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IDEA

Highway IDEA Program

*Bridge Cable Inspection with Long Range
Ultrasound*

Final Report for Highway IDEA Project 152

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March 2012

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Bridge Cable Inspection with Long Range Ultrasound

NCHRP IDEA Final Report

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EXECUTIVE SUMMARY

The project was initiated by assembling a panel of experts from the wire rope industry and transportation sectors. The panel was consulted to develop and document a basic inspection specification for bridge suspender ropes and cables less than 3 inches in diameter. Using this specification, an initial laboratory testing plan was documented for single legged and double legged suspender rope which included length of rope, defect type, and location.

Field testing of the technology was performed on the Manhattan Bridge suspender ropes. Of the five ropes tested, all of them contained cross-sectional area changes that were identified using guided wave ultrasound. On three of the ropes, it was possible to visually confirm the presence and location of each cross-sectional area change detected. On two of the ropes, it was impossible to visually confirm the presence of the cross-sectional area reduction due to access problems. The Manhattan Bridge suspender ropes were taken out of service and inspected visually to confirm the presence of cable defects. Also, during this reporting period, the feasibility of inspecting the main cable of a cable stay bridge was studied for the first time. From one sensor position, the technology scanned approximately 120 feet from a single sensor position. Ultrasonic data were acquired at 4 four different locations. A total of 4 Collar reflections were observed at every 20 feet. Between the collars, no significant reductions in cross-sectional area due to wire breaks or corrosion were observed. The study showed, for the first time, that main cables may also be inspected with the proposed technology.

Laboratory testing focused on obtaining out-of-service suspender ropes for controlled testing in-house and at Lehigh University. The first socketed rope was tested in-house. Wire breaks were then inserted at the cable socket interface. Data were acquired at 5, 10, 15, 25 and 50% cross-sectional area (CSA) reduction. The results demonstrated clearly that the proposed technology is sensitive to changes in CSA as small as 5%. More importantly, the results showed that changes in some waveform features correlated to the increase in damage size. Full scale testing on a tensioned cable was also performed at Lehigh University. Wire breaks were inserted at the cable-socket interface from 3 to 25% CSA. These results also showed that the technology was sensitive to changes as small as 3% CSA and that there is a strong correlation between changes in select waveform features and increases in CSA loss.

Similar tests were performed on a double legged suspender rope at Lehigh University. The objective of the test was to determine if the technology could detect wire breaks at the gatherer. After baseline data was acquired, wires cuts were inserted until about 25% cross-sectional area reduction occurred. The tests confirmed that wire breaks was sensitive to wire breaks at the gatherer. Wire breaks equivalent to 3 % CSA were detected.

Finally, a commercialization plan for the technology was documented. An initial estimate to retrofit a bridge with the technology was completed. The cost to inspect one bridge using the retrofitted technology was also estimated. Initial estimates put the retrofit and periodic inspection costs at \$34,000 and \$8,000, respectively, for a 200 cable bridge.

KEYWORDS

Bridge cable inspection, suspender rope inspection, guided waves, and ultrasound.

ACKNOWLEDGEMENT

The full-scale laboratory testing for the research reported herein was conducted by the ATLSS Engineering Research Center, Lehigh University under a subcontract from WINS. Dr. Sougata Roy, Principal Research Scientist at ATLSS, served as the Principal Investigator for this component of the study.

The testing was performed in the Fritz Engineering Laboratory. The suspender ropes used for this study were taken from the Verrazano Narrows Bridge in New York City and were available with ATLSS as remnant of another test program. Special thanks are due to the laboratory staff and Mr. Yeun Chul Park, Graduate Research Assistant of ATLSS for providing test support.

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1 IDEA PRODUCT

WINS commercialization strategy is based partially upon the development of an inspection product that would rapidly screen bridge cables and suspender ropes *remotely* for structural deficiencies. In addition to supplying the equipment, WINS would position itself as a supplier of the inspection service. Thirdly, WINS would develop a database management system for handling inspection data specific to bridge cables and suspender ropes that would minimize the direct labor required to interpret bridge cable or suspension rope data.

1.1 Inspection Product

The inspection product will consist of a hand held ultrasonic device that may be transported easily from bridge to bridge. On a bridge, it will be lightweight and small enough to move easily from cable to cable. There are numerous ultrasonic hand held devices available commercially but only a limited number of higher end devices will satisfy the high voltage and large pulse width that are required to generate LRUT in steel cables. The current ultrasonic pulser/receiver unit is controlled by a laptop and has custom built electronics in a hard plastic case. This option is shown on the right hand side of Figure 1. While this hardware option does provide high quality inspection data, it is expensive, relatively heavy, and requires a dedicated laptop. There is a new handheld ultrasonic instrument that became available in 2011 that is more suitable for cable/rope inspection application. The device, shown in the right hand side of Figure 1 is lightweight and operates independent of a laptop. It can be acquired at about 15% of the cost of the laptop system.

