack exists it must be smaller than the AE active crack size indicated in Figure 30 for a stress range of 3 ksi.

The equivalent stress range Sre_{rms} may be determined from the relationship $Sre_{rms} = (\Sigma\gamma_i \sigma_{ri}^2)^{1/2}$, where γ_i is the frequency of occurrence of the preselected stress ranges σ_{ri}. Knowing Sre_{rms}, the number of cycles to structural failure can be determined using the Paris fatigue-crack growth equation: $da/dn = A(\Delta k)^n$, where A and n are known constants, da is the incremental crack growth per load cycle dn, and Δk is the change in stress intensity for Sre_{rms}, or $\Delta k = k_{max} - k_{min}$. Knowing a_{crit} (the crack size necessary for a structural element to fail by fracture), a_m, and σ_m, the required inspection frequency may be determined for AE testing with a high probability of crack detection (two or more chances (inspections) at 90-percent probability of detection).

It is likely this approach is the most technically correct to apply for AE inspection of bridges. Laboratory verification of this concept has not been obtained. A major concern or drawback with this approach is that AE dead periods are possible during fatigue-crack growth. Not every load (stress) cycle on a bridge member may be expected to produce crack growth or AE activity. That has been verified by previous laboratory tests. KTRP-GARD personnel experience on bridges indicates the presence of AE dead periods in the field under strain-limiting loading (out-of-plane conditions). That behavior is believed to be related to either fatigue crack retardation or to temporary reorientation of the crack front. Fisher has indicated that full-size welded specimens containing residual or reaction stresses do not show the effects of retardation (12). AE dead periods may be a phenomenon restricted to small specimens lacking residual or reaction stresses when fatigue cracks do not retard in large structures under normal stress-limiting loading conditionswhen fatigue cracks do not retard in large structures under normal stress-limiting loading conditions. Their behavior should be determined experimentally when AE dead periods exist. They will affect the crack size or growth rate that can be detected in a given structure and also the required duration of any AE test.

It is doubtful that crack initiation, as such, may be detected by AE monitoring. Ghorbanpoor has detected fatigue-crack growth in laboratory specimens through AE monitoring prior to the onset of visible cracking (13). Smith has noted that microscopic fatigue-crack growth occurs very early in the cyclic loading of welded specimens having stress-intensifying details (14). In an early laboratory test by GARD, the AEWM was able to detect the presence of a fatigue crack in a high-strength aircraft aluminum beam subjected to fatigue where the crack length was between 0.01 and 0.03 inch. Those facts indicate the possibility of early detection of fatigue cracks. The proposed approach to bridge inspection may be implemented in a useful manner once backup laboratory information has been obtained to determine the reliability of AE detection at a given stress range.

CONCLUSIONS AND SUMMARY

KTRP and GARD personnel have accumulated several hundred hours of on-bridge test experience using the AEWM. The device has been used to perform thirteen tests on nine different bridges in four states. The unit has proved successful in detecting AE activity from crack sources against high background noises typical of in-service bridges. AE activity was generated by normal traffic loading in 12 tests. Proof loading was applied (the I-310 bridge at Luling, Louisiana) in one case. Service loading of bridges appears to be the superior flaw-activation method for many applications. The AEWM offers many features desirable for in-service monitoring: 1) relative ease of operation, 2) ability to detect and locate flaws, 3) ability to characterize flaws, 4) elimination of need for operator interpretation of results, and 5) ability to produce hard-copy records. The system has detected cracks and simultaneously rejected noise backgrounds exceeding 15,000 events per hour. The equipment has produced definitive results relatable to existing cracks with no ambiguity or interpretational difficulties. The AEWM is easy to operate in the stand-alone test mode. It may be operated by technicians having a minimal amount of familiarity with the test method and equipment. Persons having considerable experience in AE testing should be used. The unit shows capabilities for addressing many nondestructive test needs of highway agencies in an economical manner and for detecting and locating fatigue cracks.

Acoustic emission testing using the GARD AEWM does not limit test productivity to the output of an operater dedicated to one test instrument (typical of conventional NDT methods and instruments). Once a transducer array is placed on a structural member and the system is calibrated, the operator may commence the test and move to other sites to place sensor arrays for other AEWMs. By providing many test instruments (AEWMs) and a few operators to place sensors and provide initial calibration, high test rates and low test costs can be achieved.

AE testing has some limitations. It is dependent upon external excitation of flaws by vehicular loading to generate AE flaw activity. Many sites should be monitored concurrently to make periodic bridge AE inspection economically viable. AE testing is not a good flaw-evaluation tool. It may determine the presence of flaw activity and the flaw location on a structural member, but it cannot geometrically define a defect suitably for removal or repair.

New AE testing criteria should to be developed. This includes the correlation of AE activity with crack size, fatigue-crack growth rates, and bridge loadings to determine inspection frequencies and durations.

It is likely that no single nondestructive test method would be suitable for all portions of the bridge inspection process. The greatest portion of that effort will be to detect and locate the presence of hidden flaws such as fatigue cracks in steel bridges. It is likely that AE testing will play a key role in performing that task. A few years ago, problems with noise in conventional AE equipment appeared to be so serious that the method was considered not to be viable for use on large structures such as in-service bridges. The AEWM has been designed to overcome those problems and will be a viable candidate for use in future bridge inspection programs.

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7. Harris, D. O., "Acoustic Emission Monitoring of Lift Span Cables on Dunbarton Bridge," Dunegan Corporation, Technical Memorandum DC-72-TM11, Livermore, CA, October 1973.

8. Hopwood, T., "Acoustic Emission, Fatigue and Crack Progation," Kentucky Department of Transportation, Research Report No. 457, October 1976, p 29.

9. Hutton, P. H. and Skorpik, J. R., "Acoustic Emission Methods for Flaw Detection in Steel in Highway Bridges, Phase I," Federal Highway Administration Report No. FHWA-RD-78-97, Battelle Pacific Northwest, Richland, WA, March 1975.

10. Hutton, P. H. and Skorpik, J. R., "Acoustic Emission Methods for Flaw Detection in Steel in Highway Bridges, Phase II," Federal Highway Administration Report No. FHWA-RD-78-98, Battelle Pacific Northwest, Richland, WA, March 1975.

11. "Acoustic Emission Monitoring of Electroslag and Butt Welds on Dunbar Bridge, West Virginia (June 1, 1980 to April 30, 1955), Final Report; West Virginia Department of Highways Project 64," Dunegan Corporation, San Juan Capistrano, CA, 1985.

12. Miller, R. K., Ringermacher, H. I., Williams, R. S., and Zwicke, P. E., "Characterization of Acoustic Emission Signals," Report No. R83-996043-2, United Technologies Research Center, East Hartford, CT, 1983.

13. Ghorbanpoor, A., and Vannoy, D. W., "Laboratory Acoustic Emission Investigation of Full-Size ASTM A-588 Bridge Beams," paper presented at the Second International Conference on Acoustic Emission, Stateline, NV, October 31, 1985.

14. Smith, I. F. C., "Fatigue Design Concepts for Structural Engineers," paper presented at the International Conference and Exposition on Fatigue, Corrosion Cracking, Fracture Mechanics Failure Analysis, Salt Lake City, UT, December 5, 1985.

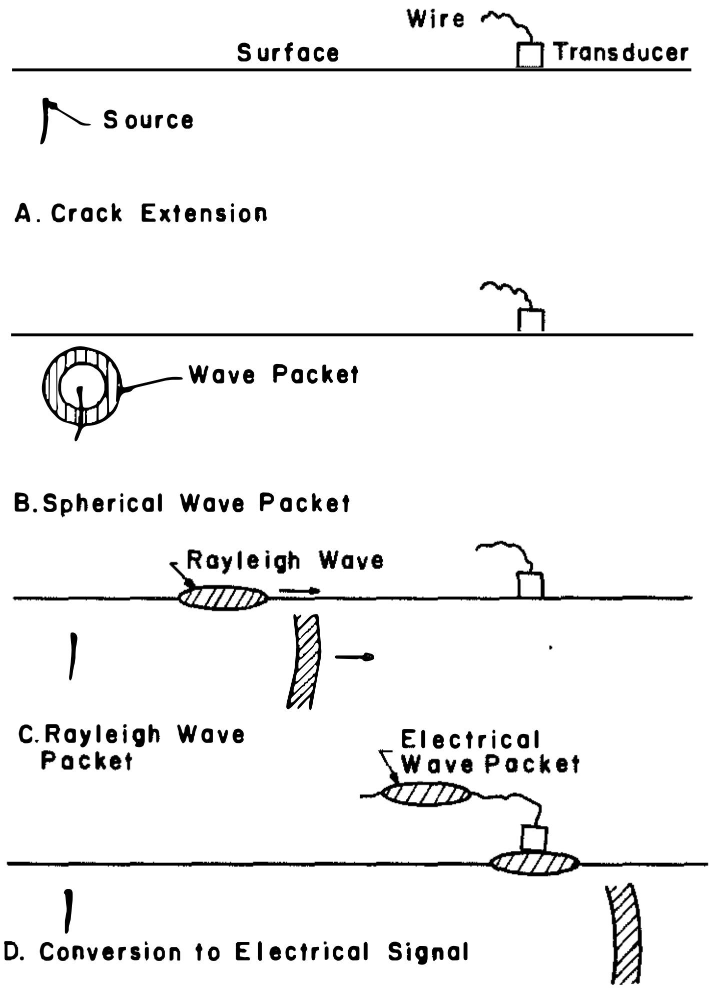


Figure 1. Simple Illustration of an AE Event.

