Acoustic Emission Non-Destructive Integrity Assessment of Intermodal Transportation Infrastructure Asset Interactions

Final Report

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Final Report

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Disclaimer:

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Abstract

It is imperative to conduct research and utilize technologies that enhance highway bridge safety by predicting and thus preventing bridge failures. In this work, the technology of acoustic emission (AE) is applied to study the integrity of a highway bridge, the Interstate I-64 bridge crossing over Kempsville Rd in Norfolk, VA. The bridge that comprises the westbound lanes of this crossing utilizes three steel girder spans. One of the girders in the middle span is suspected to carry a defect and the AE monitoring technology is a promising technique in such applications. The AE tests carried out on that girder indicated that the crack is not active and does not pose any threat to the integrity of the structure.

The northern span of this bridge has ten steel girders to support the highway. These ten girders are subjected to fatigue loading due to the traffic and it is required to periodically examine their integrity against fatigue cracks. It is expected that the middle girders may undergo heavier load conditions and our measurements did show such a trend. However, the AE measurements also indicated that one girder showed distinctly higher AE activity which was not expected. Thus it is deduced that this girder may have an active crack site, which needs further detailed examinations. It is therefore advised to carry out further NDT tests to check for the integrity of the girder. Visual examinations, dye penetrant tests, and ultrasonic tests can be carried out to locate the source of the defect, if any.

Background and Objectives

Incorporating U.S. D.O.T.'s stated priority for improving the safety of the nation's transportation infrastructure, this project focuses on the improvement of the safety of highways and highway bridges. MTIC's main goal is to undertake research projects that have significant impact on the economic growth through the development of the region. Promoting the development of an integrated, economically competitive, efficient, safe, secure, and sustainable national intermodal and multimodal transportation network by integrating all transportation modes for both freight and passenger mobility is one of the best ways to achieve such a goal. Keeping highway and rail bridges safe is crucial for the efficient performance of the intermodal and multimodal transportation networks – this ensures faster flow of goods and services to be economically competitive.

With these stated objectives, it is imperative to conduct research and utilize technologies that enhance highway bridge safety by predicting and thus preventing bridge failures. While U.S. has a vast and world's best transportation infrastructure, it has been aging fast. According to the 2013 Report Card for America's Infrastructure, the federal, state, and local bridge investments have not been keeping pace with the growing costs of maintaining aging bridges, therefore making it necessary to investigate other technologies to reduce the conventional time and effort required to inspect and maintain such bridges for their integrity and safety. To illustrate, the nation's 66,749 structurally deficient bridges make up one-third of the total bridge decking area in the country. In 2014, almost 24% of all nation's bridges were classified either as structurally deficient or functionally obsolete. Both, however, do not pose an immediate threat to the safety. A bridge is defined as structurally deficient if it requires significant maintenance and repair investments as well as regular inspection efforts. A functionally obsolete bridges no longer meet current standards due to, for example, narrow lanes or excessive traffic flow. Allowing such bridges to remain in service can lead to unexpected closures and significant traffic disruptions later on, therefore undermining the economic competitiveness and effectiveness of the transportation infrastructure.

The hazards affecting highway bridges and leading to their deterioration include aging, extreme events such as natural disasters (e.g. hurricanes, floods, major storms, etc.), hazards stemming from negligence, improper maintenance and collisions, and, most importantly, operational loads from the increased freight transportation truck weights. Bridge structures, being vital for safety and economics, need the best protection, and the evaluation of their integrity becomes paramount. The ability to obtain necessary information regarding the bridge technical condition is often expensive and time consuming; furthermore, the inspection methods and techniques used need to be non-destructive, devoid of introducing any new damage during the monitoring process.

Currently, visual inspection is the most common NDT method used to evaluate the condition of the majority of the nation's highway bridges. However, due to the obvious periodical nature of the inspections, it cannot provide a continuous monitoring of the condition of a bridge. Another issue with this approach is that it can only identify a deterioration once it becomes visible. Therefore, other approaches and techniques need to be investigated to resolve these shortcomings. Available NDT methods include radar and laser imaging, electrical and magnetic flux methods, acoustic measurements such as ultrasonic testing and acoustic emission monitoring, or a combination of methods. Although these methods have been used successfully on a variety of concrete and steel structures, there is a general lack of confidence in the techniques because there is little independent advice on their applicability, capability, accuracy, and reliability. In general, more than little experience is necessary for proper interpretation of test data and generally there is a need for development of reliable interpretation procedures.

With these goals in mind, this research addresses the application of the acoustic emission (AE) non-destructive testing technology to evaluate and monitor the highway bridge integrity. The overarching goal of this work is to advance the state of art in the steel girder bridge structural monitoring via the use of AE technology to reduce the conventional time and effort required to inspect such bridges for their integrity and safety. The impact will include the advancement of the NDT technology application expertise by utilizing the AE technology for data acquisition and real-time analysis for prediction of factors that lead to deterioration and wear in the highway structural components under the stresses of traffic environment. The objective is to determine methodology to identify defects within the bridge structure utilizing their AE footprint. The twofold goal of this research also includes the enhancement of the HU's capabilities and increased participation of the minority students in the transportation-related projects by actively engaging them in the research and training, thus forming the next generation of transportation workforce.

Methodology Overview and Scope

The phenomenon of AE represents transient elastic waves produced by the rapid release of energy in a stressed material. When a material is subjected to some external effect such as a load or a change in temperature, localized sources trigger the release of energy in the form of stress waves, which propagate to the surface and are captured by AE sensors. The classic sources of AE in engineering structures such as bridges are the defect-related deformation processes such as crack initialization and growth as well as plastic deformation. Sudden movement at the source produces a stress wave, which then radiates out into the structure. AE have also been measured and recorded in polymers, wood, and concrete, among other materials.

AE differs from most other NDT methods in that it does not require supplying any external energy to the structure to locate any irregularity – it simply "listens" to the structure and captures any energy released by the structure itself under its normal operating loads. Another useful aspect is that AE is able to discern between active and inactive defects, although one has to be careful about this since it is possible to not have high enough loading force to cause acoustic emission. Unfortunately, AE can only qualitatively assess the deterioration within the structure and additional testing using other methods is often necessary unless the defect is visible. Also, the sensitivity of an AE system is often limited by the amount of the background noise.

The diagram below (Fig. 1) represents a general schematic of an AE monitoring system. Such system would include a transducer which detects the bursts of energy emitted by the source within the structure and a data acquisition hardware and software that receives, stores, and analyzes the AE data.

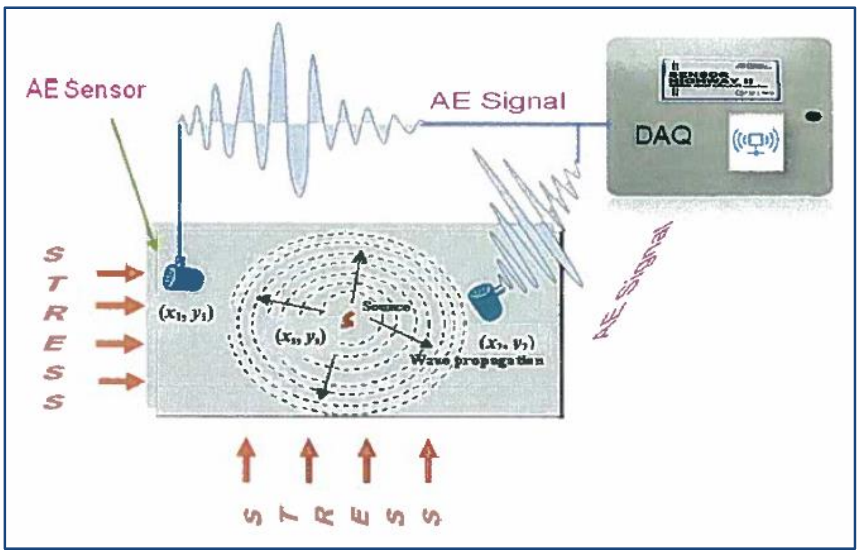

Figure 1: Schematic of the AE technology application.