The novelty will be linked to the sensor used for the application. The magnetostrictive sensor (MSS) used currently is shown in the left hand side of Figure 2. It uses 2-3 large magnets and flexible coils to generate ultrasound via the magnetostriction phenomenon. The current sensor design is not amenable to long term monitoring applications where small changes in ultrasonic reflections are sought. For example, the magnets or ribbon cables may displace slightly causing a change in signal unrelated to the cable structure. An alternative sensor was developed and tested during this project with some positive initial results which are not presented here for confidentiality reasons. Using this sensor small reflections were observed from the cable socket. The sensor is shown on the right of Figure 2. It consists of a flexible piezopolymer that is clamped on to the cable. The piezopolymer is low cost and extremely low profile. Moving this technology forward to a permanent monitoring solution will require a new low profile MMS sensor and/or further development of the flexible piezopolymer or piezocomposite based sensor.



FIGURE 1 Laptop based ultrasonic bridge cable inspection technology (left) and hand held device for bridge cable inspection (right).

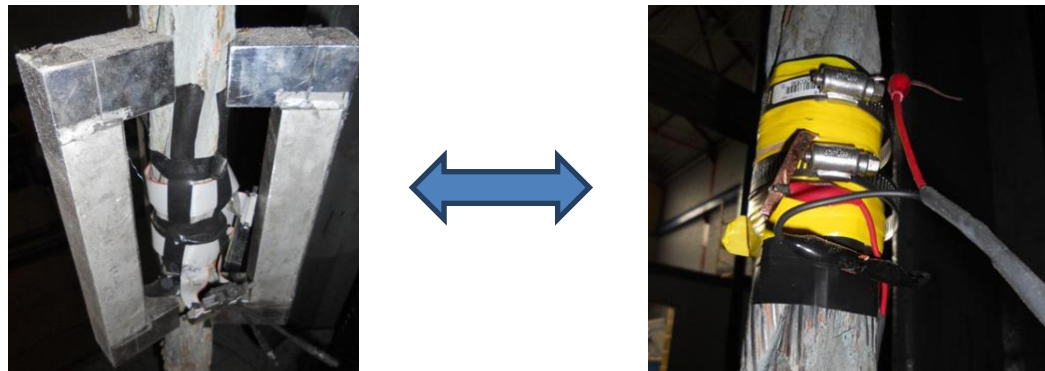
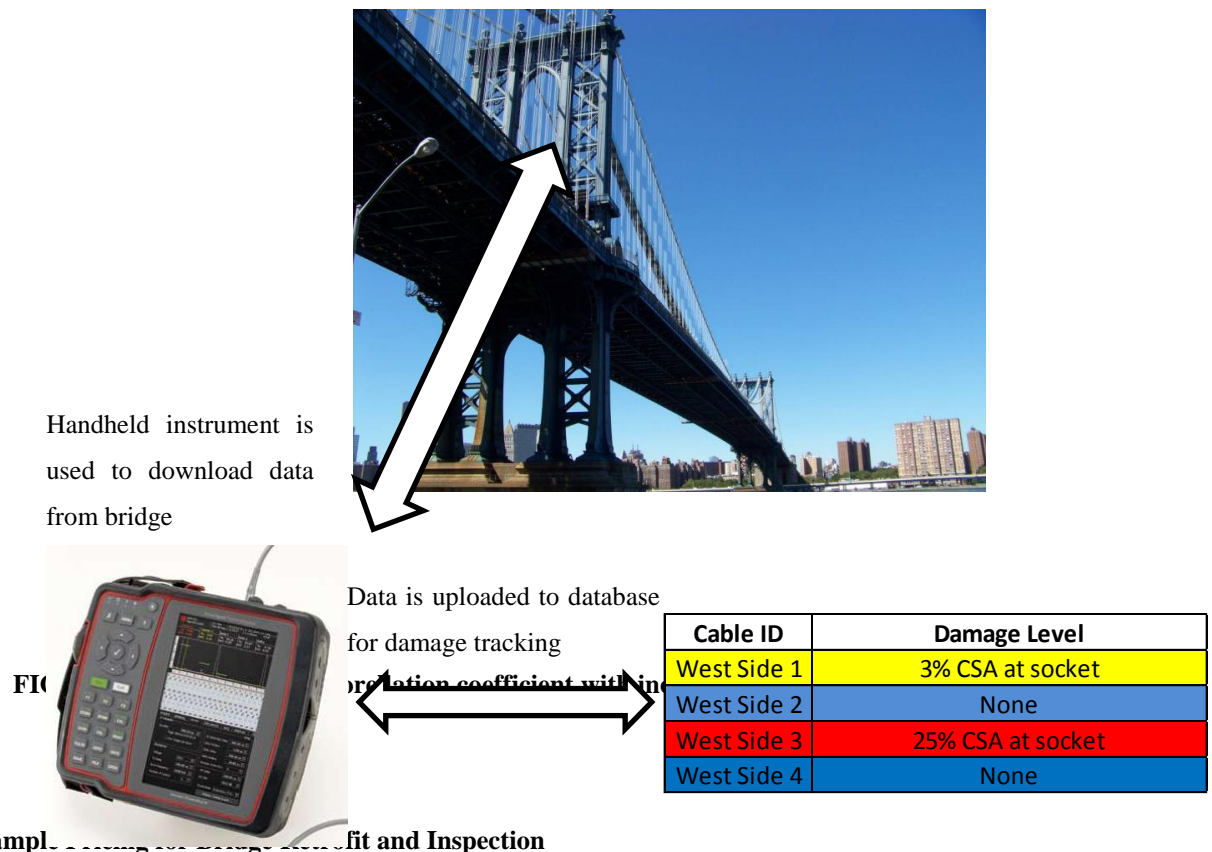