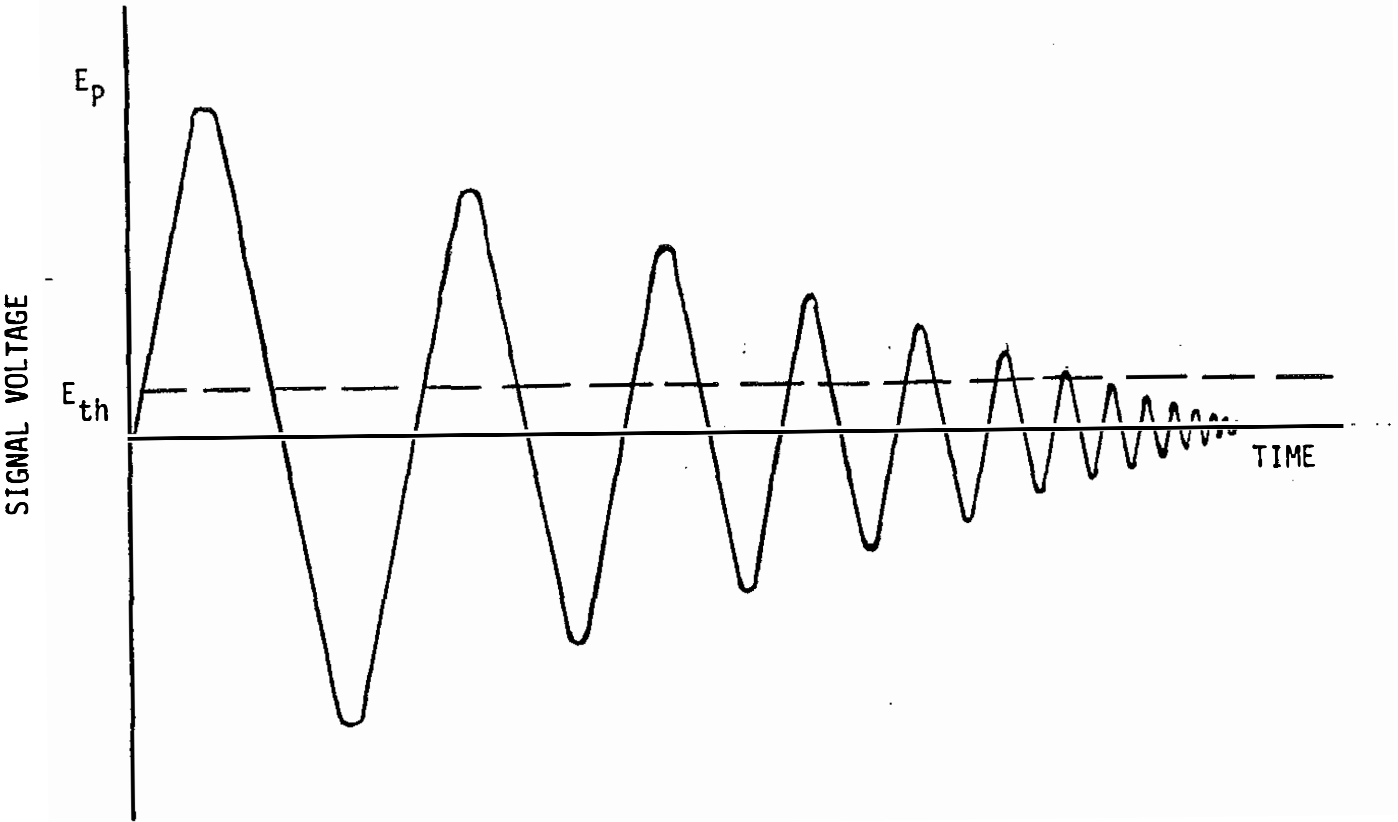


Figure 2. Idealized AE Signal.

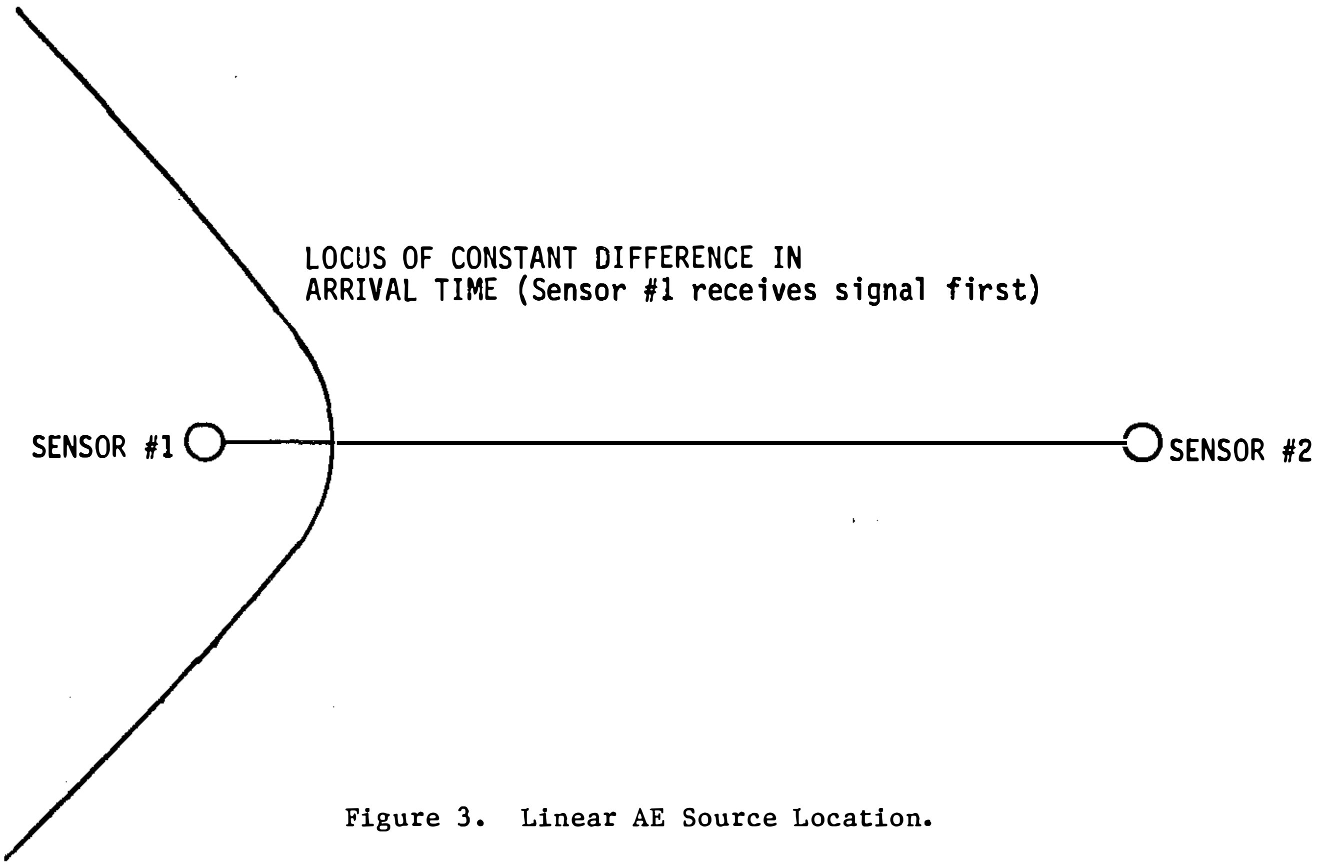


Figure 3. Linear AE Source Location.

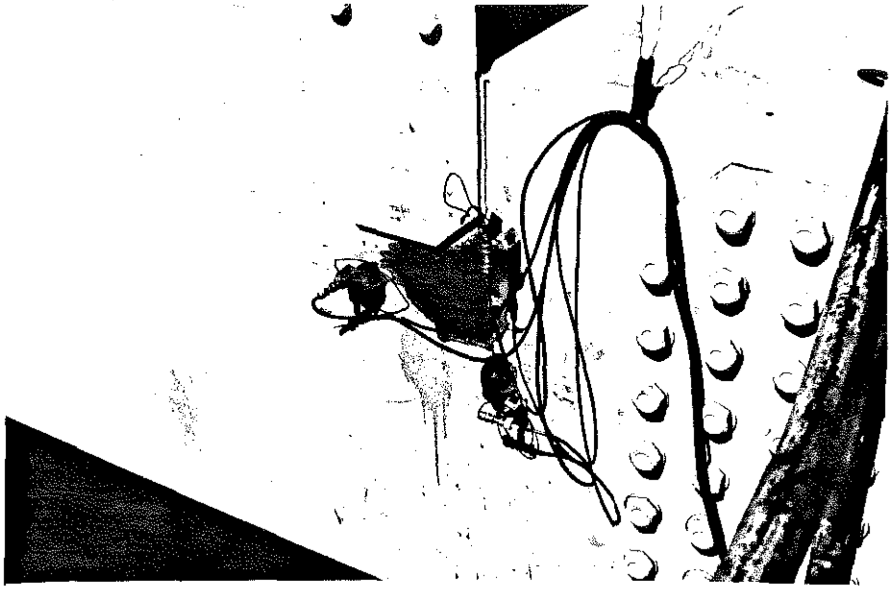


Figure 4. Planar Source Isolation Sensor Array of the Battelle Digital Acoustic Emission Monitor on the I-471 Bridge at Newport (1980).

