ABSTRACT

Active defects, such as crack growth, produce acoustic emission (AE) signals. These signals can be detected by sensors spaced between 3 and 20 m apart, depending on the structure. The sensors are mounted directly onto the external surface and no paint removal is required for their mounting. The use of sophisticated data acquisition and analysis systems enables cracks to be located very early in life, long before they are detectable by the naked eye or other non-destructive testing methods. This paper presents BOXMAP technology, which has been developed by Physical Acoustics Limited and Cardiff University over the past 5 years, as a proven method for locating cracks in steel bridges. The methodology for monitoring structures is described in detail, highlighting strategic and practical considerations for the client and the engineer. These include access requirements, structural investigation and the filtering of any extraneous “noise” from crack data. One of the main benefits comes from data collected from continuous or intermittent monitoring, which can be used as structural fingerprints. These fingerprints can then be compared at regular intervals and the change in condition and/or rate of crack growth determined. This provides qualitative and quantitative information, from which repairs can be ranked and a priority-based maintenance strategy developed. The overall benefit is reduced whole-life costs. Details about the capabilities and limitations of different monitoring strategies are presented, along with examples from bridge trials with particular emphasis on source location and characterization.

INTRODUCTION

Bridge monitoring has the aim of providing information on the structural condition of a bridge, identifying and evaluating defects, to optimize maintenance work and maximize the impact of a limited budget [1]. Currently this is done by visual inspection [2] and monitoring using traditional methods such as strain gauging with conventional non-destructive testing methods used to evaluate suspected defects. Whilst this increases confidence in the integrity of the structures, many defects remain undetected until they reach an advanced stage [3-5].

There is a need for an assessment tool that is capable of identifying defects in their early stages, as risk and cost can be reduced by early intervention before large-area damage occurs. Monitoring systems using strain gauges and deflection transducers rely on various indicators such as deformation, strain and the vibration modes of the structure as a means of evaluation. These systems concentrate on detecting major structural changes that are caused by notable deformation and redistribution of stresses in the structure, by which stage severe damage has already occurred.

Traditional NDT techniques such as X-radiography, ultrasonics, magnetic particle and dye penetrant are widely used throughout industry but are generally cumbersome to use on site. All of these techniques assess local areas, which require good access to the structure and may entail working at height, above water, or in the proximity of fast moving traffic.
Indeed, some structures have areas that are so difficult to access that it becomes unfeasible, dangerous, or too costly to inspect. These techniques also provide a “snap shot” of defects and are unable to provide any more than speculative information about future behavior. They are ineffective and too costly as a “global” inspection method.

The benefits of acoustic emission (AE) are long known in the oil/petrochemical and aerospace industry, and are becoming increasingly recognized within the civil engineering industry. For 6 years, the Federal Highways Agency and Physical Acoustics Corporation in the USA monitored known defects and evaluated repairs on a number of bridges and produced a report with guidelines for the local monitoring of cracks and repairs [6]. Over the past 6 years during fatigue tests at Cardiff University’s School of Engineering, AE from large structural specimens has been studied to identify the characteristics of the different stages of crack growth [7-9].

Physical Acoustics Limited and Cardiff University have developed an AE-based condition monitoring technique for steel and composite bridges after a number of investigations and trials on a variety of bridges [10]. The AE system detects and locates active defects, such as crack initiation, anywhere in a structure using externally mounted sensors, positioned meters away from defects. This method allows non-invasive 100% volumetric assessment of structures and is therefore particularly effective for box girders, which has led to the development of the BOXMAP technique.

**STRATEGIC CONSIDERATIONS FOR AE BRIDGE MONITORING**

Before carrying out an AE test, there are strategic considerations to be made. Three main factors, structural detail, the acoustical behavior of the structure and the monitoring strategy, namely Global, Semi-Global and Local, will dictate the number and location of sensors.