FIGURE 2 Large footprint magnetostrictive sensor with large magnets and flexible coils (left). Small footprint flexible piezopolymer sensor (right).

1.2 Inspection Service

The inspection service will have to be carried out by technicians with a moderate to high level understanding of ultrasound. The technicians will be responsible for acquiring data from each bridge cable. The service will entail a trained technician walking to and accessing each suspender rope or individual strands on a main cable (possibly in the anchor chamber). The technician would then connect the hand held ultrasonic instrument to the sensor and acquire data. These steps would be completed until all the suspender ropes are inspected. Inspection data would then be downloaded to the data management software for that specific bridge to compare the present data with previous data. If significant changes in

data are observed at sockets, gatherers, or other critical areas the client would be notified and a secondary inspection would be recommended. The overall inspection method is shown in Figure 3.



1.3 Example of Retrofit and Inspection

The cost to install the technology on a 200 cable bridge is summarized below including the assumptions:

100 sensors @ \$200 each - \$20,000 materials

1 hour installation, calibration, and database management per cable

200 hours total for 2-man team @ \$140/hour - \$28,000

Total retrofit cost - \$48,000

These costs do not include traffic control, bridge owner personnel costs, and other costs incurred during the installation.

The cost to perform a periodic inspection service as described above is provided below:

30 minutes per cable including database management per cable

100 hours total per bridge for on technician @ \$80/hour

\$8,000 total inspection cost

It should be noted that the real cost savings is through the potential minimization of traffic control and detailed inspections that would be required if the bridge were not inspected, or essentially screened, using this technology. For example, consider what a typical fracture critical bridge cable inspection costs compared to a simple 10 to 15 minute ultrasonic screening of the cable. There are many levels of support for fracture critical cable inspections ranging from traffic control to aerial lift devices. The goal of this technology is not to replace the fracture critical inspection but rather to delay it for as long as possible on a cable-by-cable basis.

2 CONCEPT AND INNOVATION

There are a number of technologies that are being used today to inspect bridge cables for wire breaks and corrosion [1]. The most common method is visual inspection. Common nondestructive techniques include magnetic flux [2,3] , acoustic emission [4,5], dynamic analysis [5,6], and more recently long range ultrasound [7,8]. None of these technologies, however, provide adequate inspection at the most fracture critical areas on cables and suspender ropes. These areas include sockets, parts of suspender ropes hidden by gatherers, separators, and collars. Note that these are areas where corrosion may be accelerated to due fretting and moisture penetration. Stress concentrations may also initiate fatigue cracking over time at these zones.



FIGURE 4 Cable inspection blind spots

Table 1 contains a brief but forthcoming discussion of the limitations of the abovementioned technologies. At this point, none of these technologies can inspect reliably the blind spots identified in Figure 4. Furthermore, these technologies can not accurately characterize or size cable defects in terms of cross-sectional area loss. Of these technologies, long range ultrasound (LRUT) is emerging as a complementary inspection technology since the entire cable (not included the blind spots) may be screened from a single sensor position rapidly and more importantly – economically. LRUT has some limited cable defect sizing capabilities (minor, moderate, severe) but to provide useful engineering data to bridge ratings defects must be characterized in terms of cross-sectional area reduction.