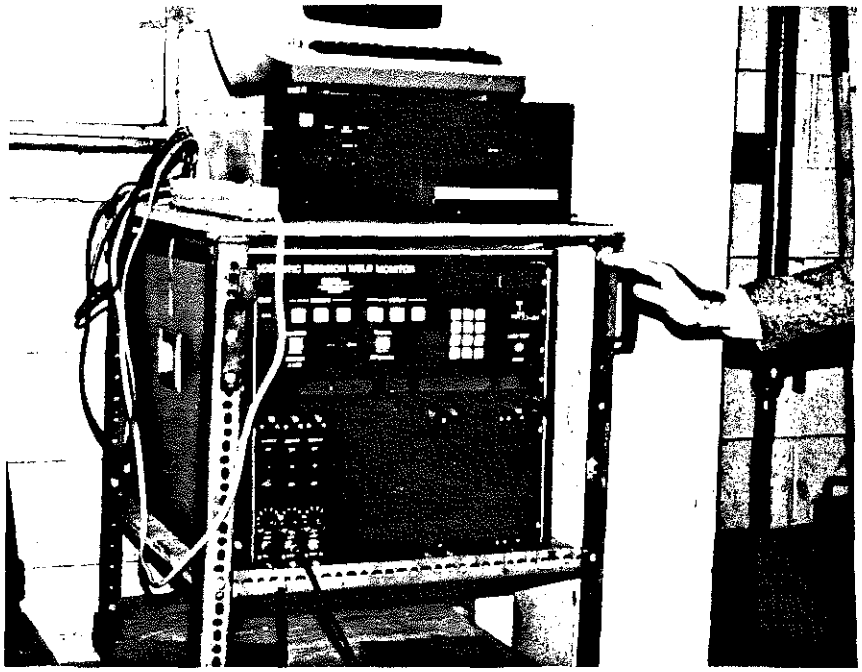


Figure 5. GARD Acoustic Emission Weld Monitor (AEWM).

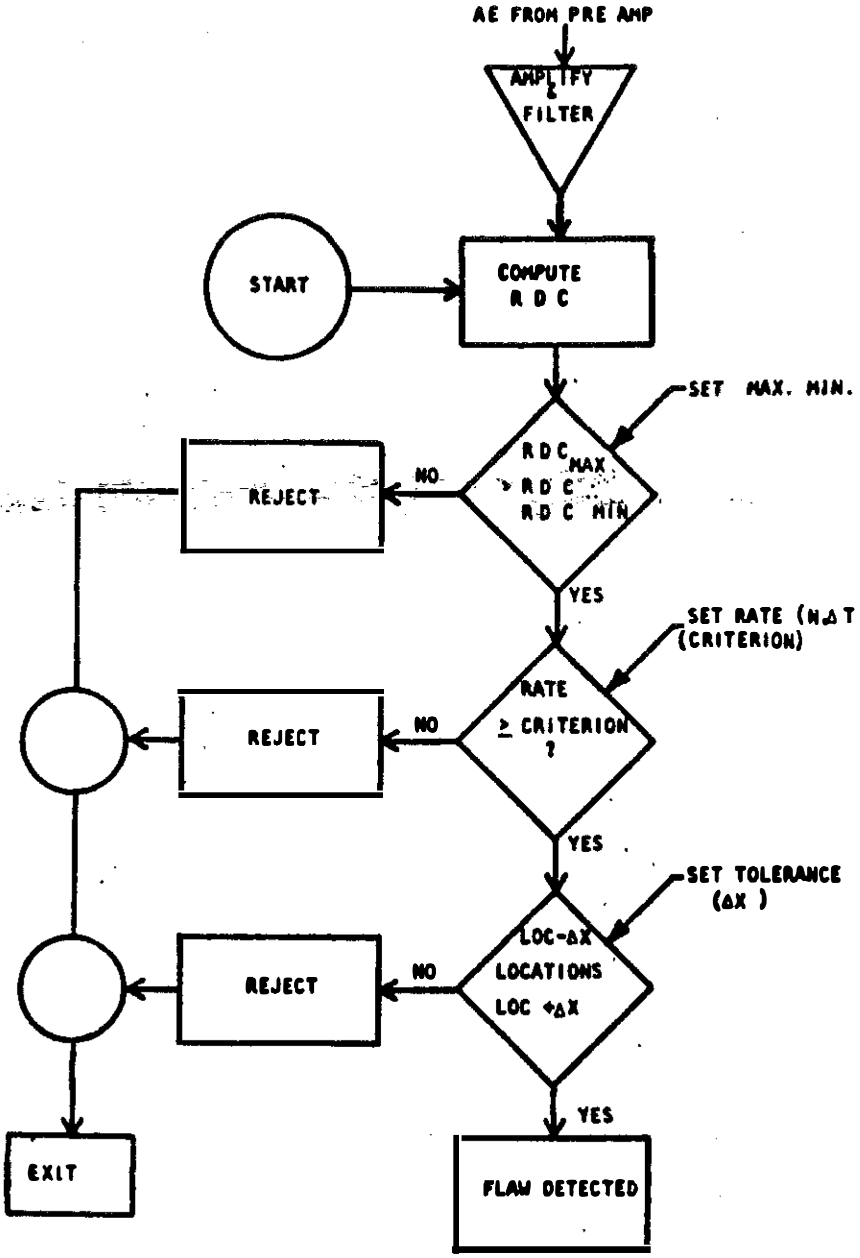
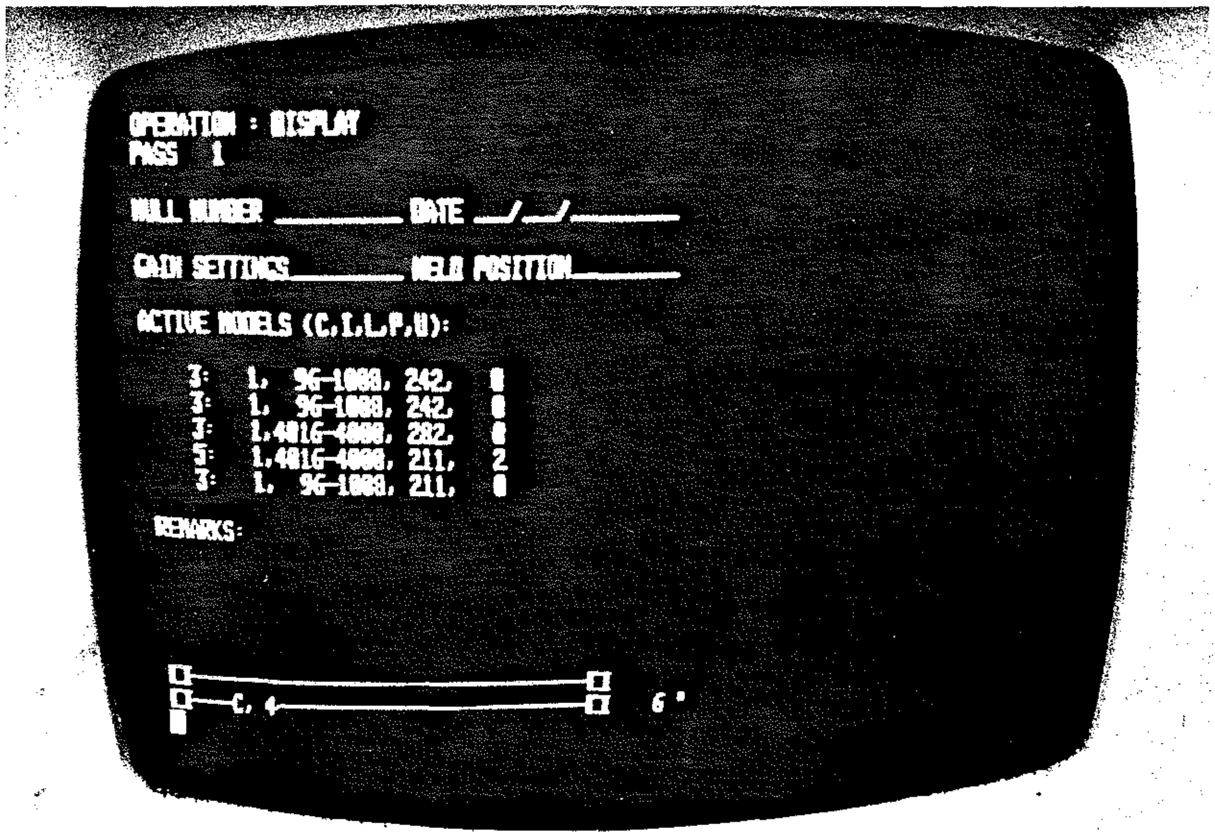


Figure 6. GARD Data Processing Flow Chart for Flaw Detection.



```
OPERATION : DISPLAY
PASS  1

HULL NUMBER ________ DATE __/__/________

GAIN SETTINGS________ WELD POSITION________

ACTIVE MODELS (C,I,L,P,U):

   3:  1,  9G-1000, 242,   0
   3:  1,  9G-1000, 242,   0
   3:  1,401G-4000, 282,   0
   5:  1,401G-4000, 211,   2
   3:  1,  9G-1000, 211,   0

 REMARKS:
```

Figure 7. Video Terminal Display of AE Test Results.