The surface waves generated by the stress in the material are detected by the piezoelectric devices, called the AE sensors or transducers, attached to the surface of the structure. The AE signals detected by the sensors are digitized and recorded by the data acquisition (DAQ) system for further processing and analysis to determine location of the source event. Three types of AE transducers produced by the Mistras Group, Inc. were used in this work - PK6I, PK15I, and PK30I (Fig. 2). These sensors are low power, resonant AE sensors with built-in 26 dB pre-amplifiers. The resonance frequencies of these sensors are 60 kHz, 150 kHz, and 300 kHz, respectively.

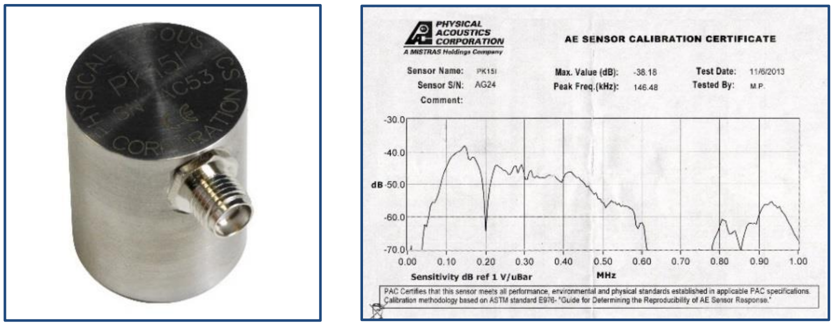

Figure 2: General view of the PK15I AE sensor (left) and a sample calibration chart of the sensor (right).

Sensor Highway II (SHII) data acquisition (DAQ) equipment as well as the 1284 Wireless AE system manufactured by Mistras Group, Inc. were available for this project (Fig. 3). SHII is a 16-channel system designed for unattended monitoring of structural health with particular application for highway bridges. This system was fitted with the internet link through the cellular phone provider to allow for remote control of the unit as well as remote download of the AE data. The 1284 Wireless AE system is a low power system that provides capability to monitor up to 4 AE channels wirelessly using the built-in battery power, which make it extremely convenient to use by eliminating the need to run long cables between the sensors and the AE system.

Figure 3: General view of the Sensor Highway II (left) and 1284 Wireless AE system (right) equipment.

Through the collaboration of the HU researchers with Virginia Department of Transportation (VDOT) and based on VDOT staff input, the interstate I-64 bridge crossing over Kempsville Road in Norfolk, VA, was selected for this study. The work focused on the westbound lanes of this bridge. The scope of this work was limited by studying the AE data on the steel girder #7 of the middle span of the bridge (span 2), and on all 10 steel girders of the smaller northern span of the bridge (span 1) (Figs. 4 and 5). The steel girder #7 of the middle span of the bridge had a visually identified (previously by VDOT) crack in the girder-to-cross-brace connection (Fig. 6). AE transducers were installed on this span to monitor the condition and to determine whether the crack was active or not.

To complete the installation of AE sensors in the middle span of the bridge (span 2), VDOT provided all necessary assistance in the form of lifting equipment, personnel, and road traffic control. Two sensors were installed using magnetic enclosures for sensor attachment to the bridge structure (Fig. 7).

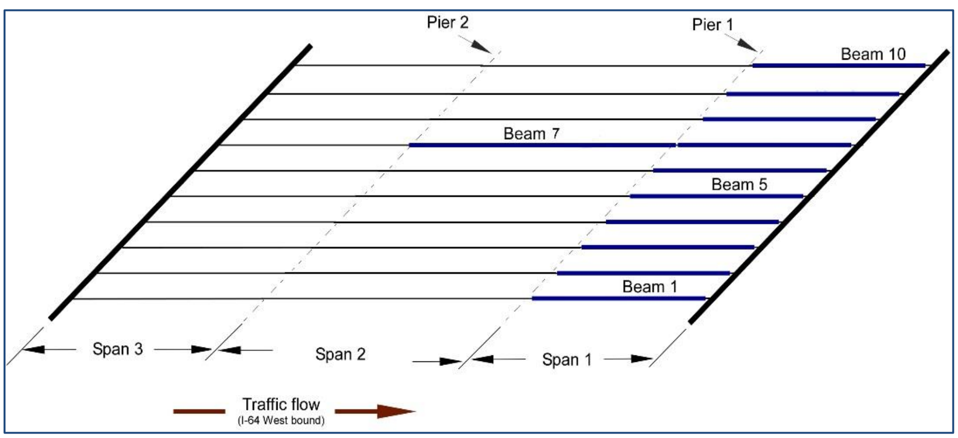

Figure 4: General diagram of the bridge showing the steel girder (beam) layout.

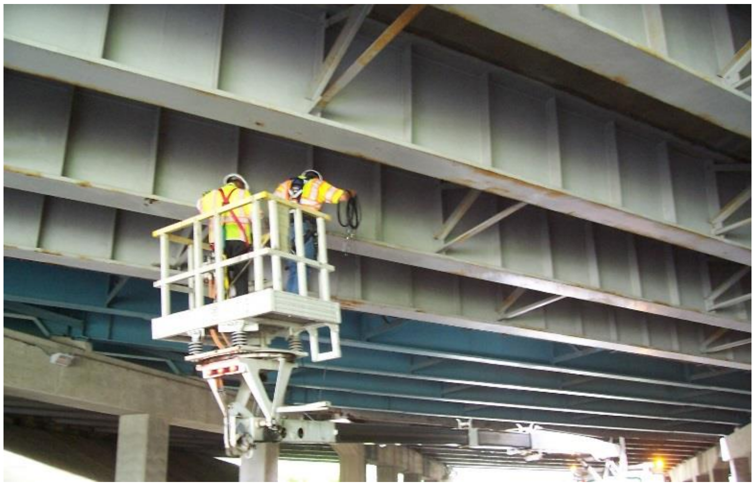

Figure 5: General view of the bridge during AE sensors installation.

Figure 6: Visually identified crack in the girder #7 connection to cross-brace (location marked with "X" by VDOT, span 2)

Figure 7: Typical AE sensor installation using the magnetic enclosure.

Figure 8: AE sensors mounted onto the steel beams in the northern span of the bridge (span 1).

The work on the northern span of the bridge (span 1) was conducted without VDOT assistance with AE sensors mounting as the relatively low bridge height in those locations allowed AE sensors installation without the use of lifting equipment and did not interfere with road traffic. Four sensors were used to monitor AE activity on each steel girder in this span of the bridge (Fig. 8).

Analysis of the Results

Bridge Span 2: Two 60 kHz AE transducers were mounted on the girder #7 which had a defect as was identified by VDOT. AE sensor 1 was installed in the immediate vicinity of the defect and AE sensor 2 was installed at the distance of approximately 40 ft. near the supported end of the girder.