Box girders may have some of the following design features; diaphragms (with and without access holes), diagonal-bracing, stiffeners, and external access holes. All of these features influence the way that the elastic stress wave travels, decays and is located by the software. It is therefore necessary to review technical drawings to make use of structural details as wave-guides to ensure the full extent of the structure is monitored.

The location and number of the sensors to be used is a function of signal attenuation, which is affected by structural geometry, plate thickness, design, paint characteristics, and background noise. In every case, there will be unwanted “noise” from external sources such as traffic activity, expansion joint impact, bearing movement and airborne electromagnetic interference (EMI). It is essential to filter any extraneous emissions from collected data so that emission from defect growth is recognizable. Background noise is overcome using a range of methods; guard sensors are used to shield sensor arrays from sources of noise such as expansion joints; pattern recognition programs filter out identified noise sources that are incorporated into the cracking data. These methods have been developed using the experience gained during 6 years of bridge monitoring work with Federal Highways in the USA and during numerous bridge trials in the UK, and fatigue testing at Cardiff University.

Structures can be continuously or intermittently monitored with permanently installed sensors from the site or remotely via a modem. Technological advances and increased accessibility to the Internet allow “remote from site” real-time structural monitoring. Permanent mounting of cables and sensors with pulse and self-test capability eliminates the need for repeated access, giving rapid payback compared with the cost of aerial lifts and aerial walkways. Short duration on-site monitoring can provide
qualitative and quantitative information that can effectively assess the structure over a period of days using temporarily mounted sensors.

Three common monitoring methods are used to obtain differing levels of information:

- Global
- Semi-Global
- Local Area

“Global” monitoring using large sensor spacing still offers maintenance engineers the ability to identify damaged structures and focus further monitoring or inspection on areas sustaining damage. Trials have shown that an entire box girder can be monitored for one day and reveal a number of active areas. We are currently developing techniques to reduce the number of sensors required to globally monitor a structure.

“Semi-Global” monitoring provides precise source location, but requires an increased number of externally mounted sensors to give 100% volumetric monitoring, i.e. capable of locating damage anywhere in the structure, including shear studs, diagonal-bracing, welds, stiffeners and diaphragms.

“Local” area monitoring is used to assess active sources and known defects, using a small array of sensors around the area of interest. Crack orientation, length, activity, and position can be determined with accuracy over a short monitoring period, whilst continuous or intermittent monitoring at this level can identify the direction of crack growth and the rate of propagation. This information is essential for the bridge engineer to determine the status of the known defect and schedule maintenance or repair.

AE monitoring strategies all offer different levels of information about structural integrity and defects. AE monitoring using all of the strategies in conjunction may provide priority based assessment and maintenance methods where structures need to be fully assessed. “Global” monitoring is initially used to grade the structure according to its condition. Structures with active defects can then be “Semi-Globally” monitored to identify and locate significant sources, which in turn can be “Locally” monitored, or assessed using traditional NDT methods, where access is possible to acquire detailed information.

FIELD TRIALS

One of the earliest AE tests of a steel bridge was carried out by Pollock and Smith [12] in 1972 on a military steel bridge. Since then there have been many more tests on a wide variety of structures, both steel and concrete. Huge experience was gained by Physical Acoustic Corporation during local area monitoring of identified defects and repairs for Federal Highways (F.H.W.A.). This work prompted Physical Acoustics to develop the Local Area Monitoring (L.A.M.) AE system.

Large area monitoring of steel structures have been developed by Cardiff University in conjunction with Physical Acoustics Limited. All tests and trials carried out used Physical Acoustics Corporation’s MISTRAS and SPARTAN AE systems, and sensors. The first trial on Trecelyn Viaduct in 1996 sought to establish the level of background noise typically encountered in bridge structures and to study the attenuation of signals in large structures. Emissions from expansion joint impact were found to “ring” throughout the structure, which required digital filtering. Bolted connections were found to significantly reduce the signal strength, yet artificial sources were adequately picked up at distances in excess of 20 meters.
Extensive trials were carried out in 1997 on Saltings Viaduct, a 26-year-old composite box girder on the A465 near Neath, South Wales (Fig. 1). This study showed that active areas were identifiable at 10-metre sensor spacing, many of which coincided with internal diaphragms. Local monitoring of the most active diaphragm identified a strong source from the access hole cut into the plate. Recent Finite Element analysis [13] showed this to be an area of particularly high stress, which has led to ongoing fatigue tests on box girder sections with a variety of diaphragm designs.