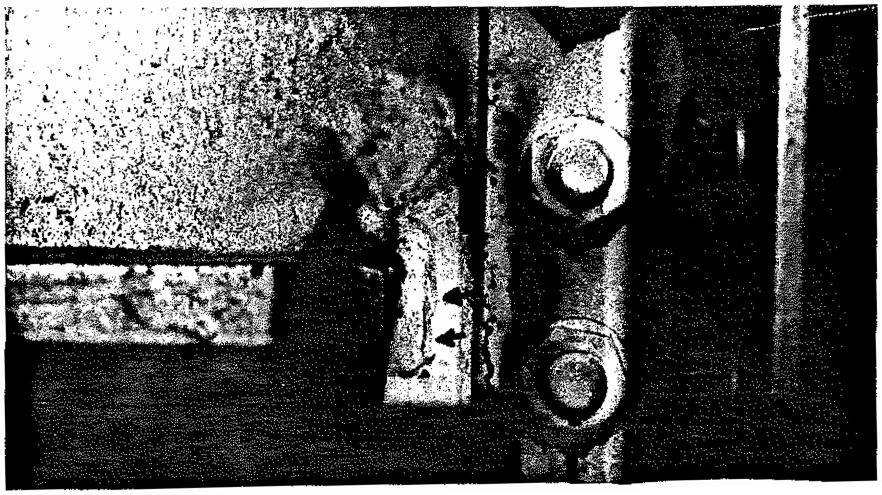


Figure 8. Crack in Floor Beam Web on the I-24 Bridge over the Tennessee River (1983).

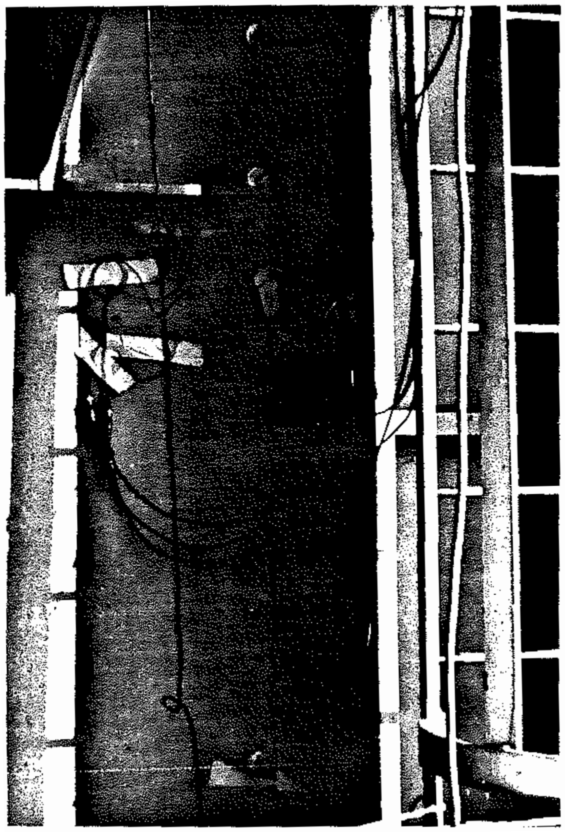
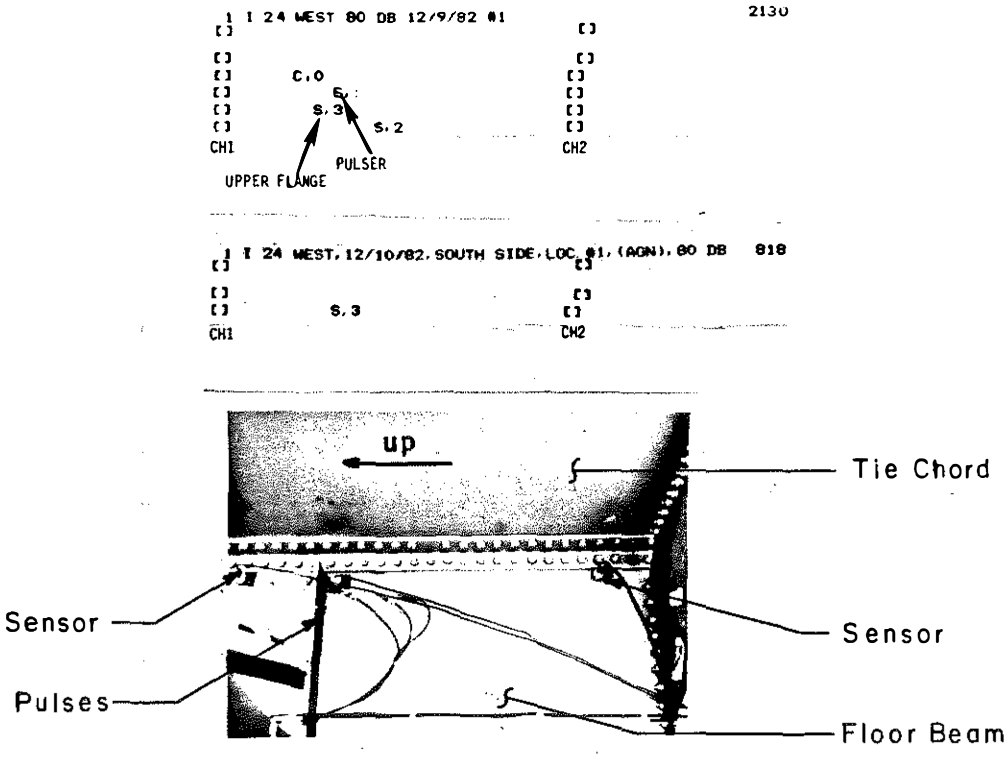


Figure 9. Linear Sensor Array on Floor Beam Adjacent to Bolted Splice Plate.

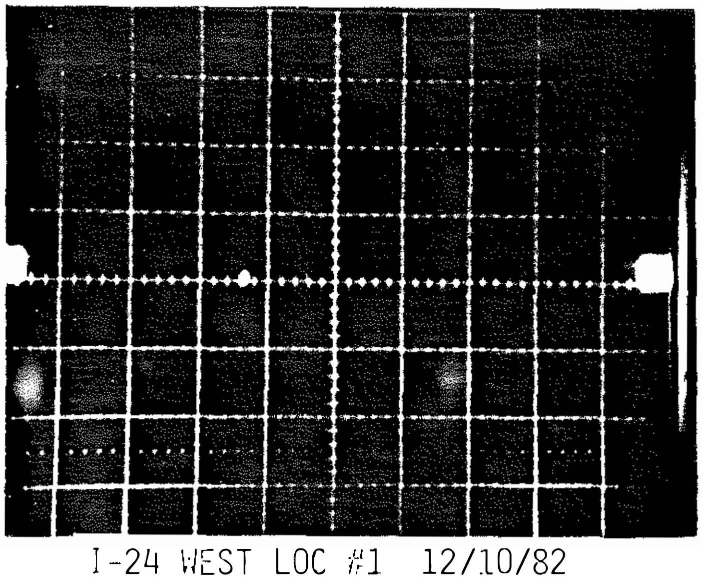
Figure 10. Motor Home Housing the AEWM Parked in the Curb Lane of the I-24 Bridge. Note the Coaxial Signal Cables Running to the Sensors.



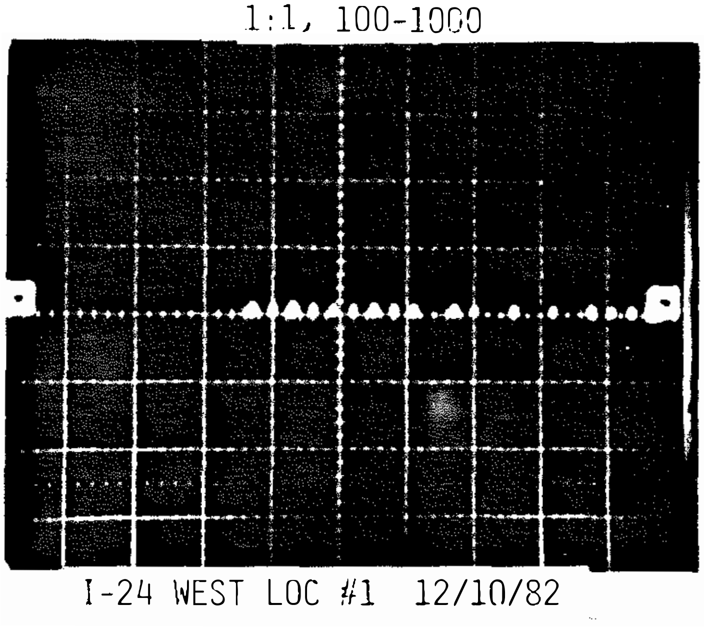
```
 1  I 24 WEST 80 DB 12/9/82 #1                          2130
[]                                  []

[]                                  []
[]       C,0                        []
[]           S, :                   []
[]         S,3                      []
[]               S,2                []
CH1                                 CH2

 1  I 24 WEST,12/10/82,SOUTH SIDE,LOC #1,(AGN),80 DB    818
[]                                  []

[]                                  []
[]           S,3                    []
CH1                                 CH2
```

Figure 11. Results of Two AE Tests on the Cracked Floor Beam on the East End of the Westbound I-24 Bridge.