Preliminary tests that were carried out in the year 2013, over a period of four months, indicated that no appreciable increase in AE activity was found during that time, in that there was no active crack propagation. Since the AE activity varies in accordance with the traffic situation on the bridge, we have additionally conducted two experiments over a period of 5,000 seconds at 10:00 AM in the morning during the busy traffic hour. Figs. 9 and 10 show AE signals measured under these conditions. We did not notice any significant increase in the AE activity during the second experiment as compared to the first one. Therefore, the measurements taken over a period of one year showed that there was no significant increase in the levels of AE emission. It is expected that an active crack will show increasing rates of AE activity as the defect grows. Since there was no increase in the AE activity over the period of one year, it is concluded that the visible crack is inactive, in that the material around the crack does not encounter any appreciable stress concentration and there is no need to take any further action.

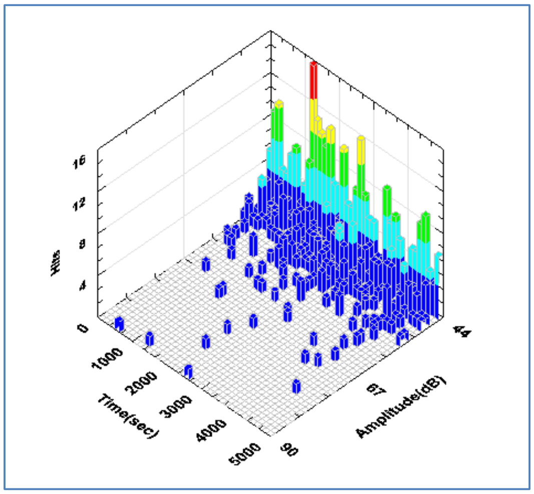

Figure 9: AE activity result measured in January 2014 for a period of 5,000 seconds during the busy road traffic hour.

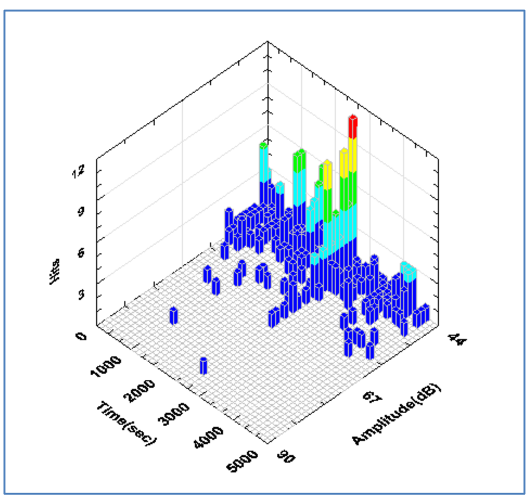

Figure 10: Subsequent AE activity measurement result to confirm the level of AE under the similar road conditions.

Bridge Span 1: In the northern span of the bridge (span 1), all ten steel girders were subjected to the test. Fig. 4 above shows the arrangement of the girders in this bridge span. On each girder, 4 AE sensors were mounted as shown in the Fig. 11. Two of the AE sensors used have resonant frequency of 150 kHz and the other two 300 kHz. In this bridge span, one end of the steel girder (left side in the Fig. 11) is fastened to the ground and the other end is supported by the concrete pier. Any active crack that is present in the beam will give rise to acoustic emission which can be sensed by the AE sensors. However, the time of travel of the signal reaching the transducer varies according to the distance; this information can be used to locate the active source of the crack.

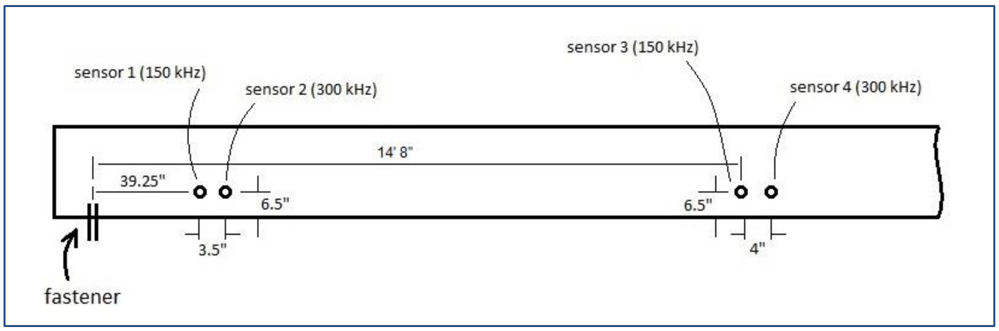

Figure 11: Arrangement of the 4 AE sensors in each girder.

3D graphs indicating the time, amplitude, and AE hits are given in Figs. 12 and 13. Fig. 12 shows the data on girders #1 to #10 using the 300 kHz AE transducers (Ch. 2 and Ch. 4), with the threshold held at 40 dB. Fig. 13 shows the data on girders #1 to #10 using the 150 kHz AE transducers (Ch. 1 and Ch. 3), with the threshold also held at 40 dB.

This bridge has four travel lanes with two shoulders. It has been observed in all measurements that the AE activity is always greater in the central portion of the road surface. The AE activity is the lowest in the girders #1 and #10, while girders #4, #5, and #6 exhibit more severe AE. This trend has been observed with measurements conducted with both 300 kHz as well as with 150 kHz AE transducers. AE hits acquired from the 300 kHz sensors (Channels 2 and 4) in the ten girders are given in the Fig. 14. Fig. 15 illustrates the same information as a summary, where it is very clear that the AE activity is greater in the middle of the road. However, it can be seen that girder #9 produces much higher level of AE activity, indicating that there is a possibility that this beam may have an active crack. It is recommended to carry out further detailed studies using visual examination, dye penetrant tests, and ultrasonic tests to check for the presence of defects.

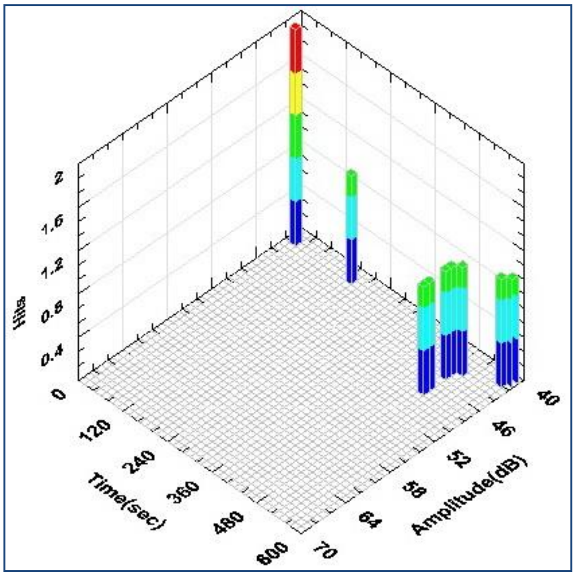

Fig. 12.1: Girder #1 (300 kHz, 40dB)

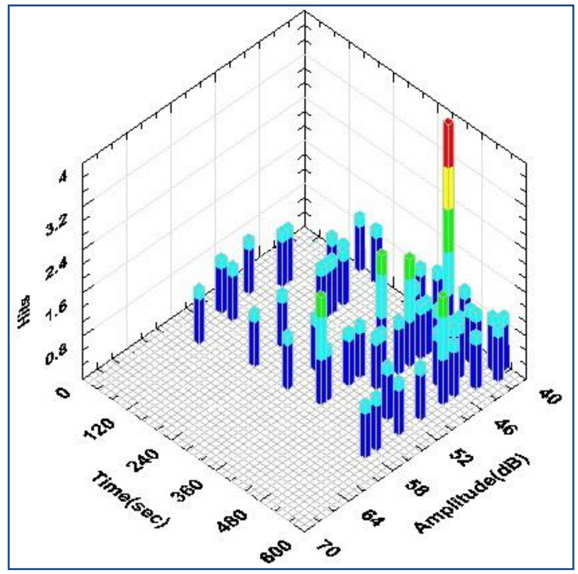

Fig. 12.2: Girder #2 (300 kHz, 40dB)