The following items are advantages of LRUT bridge cable inspection:

- Corrosion/wire break detection in cable interior and under paint
- Entire cable is inspected from single sensor location
- Long range ultrasound can inspection up to 300-feet of cable from one sensor location
- Defect location is possible using the known velocity of the sound wave in the cable
- Sensor and equipment are lightweight and portable for (about 20 lbs total)
- Average cable inspection time is 20 minutes

Table 1: Limitation of Existing Nondestructive Bridge Cable Testing Methods [1]

Technique	Limitations	Level of Use
Visual	<p>Visual inspection cannot determine condition under collars, seizing wires, separators, sockets and gatherers since due to accessibility.</p> <p>Broader disadvantages include that it cannot detect corrosion/breaks on the interior strands and under paint. Impossible to size subsurface defects.</p>	Visual inspections are the most common method used on cable bridges. Depending on the location of the bridge and regulations, the inspection cycle typically ranges from 2 to 5 years.
Magnetic flux leakage (MFL)	<p>MFL inspection cannot determine condition under collars, seizing wires, separators, and gathers since due to accessibility.</p> <p>Broader disadvantages include the requirement that the sensor be scanned along the entire cable. Defect sizing is not possible.</p>	Inspection may be condition based on findings from fracture critical inspections or to access areas of cables inaccessible to visual inspection. MFL sensors are integrated with robotic crawlers.
Acoustic emission (AE)	<p>Cable rubbing or fretting at gatherers, collars, separators and sockets generate acoustic emission which may be confused with acoustic emission generated from wire breaks.</p> <p>Broader disadvantages include that multiple sensors are required per cable with significant installation setup time. No defect sizing possible.</p>	Used periodically to measure for active fatigue in wires or for wire breaks. It has been used during new cable installation for baseline data acquisition and periodically moving forward. More recently the technology is steering towards long term permanent installations.
Dynamic analysis	No defect location capability or severity ranking. No defect sizing possible.	Used during design stage and periodically to assess cable tension.
Long range ultrasound (LRUT)	<p>LRUT is reflected back from collars, separators, sockets and gatherers. A reflection from a defect underneath the collar, for instance, may be overshadowed by the larger reflection from the collar.</p> <p>Defect sizing is limited to minor, moderate, severe.</p>	Used periodically to inspect for cross-sectional area losses. It may be used to enhance fracture critical inspections or to access areas of cables inaccessible to visual inspection.

3 LABORATORY TESTING

3.1 Small Scale Feasibility Study

Cable socket reflections are typically very large and there are many unknowns about the source(s) of the reflection. A typical suspender rope socket is shown on the left of Figure 5. The socket is essentially a cable end so a large reflector is expected. The possible sources of the reflections from the cable include:

- Cable-socket interface: Some of the incident ultrasonic wave will be reflected at this interface due to the change in cross-sectional area.
- Wire ends and socket cavity: The socket cavity and wire ends will also contribute to the reflection. Similarly the wire ends in the socket cavity will also generate an ultrasonic reflection.
- Socket end: The bottom of the socket will also reflect ultrasound if enough energy reaches it.

A small scale feasibility study was performed in-house to determine if LRUT was sensitive to small changes in CSA at the socket/cable interface. A suspender rope from the Delaware bridge was supplied by Wirerope Works, Inc. for testing. The cable was stripped down to a single strand for this preliminary work to simplify testing, sensor installation, and analysis.

The sensor was installed at approximately 6 feet from the socket and baseline data was acquired from the socket before wire cuts were inserted. Wire cuts were then inserted at 5, 10, 20, 30, 50, and 75 % cross-sectional reductions. The single strand socket and the location of the wire cuts are shown in Figure 5. The waveforms recorded at each CSA loss are shown in Figure 6.

The effect of increasing CSA loss on reflection amplitude of the cable/socket interface is shown in Figure 6. Intuition suggests that the reflection amplitude should increase with larger CSA loss and this is observed in Figure 6 except for a small decrease from 5 to 10% CSA. As discussed earlier, the socket reflection is a composite reflection made up from the cable-socket interface, socket cavity, wire ends, and socket bottom. At small CSA losses, it is possible that the composite reflection is still the dominant reflection. As the CSA loss increases, the wire cuts become the dominant reflector with less and less energy penetrating beyond the cable-socket interface. The amplitude drop between 5 and 10% may be explained by this phenomenon.

The cross-correlation coefficient between the baseline, or 0 % CSA loss, and data from the larger CSA losses is shown in Figure 7. The cross-correlation coefficient will vary between 0 and 1. If there is no change between the baseline and new data, it will remain 1. As the incoming data begins to change due to increases in CSA loss, the coefficient will begin to decrease. For the small scale test setup, the correlation coefficient changes in a predictable manner from 1 to approximately 0.6. The relationship between CSA

loss and cross-correlation coefficient show that it will be a useful analysis feature moving ahead towards a permanent monitoring solution.