(Note: Photograph Ratated Counter clockwise 90° degrees to Corespond with AEWM Printout).



a. Test with Three-Step Model Activated. The Single AE Source is Located at a Crack.



b. Retest Using the Same Data and the Three-Step Model. AE Sources are Bolt Holes Adjacent to the Linear Array.

Figure 12. Replay of AE Test Data Demonstrating the Function of the GARD Three-Step Flaw Model.

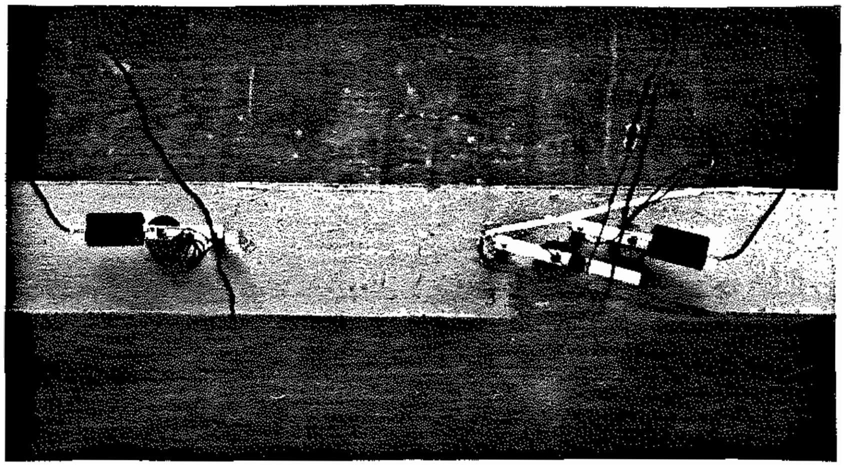


Figure 13. Linear Sensor Array at Cover Plate Termination of Lower Flange.

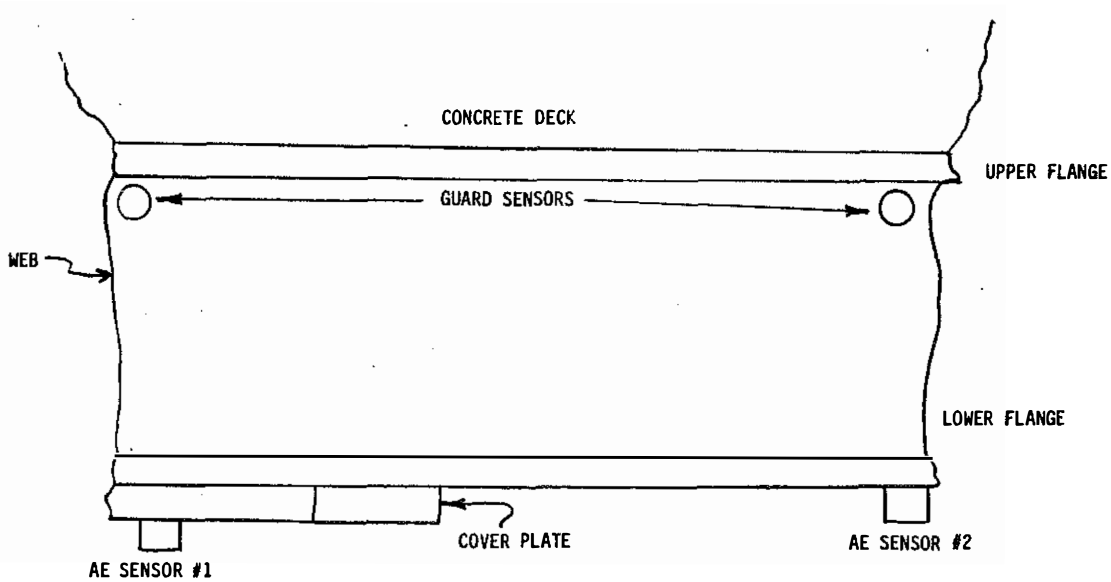


Figure 14. Placement of Guard Sensors to Prevent Deck-to-Beam Fretting Noises from Entering the Linear Sensor Array.

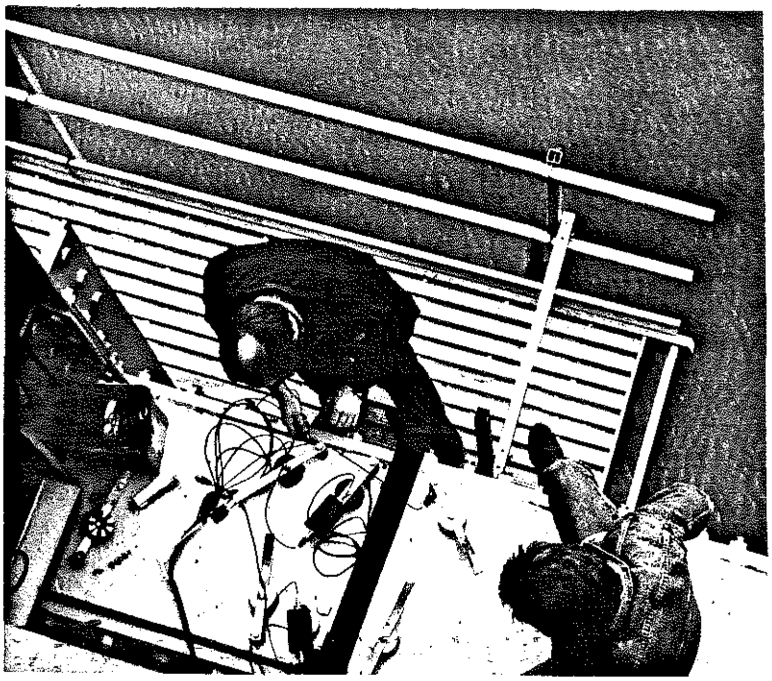


Figure 15. Placement of Six-Sensor Array to Monitor a Butt Weld on a Tie-Chord Upper Flange of the I-24 Bridge at Paducah.

```
PASS 2

HULL NUMBER: Ohio River Bridge  DATE: 11/13/84

GAIN SETTINGS: 63db             WELD POSITION: Leading Downstream
                                               Weld, Pos. 10
ACTIVE MODELS (C, I, L, P, U):

3:   1,  96- 008, 242,  0
3:   1,  96- 008, 242,  0
3:   1,4016-1000, 282,  0
5:   1,4016-1000, 211,  2
3:   1,  96- 008, 211,  0

REMARKS:


[]--------------------------------------------[]
[]----------------------------C, 4------------[]      24"
[]--------------------------C, 6- ------------[]      22"
[]--------------------------C, 6- ------------[]      22"
[]--------------------------U, 6- ------------[]      22"
```

Figure 16. AEWM Printout for the I-24 Bridge over the Ohio River.

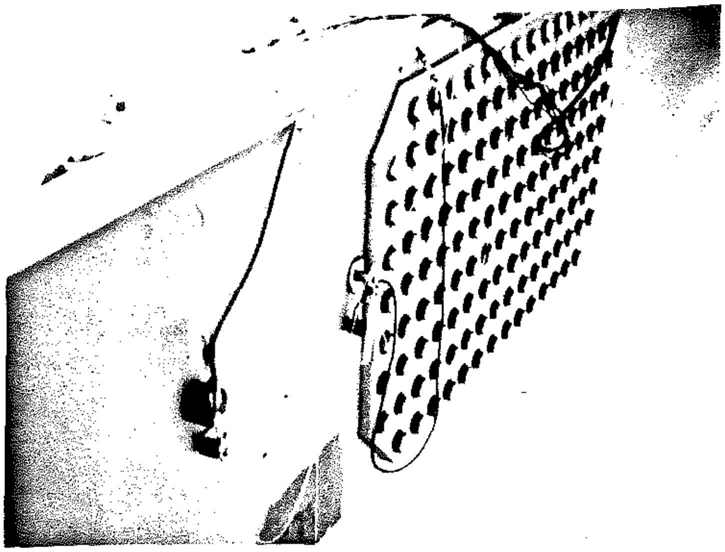


Figure 17. Portion of Sensor Array on the I-471 Bridge at Newport Using Integral Preamplifier Transducers.