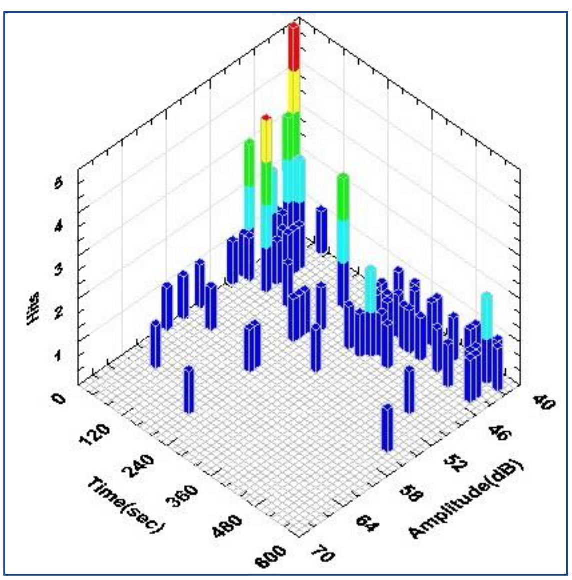

Fig. 12.3: Girder #3 (300 kHz, 40dB)

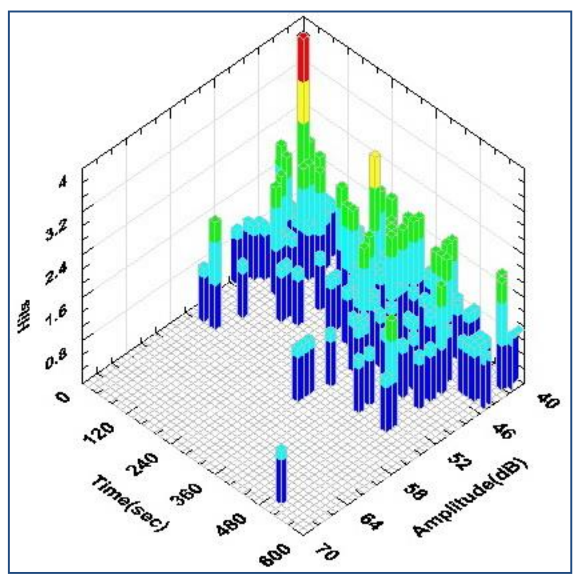

Fig. 12.4: Girder #4 (300 kHz, 40dB)

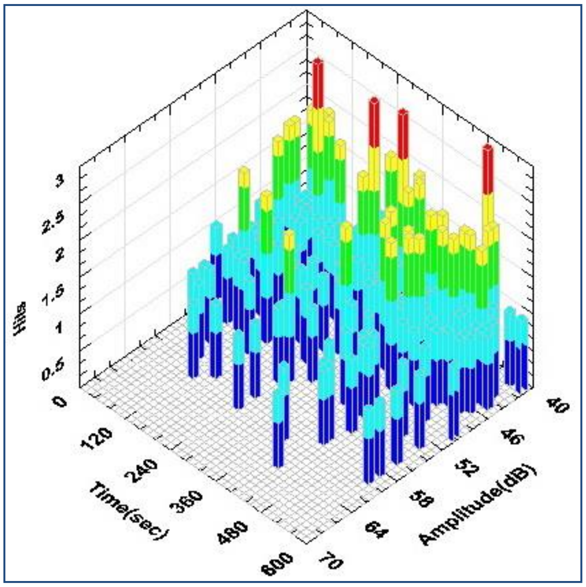

Fig. 12.5: Girder #5 (300 kHz, 40dB)

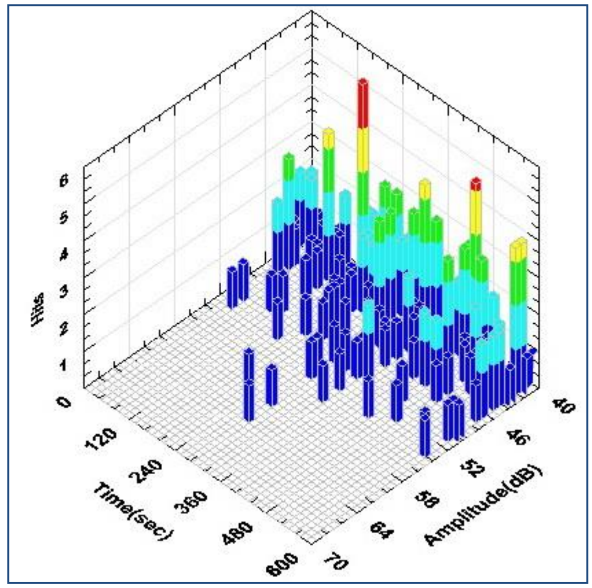

Fig. 12.6: Girder #6 (300 kHz, 40dB)

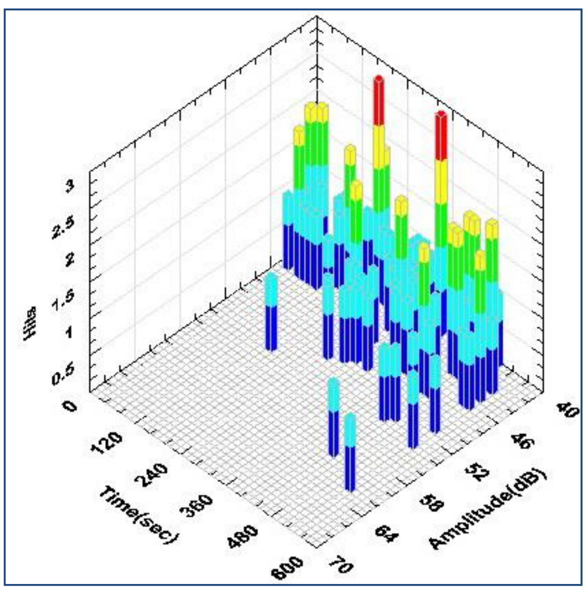

Fig. 12.7: Girder #7 (300 kHz, 40dB)

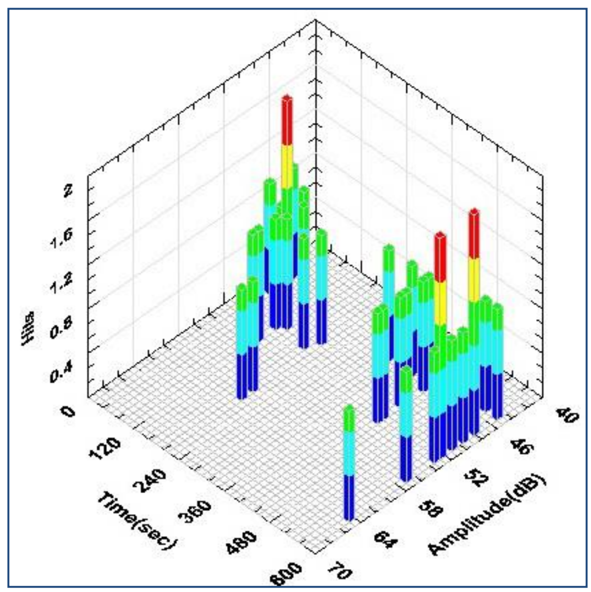

Fig. 12.8: Girder #8 (300 kHz, 40dB)