**MOTORWAY TRIAL I - PRELIMINARY INVESTIGATION**

During preliminary investigations, a composite box girder bridge was monitored during the morning rush hour. Prior to monitoring, an acoustic investigation was conducted using an artificial source to confirm location accuracy for a variety of details within the structure, including stiffeners, diaphragms and the internal welds. The bridge was monitored using a Semi-Global, externally mounted array. This test revealed that the bridge was in a very good condition with very few AE signals detected. This preliminary investigation enabled an optimum test set-up to be determined for the following major bridge trial.

**MOTORWAY TRIAL II - MAJOR TRIAL TEST DETAILS**

A 40m span composite box girder was studied over a two-week period, during which it was semi-globally monitored for a one-week period between 5am and 10pm. The most significant AE sources, identified during investigations in the first week, where locally monitored during the second week. The girder lies underneath the cheveroned area between the 3 lanes south bound and the merging area of a two-lane slip road, Fig. 2. This girder was chosen since transverse deformation across the deck induces high stresses in the diagonal bracing members, Fig. 3.
In order to identify any sources in the girder and attachments, the beam was monitored using a semi-global array that gave 100% volumetric monitoring. Two-dimensional location was achieved by “unwrapping” the structure, with damage locations shown on an “opened-up” diagram. Integrity of the cross braces was assessed using linear source location between sensors at either end of each cross brace. An initial AE study identified the expansion joint as a large source of extraneous noise. To filter this noise from the test data, guard sensors were placed to the ends of the girder. One-day trial monitoring in the first week identified 62 sources. Local arrays were set up around the two most active sources.

**RESULTS OF THE TRIAL**

From the 62 identified sources, 18 were identified as significant and analyzed in detail. These were all found to be active on a daily basis. All but one of the 18 significant sources were found to be located at the end of the diagonal bracing. The main source “A”, identified by “Semi-Global” monitoring during the first day and subsequently monitored by a local array, is crack like and approximately 250 mm long, as illustrated in Fig. 4. It was located below the end of a diagonal bracing connection at the bottom of the flange. It is difficult to state whether the source is in the internal seal weld or bottom flange/web weld. The absence of emission from the central region of the suspected crack suggests that there is no further growth in this area.

AE activity showed a strong correlation with traffic flow. During periods of peak traffic flow, the average traffic speed dropped and at times traffic was stationary. These periods saw a reduced amount of emission. Most activity occurred when there was a high percentage of lorries travelling at a high speed, 55-65 mph. Figure 5 shows the correlation between strain due to free flowing traffic and AE events detected from the most active source, source "A".
Fig. 4: Local monitoring location graphs for Source “A”; top graph shows activity in 2D, lower graph shows AE activity along the length of the crack like source.

Fig. 5: Correlation between events from Source “A”, and strain, over the same time period during peak but free flowing traffic conditions.
CONCLUSIONS

Acoustic emission monitoring trials on motorway bridges using “Semi-Global” and “Local” sensor arrays have demonstrated that AE is a very effective method for detecting damage in bridges and steel structures, and for continuous monitoring of defect growth. A major advantage is that there is no need for internal access or paint removal. In addition, it is 100% volumetric testing, and damage location is achieved with relatively few sensors. Global monitoring has been developed as a method for identifying damaged structures; further research is being carried out by Cardiff University and Physical Acoustics Limited to develop this method to its full potential.

REFERENCES