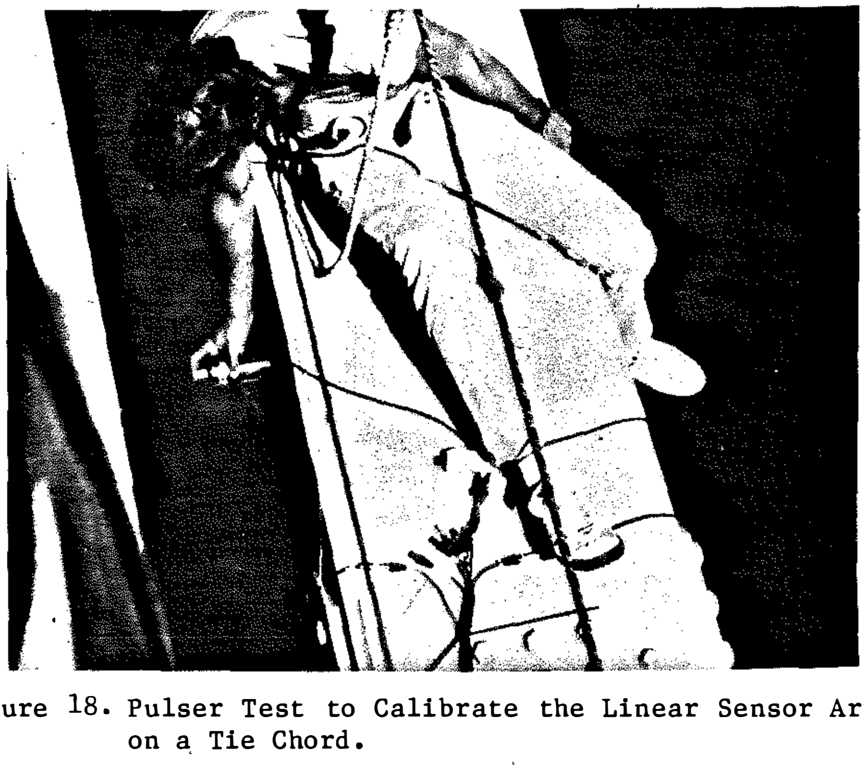


Figure 18. Pulser Test to Calibrate the Linear Sensor Array on a Tie Chord.

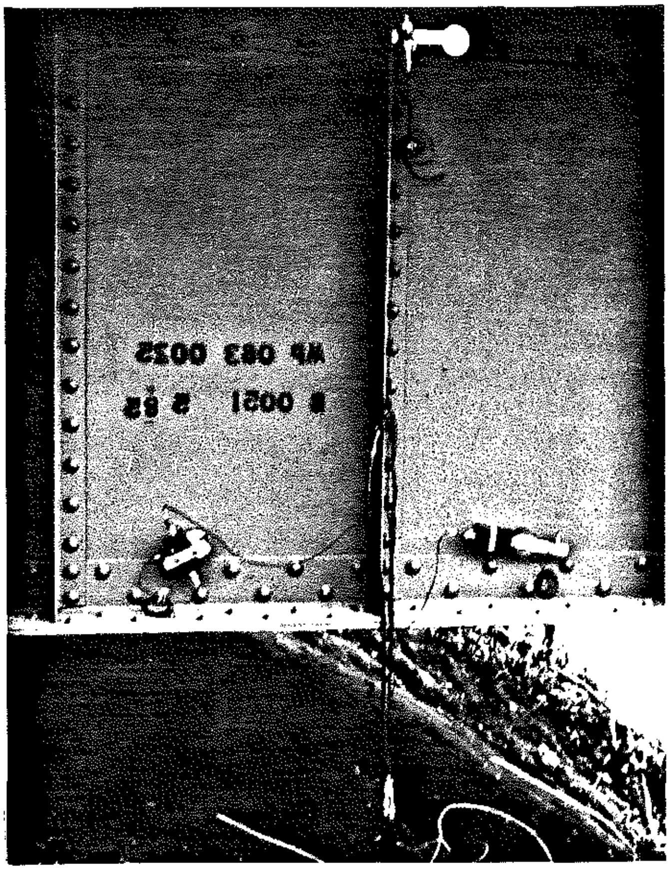


Figure 19. Linear Sensor Array Placed along the Lower Portion of the Web of the US-25 Bridge over the Rockcastle River.

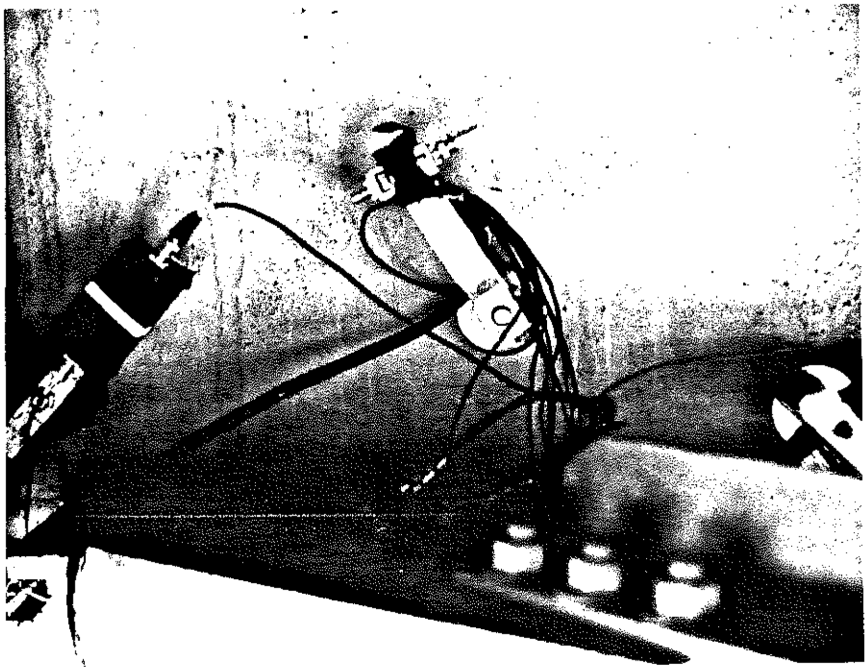


Figure 20. Linear Sensor Array Placed Adjacent to a Crack in a Stringer Web on the I-64 Bridge over the Ohio River at Louisville, KY.

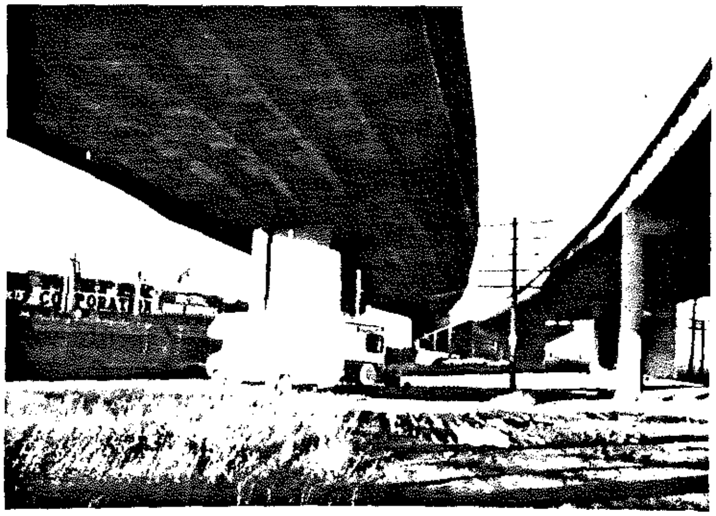


Figure 21. I-94 Overpass with Mobile Home Parked under the Test Pier Cap.

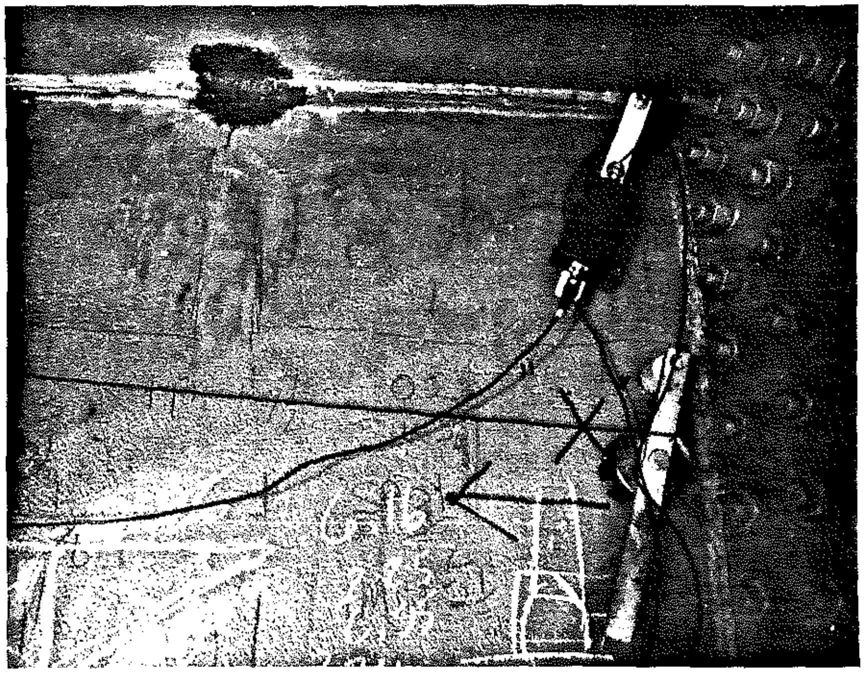


Figure 22. Portion of Linear Array on a Pier Cap Box Beam.

```
PASS 1

HULL NUMBER: I-94 Southbound     DATE: 11/08/84

GAIN SETTINGS: 85db              WELD POSITION: Site 1

ACTIVE MODELS  (C, I, L, P, U):

3:   1,  96-1008, 242,   0
3:   1,  96-1008, 242,   0
3:   1,4016-4000, 282,   0
5:   1,4016-4000, 211,   2
3:   1,  96-1008, 211,   0

REMARKS:



[]────────────────────────────────────────[]
[]─────────────────────────────C, 6───────[]     60"
```

Figure 23. AEWM Printout for the I-94 Bridge.