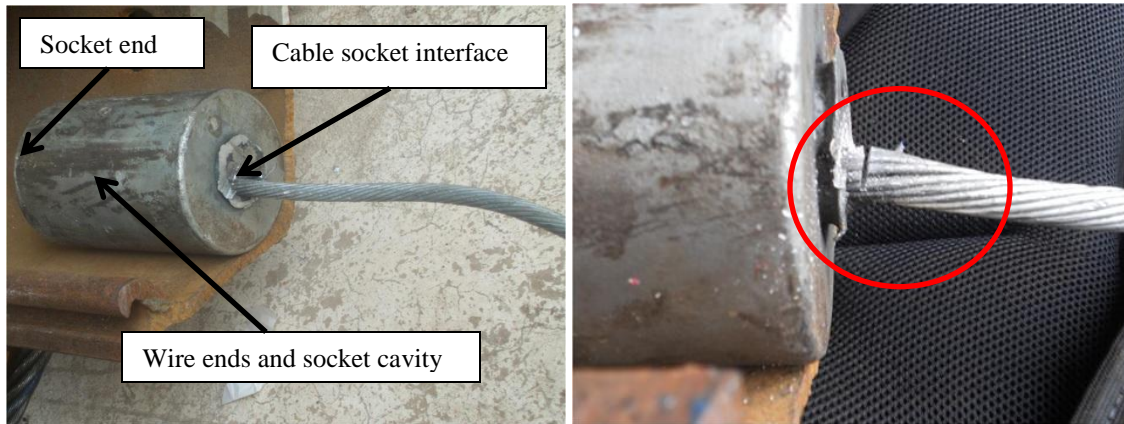


FIGURE 5 Single strand (left) socket and location of wire cuts (right).