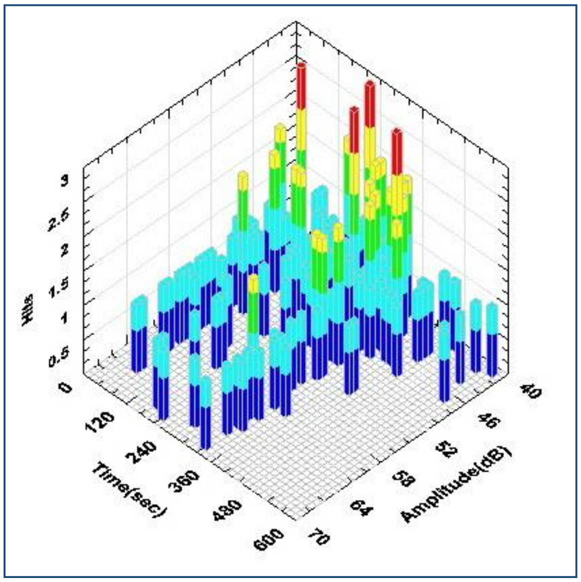

Fig. 12.9: Girder #9 (300 kHz, 40dB)

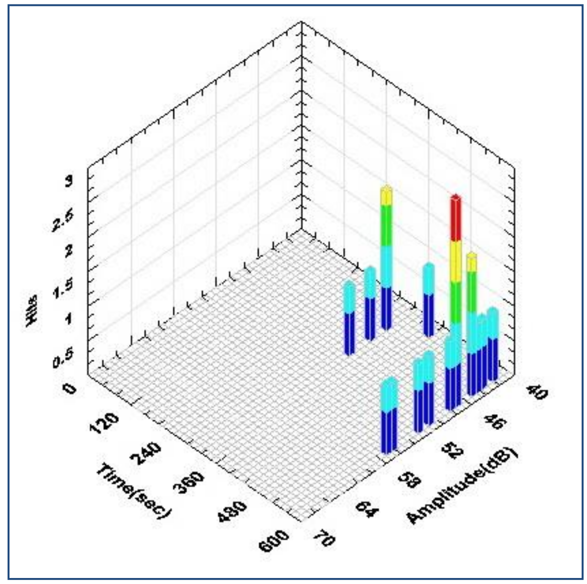

Fig. 12.10: Girder #10 (300 kHz, 40dB)

Figure 12: 3D test results using 300 kHz AE transducers.

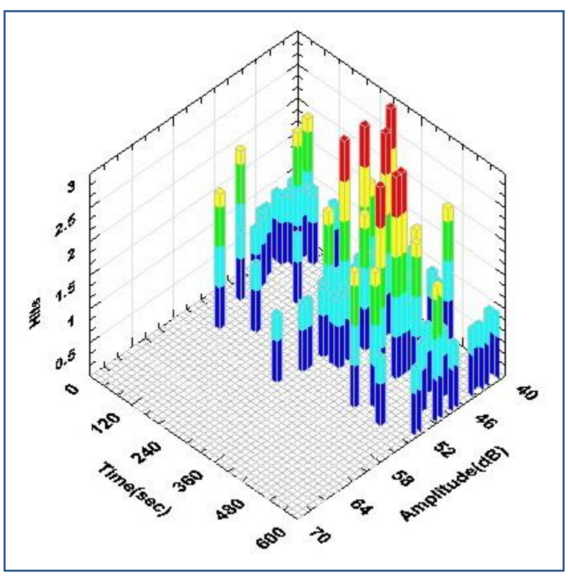

Fig. 13.1: Girder #1 (150 kHz, 40dB)

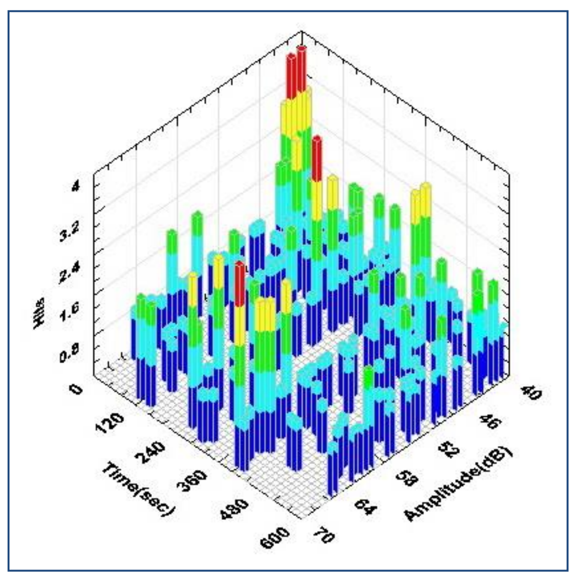

Fig. 13.2: Girder #2 (150 kHz, 40dB)

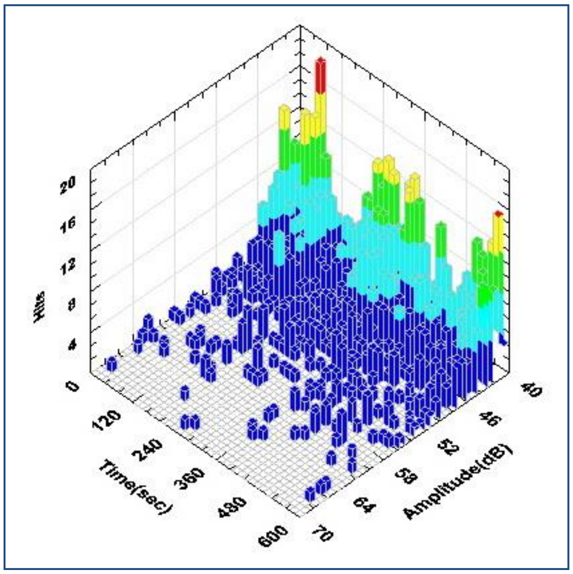

Fig. 13.3: Girder #3 (150 kHz, 40dB)

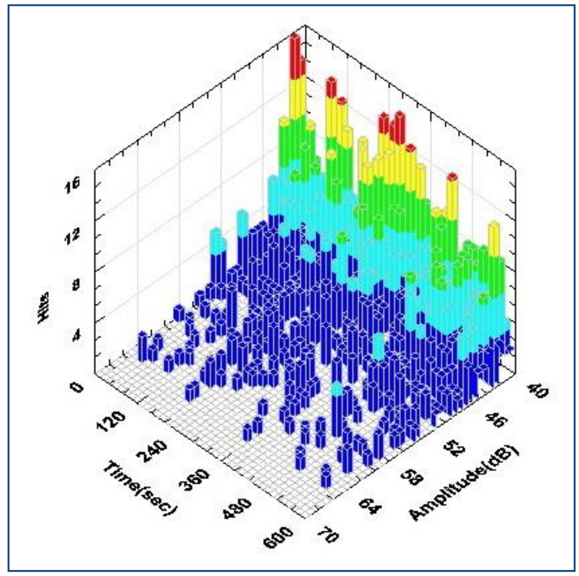

Fig. 13.4: Girder #4 (150 kHz, 40dB)

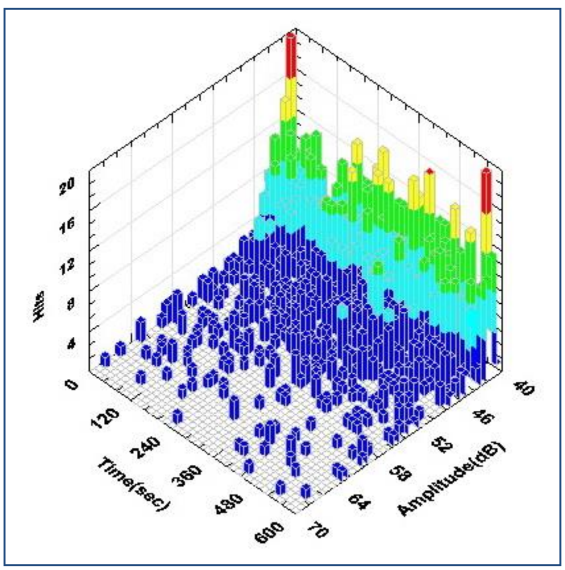

Fig. 13.5: Girder #5 (150 kHz, 40dB)