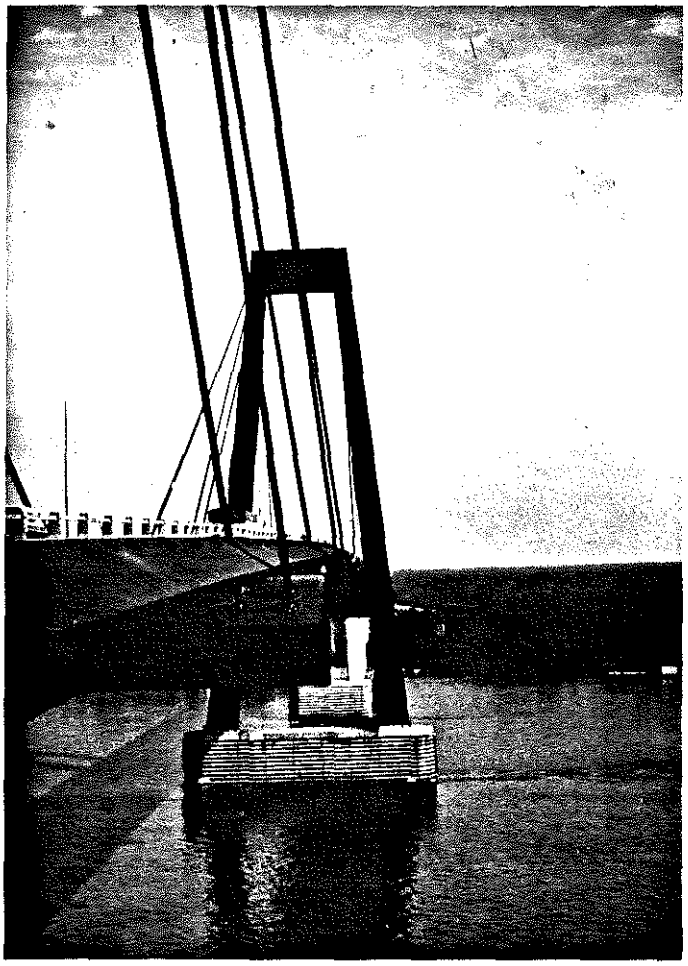


Figure 24. Cross Girder Detail on the I-310 Cable-Stayed Bridge at Luling, LA.

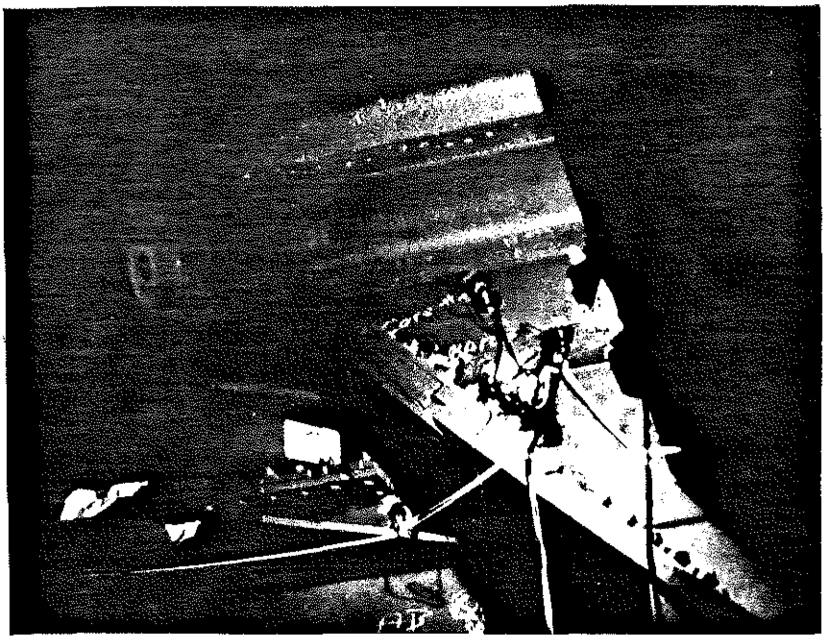


Figure 25. AE Monitoring of Test Site.

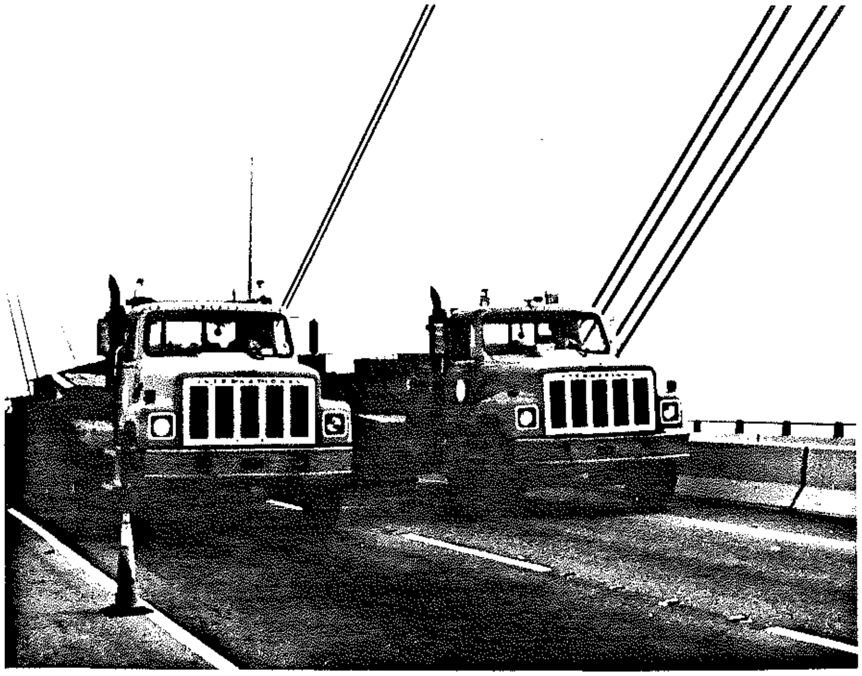


Figure 26. Proof Loading of the I-310 Bridge by Two 80,000-pound Trucks.

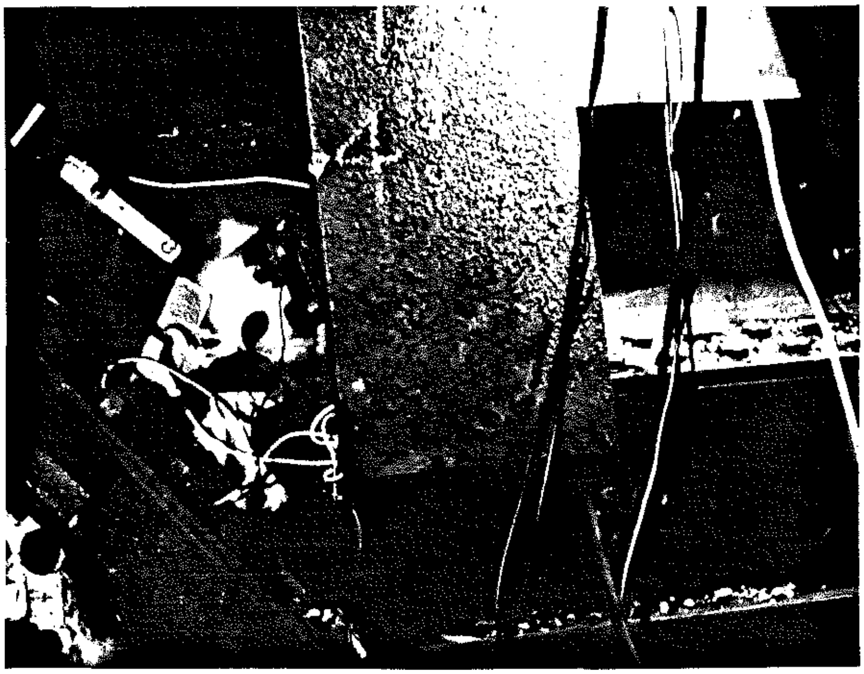


Figure 27. Monitoring AE Activity from Uncracked Ligament between Check Hole and Crescent Hole.