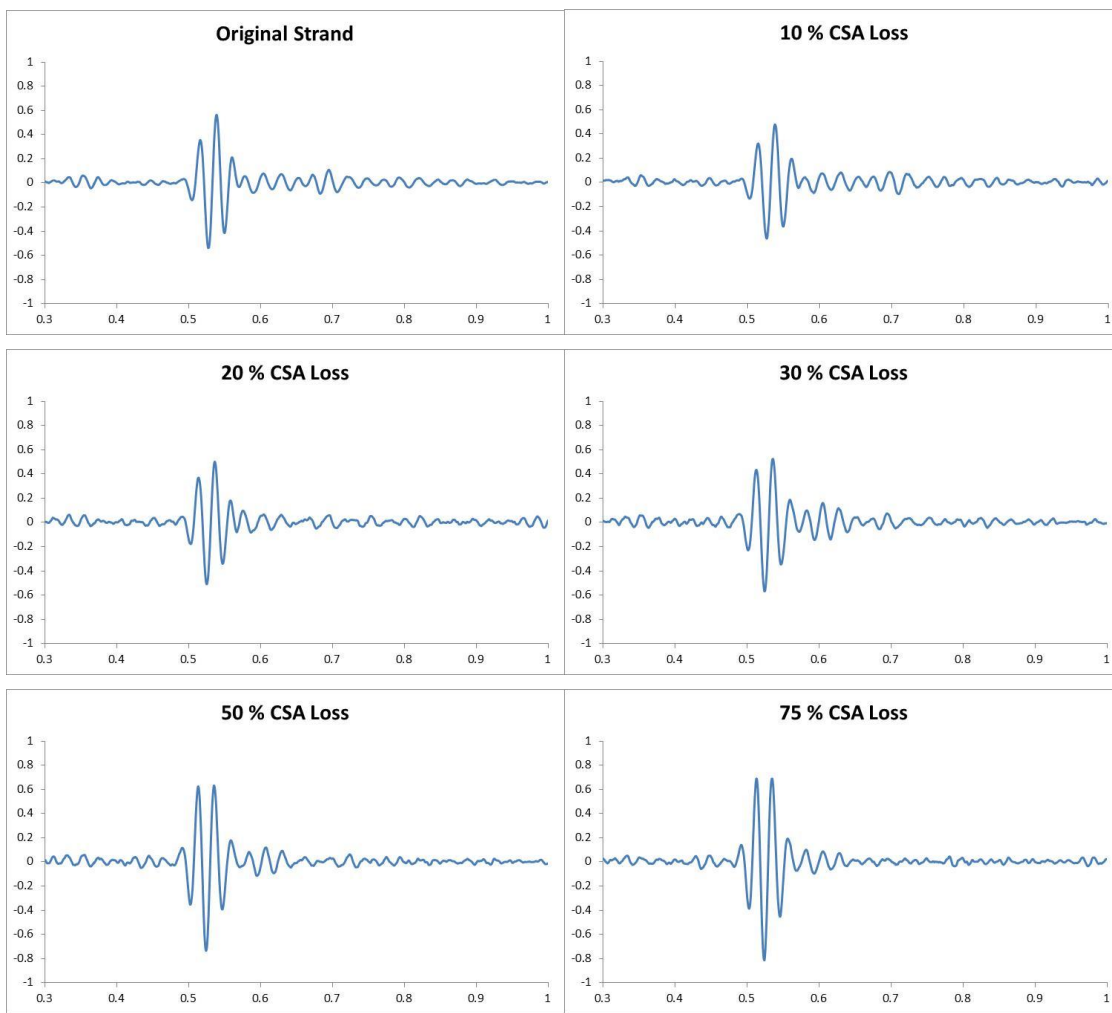


FIGURE 6 Baseline and CSA loss data from single strand socket.

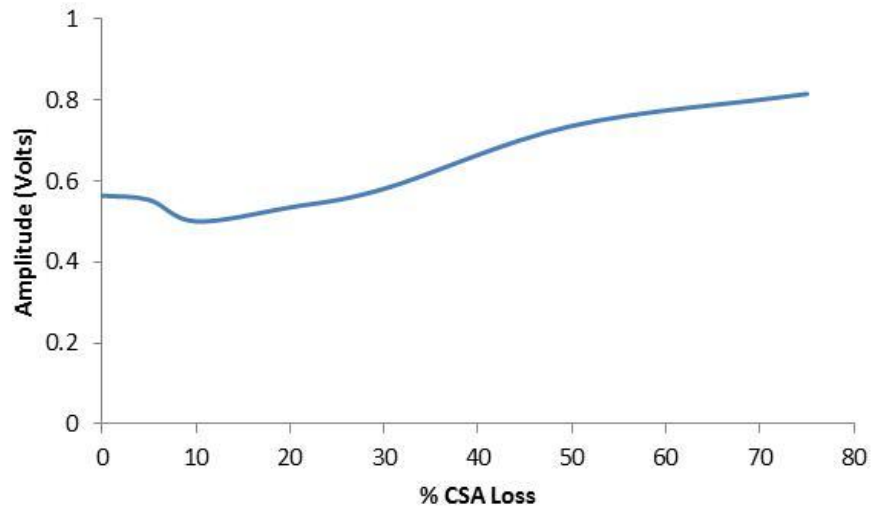


FIGURE 7 Single strand socket reflection amplitude with increasing % CSA loss.

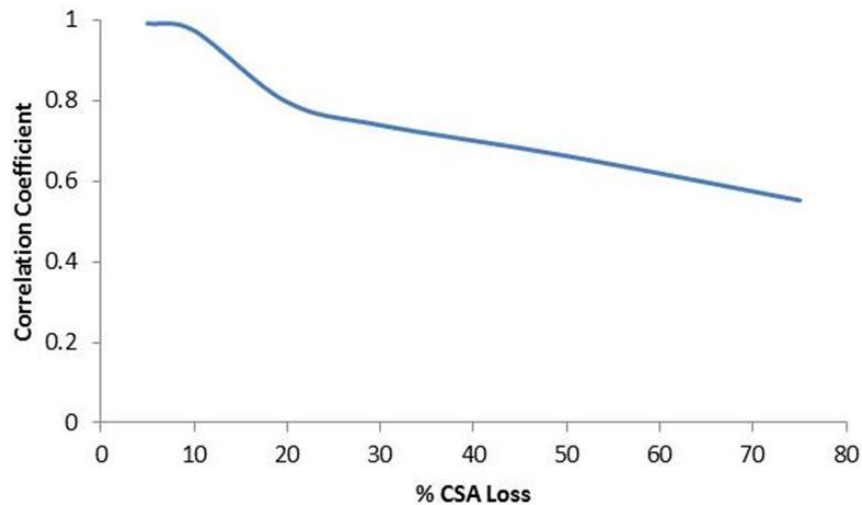


FIGURE 8 Single strand socket correlation coefficient with increasing % CSA loss

3.2 Large Scale Feasibility Study

Full-scale feasibility tests were undertaken on single-legged and double-legged suspender ropes, at Lehigh University's ATLSS Center. The testing was performed on a 2.25" diameters suspender ropes removed from the Verrazano Narrows Bridge. The ropes were approximately 20 feet long. The rope was mounted vertically and tension was applied to 100 kips. The sensors was mounted approximately 1/3 of the rope length from the bottom socket. Baseline data was acquired from the top socket. For the single-legged suspender rope study, wire cuts were then inserted at 3, 5, 10, and 25% CSA loss. Tests were not performed at greater CSA loss for technician and instrumentation safety. For the double-legged rope study, wire cuts ranging from 2 wires to 26 wires were placed.