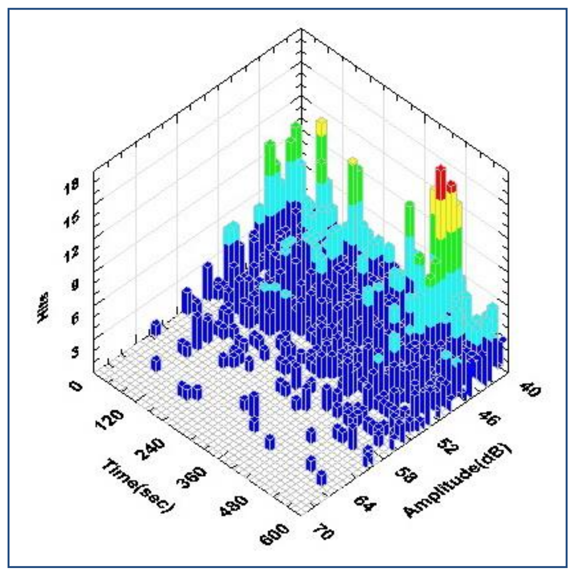

Fig. 13.6: Girder #6 (150 kHz, 40dB)

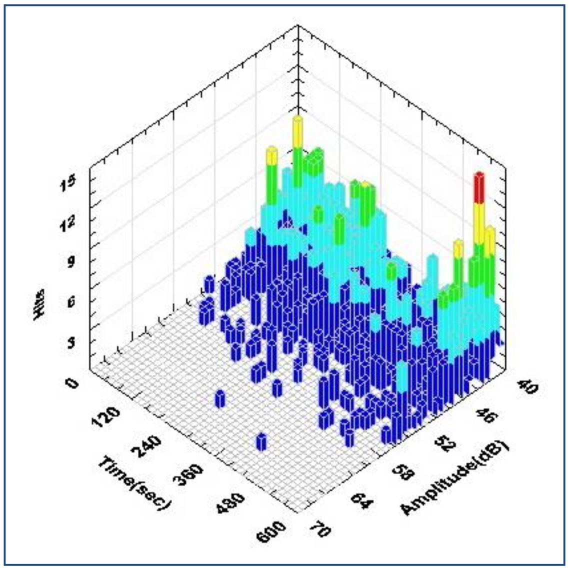

Fig. 13.7: Girder #7 (150 kHz, 40dB)

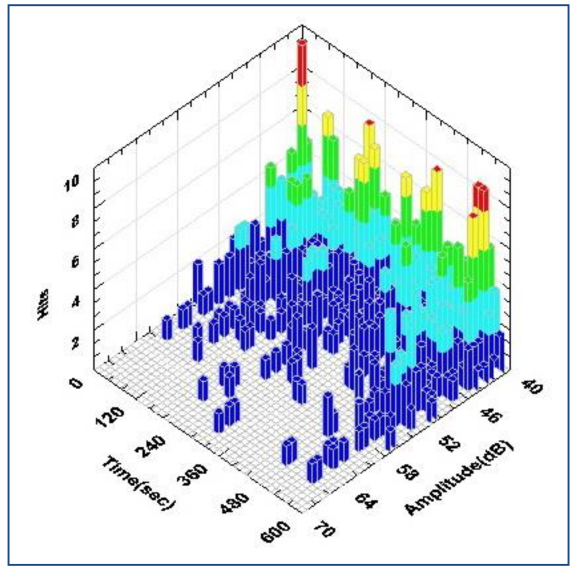

Fig. 13.8: Girder #8 (150 kHz, 40dB)

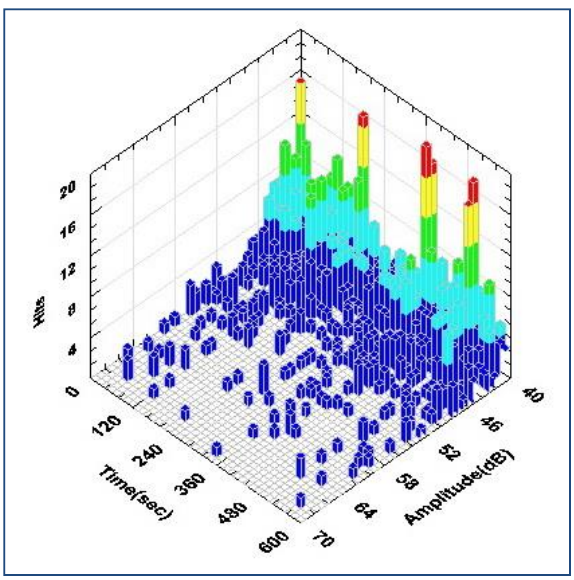

Fig. 13.9: Girder #9 (150 kHz, 40dB)

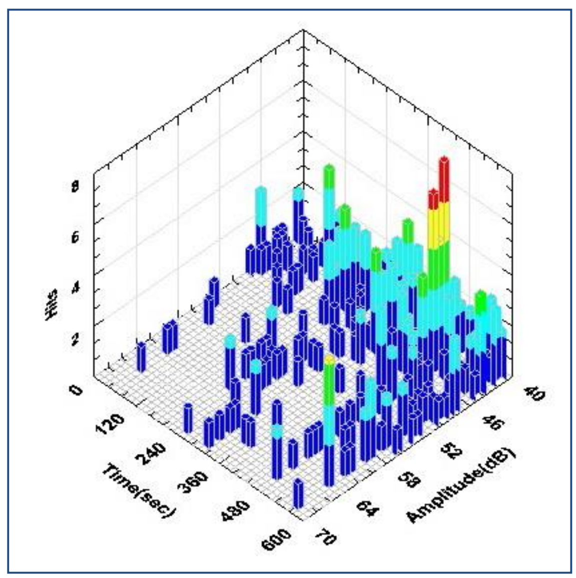

Fig. 13.10: Girder #10 (150 kHz, 40dB)

Figure 13: 3D test results using 150 kHz AE transducers.

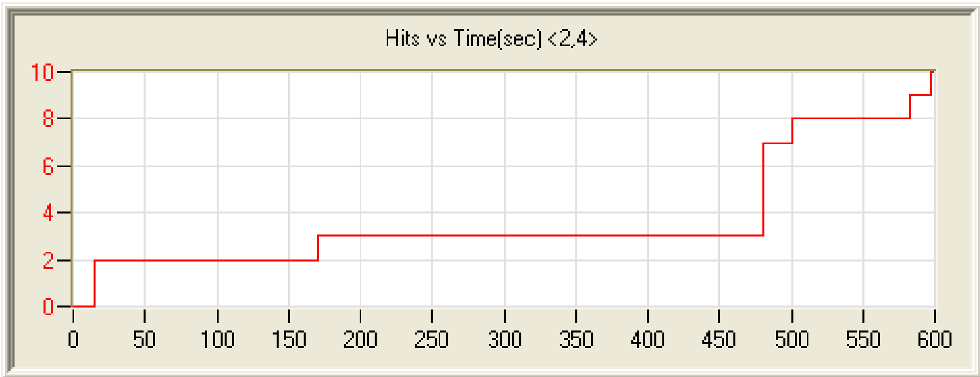

Fig. 14.1: Girder #1 (300 kHz, Ch. 2 and Ch. 4)