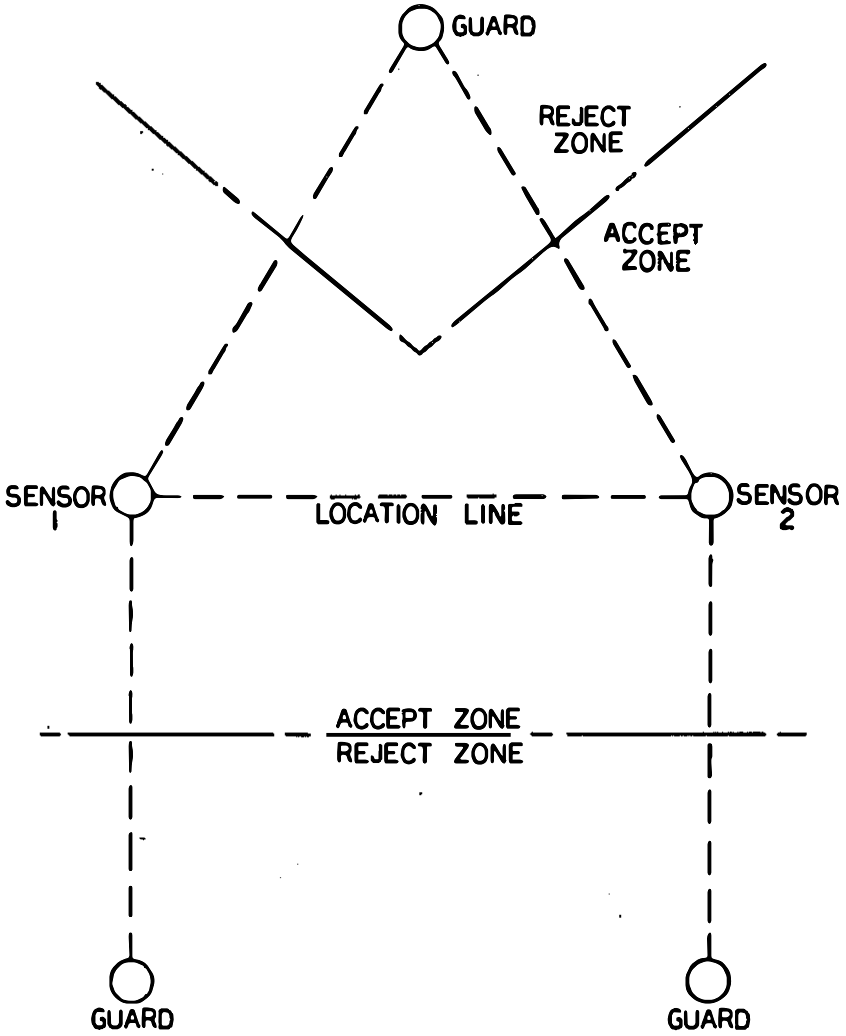


Figure 28. Guard Sensor Configurations for Linear Sensor Arrays.

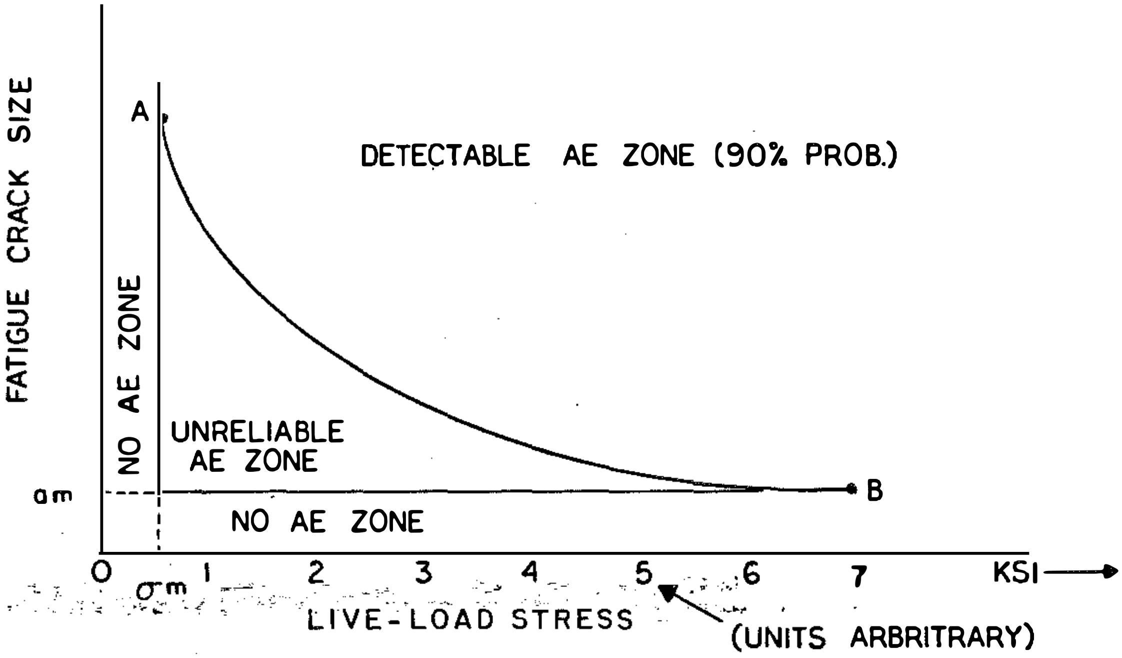


Figure 29. Limit of AE Detection Curve.

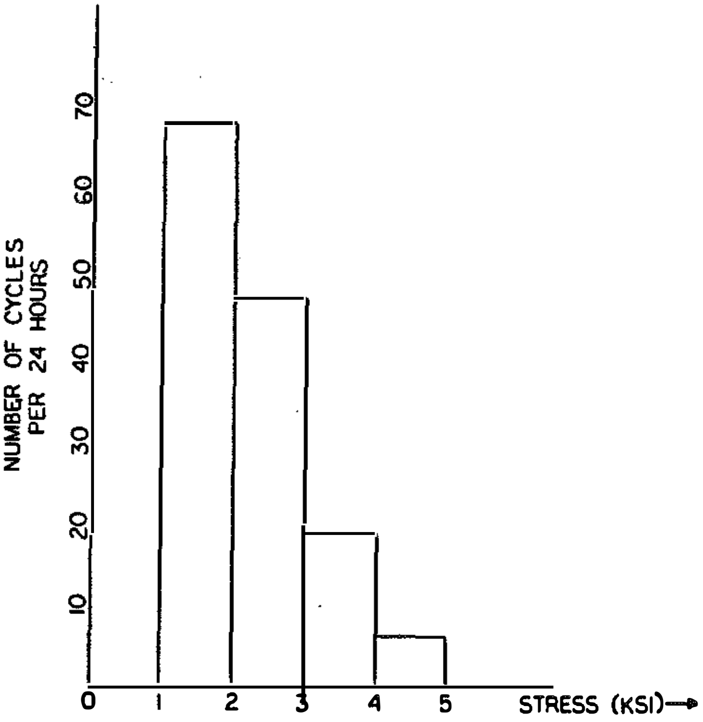


Figure 30. Stress Distribution Histogram for a Bridge Member.

TABLE 1. SUMMARY OF BRIDGE TESTING EXPERIENCE

	SITE	DETAIL	PROBLEM	AEWM Results	DECISION
KTRP/GARD	I 24 Tennessee River (multiple tests)	Floor Beam Horizontal Stiffener	Visible Out-of-plane Bending Cracks	Crack Growth Indications (less each retest)	No Repair; Self-extinguishin Cracks
KTRP/GARD	I 75 Ohio River	Termination of Welded Cover Plate on Lower Flange of Longitudinal Stringer	Potential Fatigue Crack Location (nothing visible)	No Crack Growth Indications	No Repair; Periodic Retest
GARD	I 94 Ohio River	Upper Web to Flange Weld in Double Cantilever Box Beam	Visible Cross Cracks in Weld	Crack Growth Indications (8-hr rate)	Repair
KTRP/GARD	I 24 Ohio River	(a) Butt Weld in Tie Girder	Non-visible Ut Indications, Hidden by Retrofit Bolted Coverplates	Crack Growth Indications (4-hr rate)	Repair was Justified
		(b) Floor Beam Vertical Stiffener	Visible Out-of-plane Bending Cracks	Crack Growth Indications (1/4-hrs rate)	Repair
GARD	US 18 Mississippi River Prairie Du Chien, Wisconsin	Electroslag Welds in Lower Flange of Tie Girders	UT Indications	No Crack Growth Indications	Periodic Retest
KTRP	I 471 Ohio River	Transition Butt Welds Adjacent to Bolted Dield Splices in Tie Girders	New Array Evaluation	No Crack Growth Indications	N/A
KTRP	US 25 Rockcastle River Corbin, KY	Web Adjacent to Lower Flange of Riveted Girders	Background Noise Evaluation	High Noise Level Totally Rejected - No Indication	N/A
KTRP	I 64 Ohio River Louisville, KY	Stringer Attachment to Floor Beams	Visible Cracks (no measureable growth)	No Crack Growth Indications	Periodic Retest
KTRP	I 310 Mississippi River Luling, LA	Pierced Box Girder	Visible Cracks (no measureable growth)	No Crack Growth Indications	Periodic Retest