3.3 Single Legged Suspender Rope Study

The single-legged rope testing setup is shown in Figure 9. The waveforms from the cable-socket interface are shown in Figure 10. The effect of inserting wire cuts at the cable-socket interface is shown in Figures 11 and 12. For this cable-socket combination, the amplitude drops slightly from 0.44 to 0.38 Volts, or roughly 15%, from 3% CSA to 25% CSA.

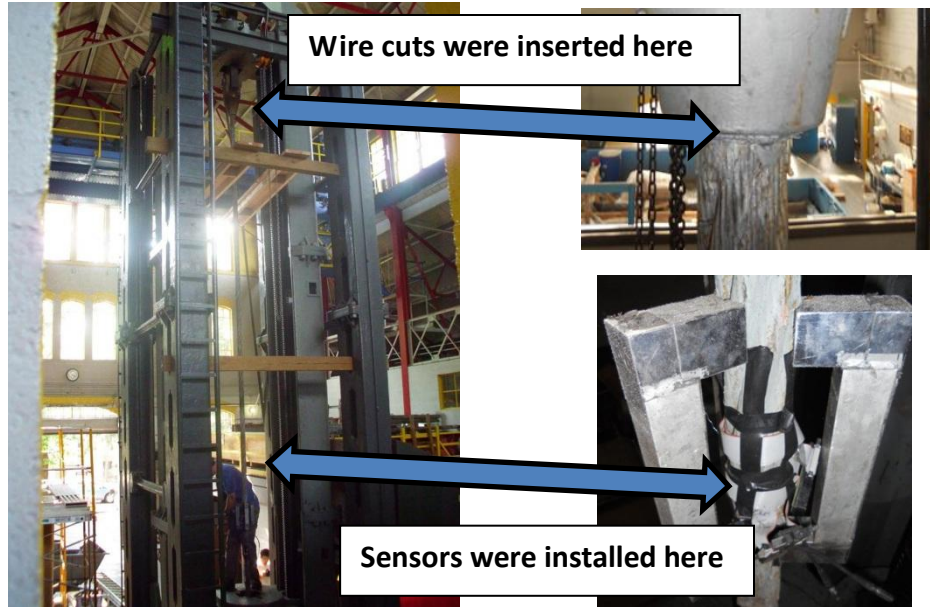


FIGURE 9 Test setup at Lehigh University's ATLSS Center

The effect of inserting the wire cuts on the cross-correlation coefficient is shown in Figure 11. As observed in the small scale feasibility study, the cross-correlation coefficient decreases in a predictable manner with increasing CSA loss further demonstrating that this waveform feature may be used to monitor for changes as small as 3% CSA loss at cable-socket interfaces.