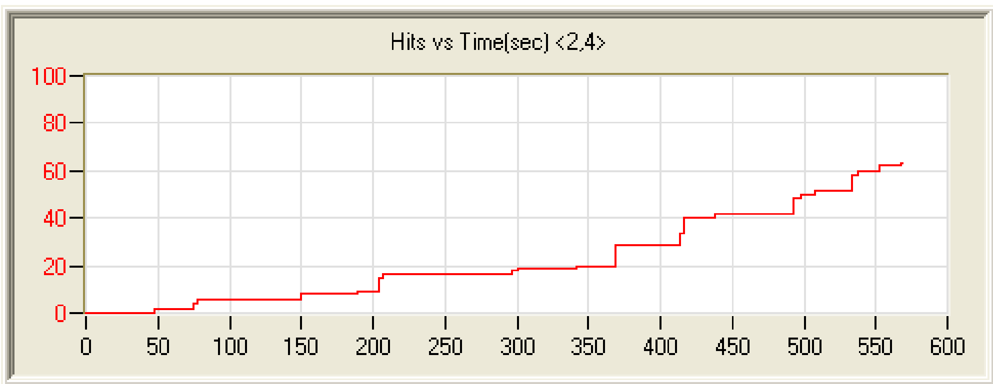

Fig. 14.2: Girder #2 (300 kHz, Ch. 2 and Ch. 4)

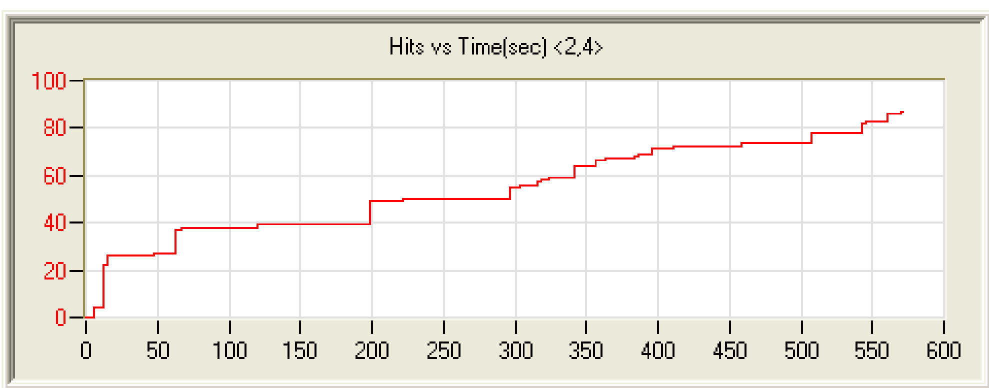

Fig. 14.3: Girder #3 (300 kHz, Ch. 2 and Ch. 4)

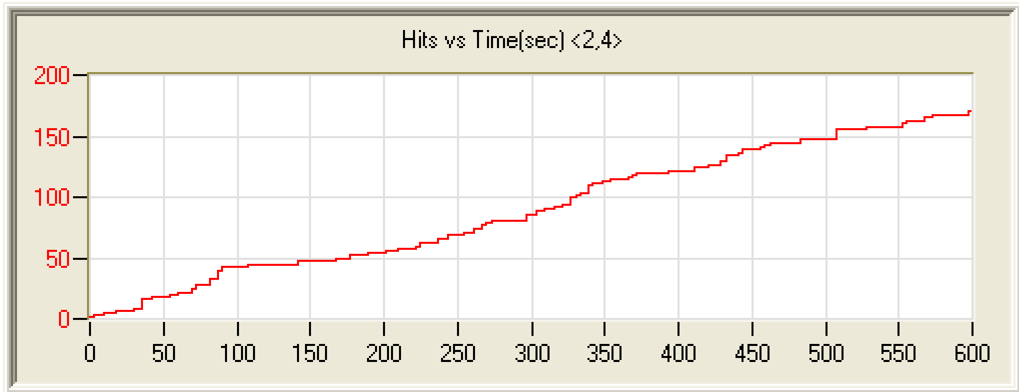

Fig. 14.4: Girder #4 (300 kHz, Ch. 2 and Ch. 4)

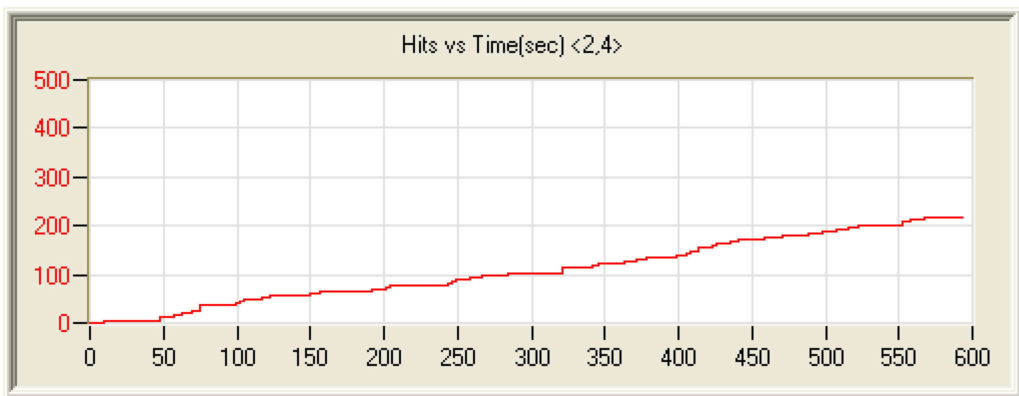

Fig. 14.5: Girder #5 (300 kHz, Ch. 2 and Ch. 4)

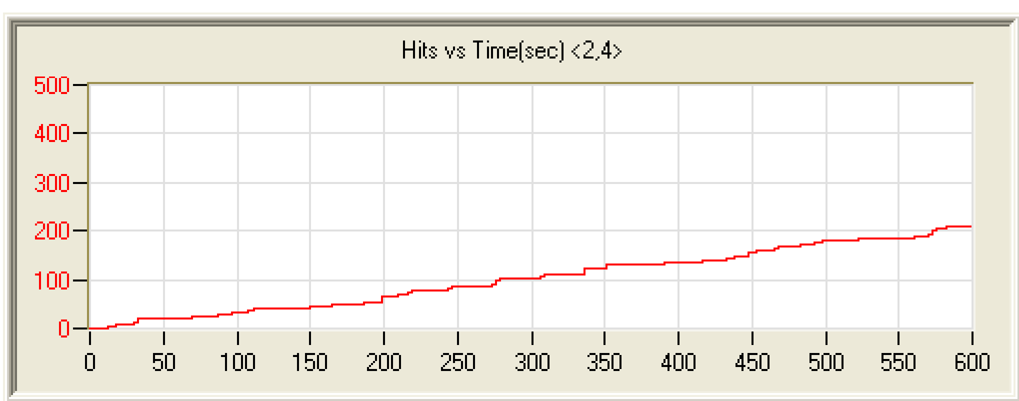

Fig. 14.6: Girder #6 (300 kHz, Ch. 2 and Ch. 4)

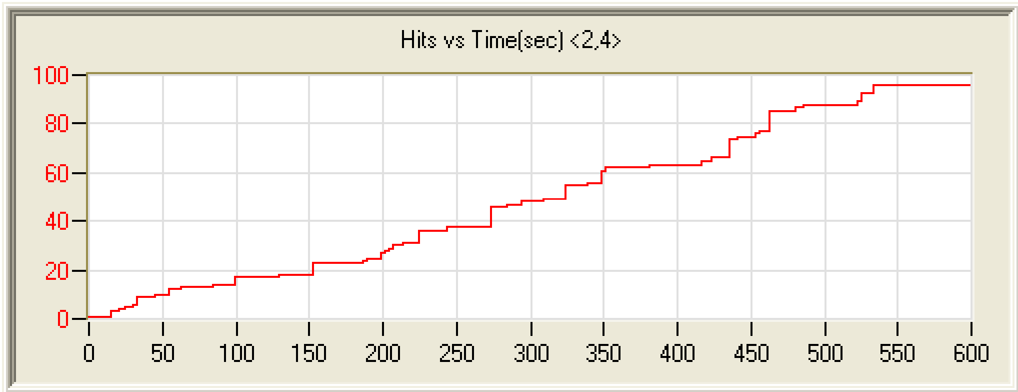

Fig. 14.7: Girder #7 (300 kHz, Ch. 2 and Ch. 4)

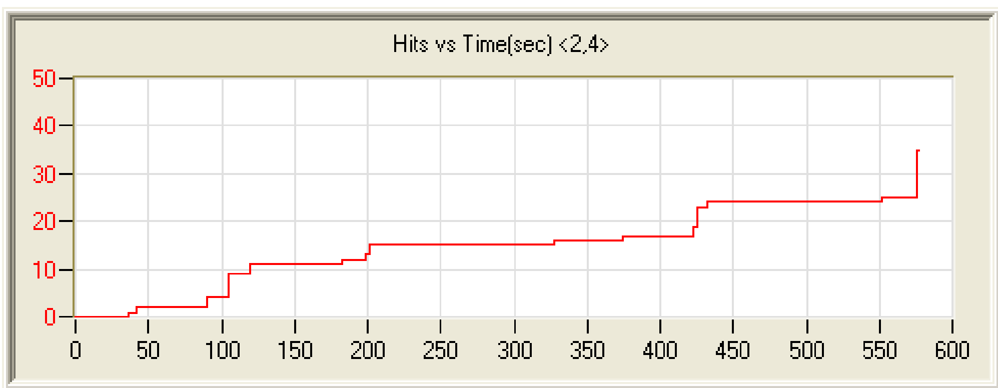

Fig. 14.8: Girder #8 (300 kHz, Ch. 2 and Ch. 4)

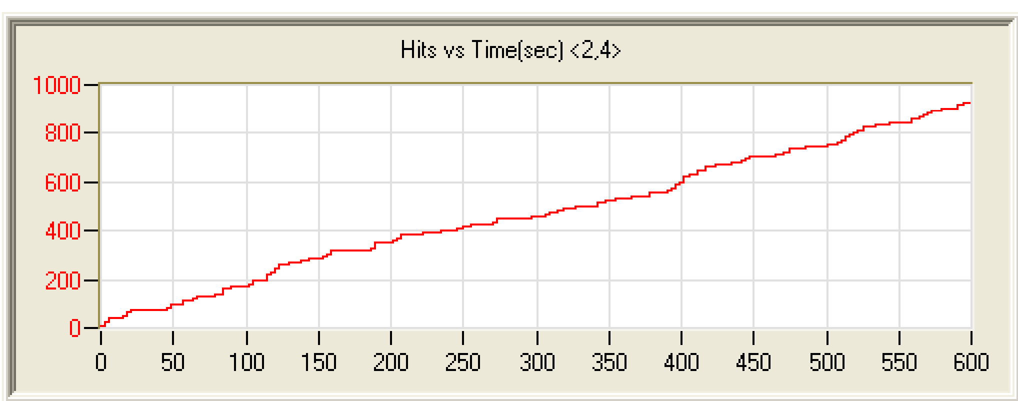

Fig. 14.9: Girder #9 (300 kHz, Ch. 2 and Ch. 4)

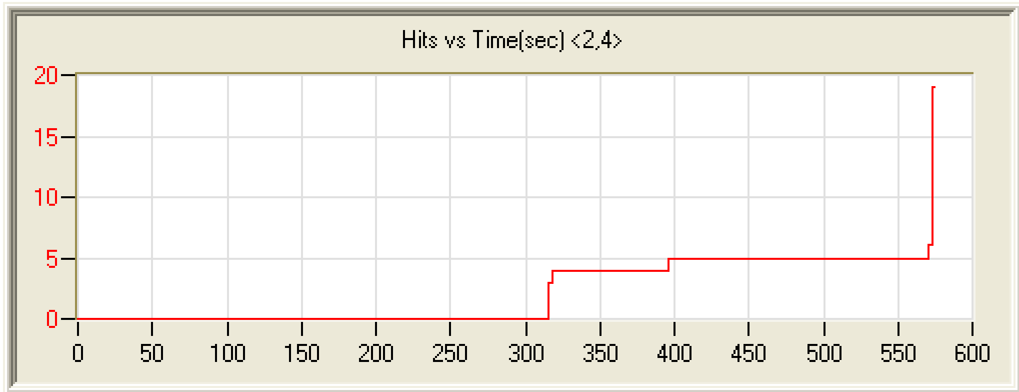

Fig. 14.10: Girder #10 (300 kHz, Ch. 2 and Ch. 4)

Figure 14: Total hits encountered during 600 seconds of tests using 300 kHz AE transducers.

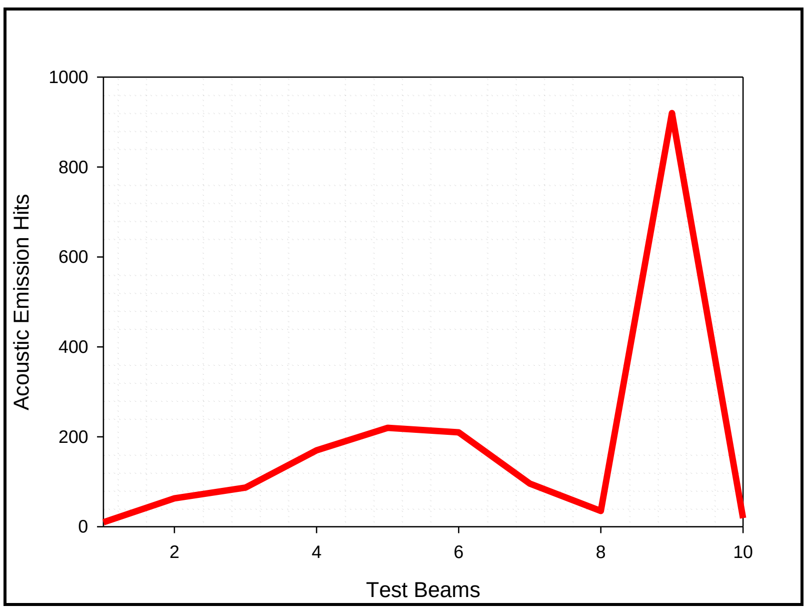

Figure 15: Plot of AE hits acquired in the ten girders.

Conclusions

The bridge under investigation has three spans. The middle span (span 2) was identified to carry a defect (crack) in the girder #7 girder-to-cross-brace connection. The AE tests, carried out in the suspected area, indicated that there is no active defect in this girder, meaning that the material around the visible crack would have plastically deformed and does not pose any further threat to the integrity of the structure.

The northern span (span 1) is also supported by ten steel girders with I-sections. AE tests carried out on these 10 girders showed AE activity levels with distinctly higher AE occurring in girder #9. This girder is very close to the side of the bridge, where the load conditions normally are not that severe, compared to the central region, where girders #4, #5, and #6 support the road. It is therefore possible that girder #9 may have an active crack source which emits strong AE signals when subjected to normal traffic loads. It is advised to carry out further NDT tests on the girder #9 to check for the integrity of the structure. Visual examinations, dye penetrant tests, and ultrasonic tests can be carried out to locate the source of the defect, if any.