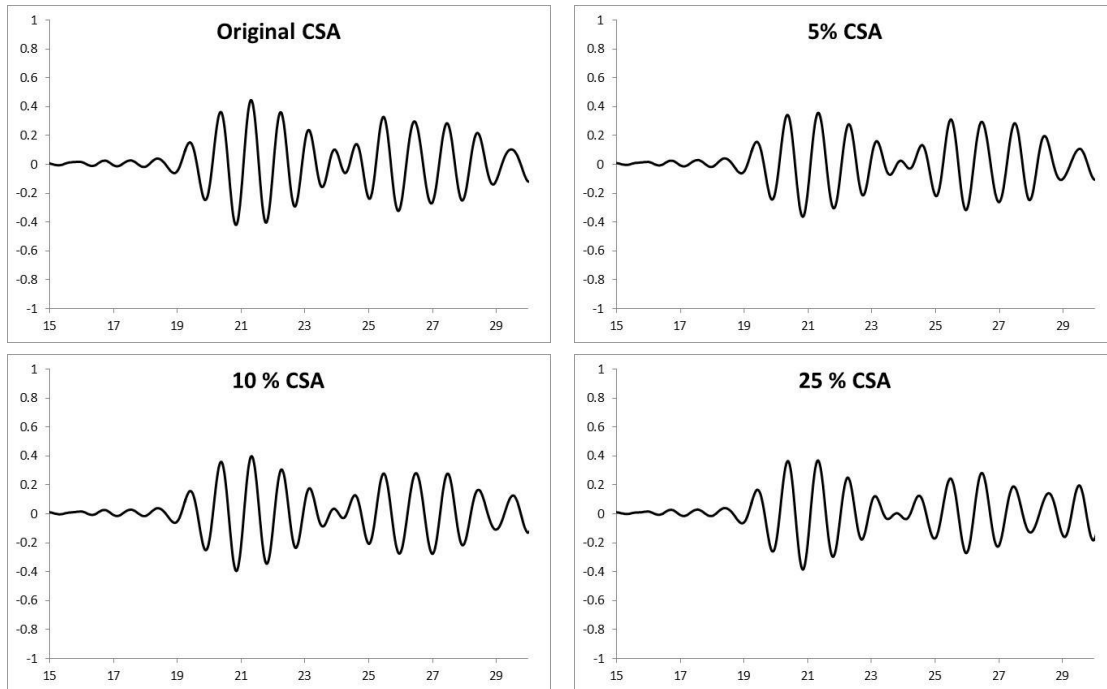


FIGURE 10 Baseline and CSA loss data from single legged suspender rope

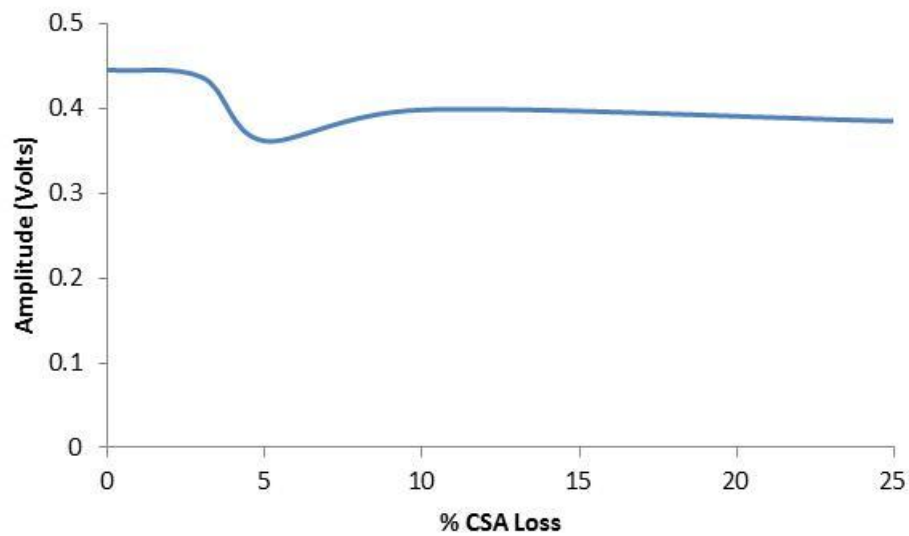


FIGURE 11 Suspender rope socket reflection amplitude with increasing % CSA loss

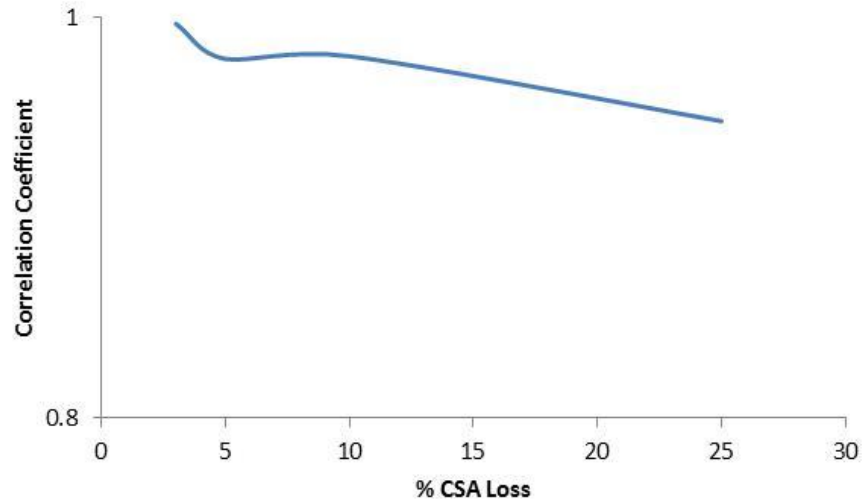


FIGURE 12 Single legged suspender rope correlation coefficient with increasing % CSA loss

3.4 Double Legged Suspender Rope Study

The double-legged rope testing setup and inserted wire cuts are shown Figures 13 and 14, respectively. The waveforms from the cable-socket interface are shown in Figure 15. The effect of inserting wire cuts at the cable-socket interface is shown in Figure 16.



FIGURE 13 Double legged suspender rope test setup at Lehigh University's ATLSS Center



FIGURE 14 Wire cuts inserted at top of gatherer in double legged suspender rope

As observed in the single legged suspender rope tests, the cross-correlation coefficient decreases in a predictable manner with increasing CSA loss (increasing number of wire cuts) further demonstrating that this waveform feature may be used to monitor for changes at cable-socket interfaces.

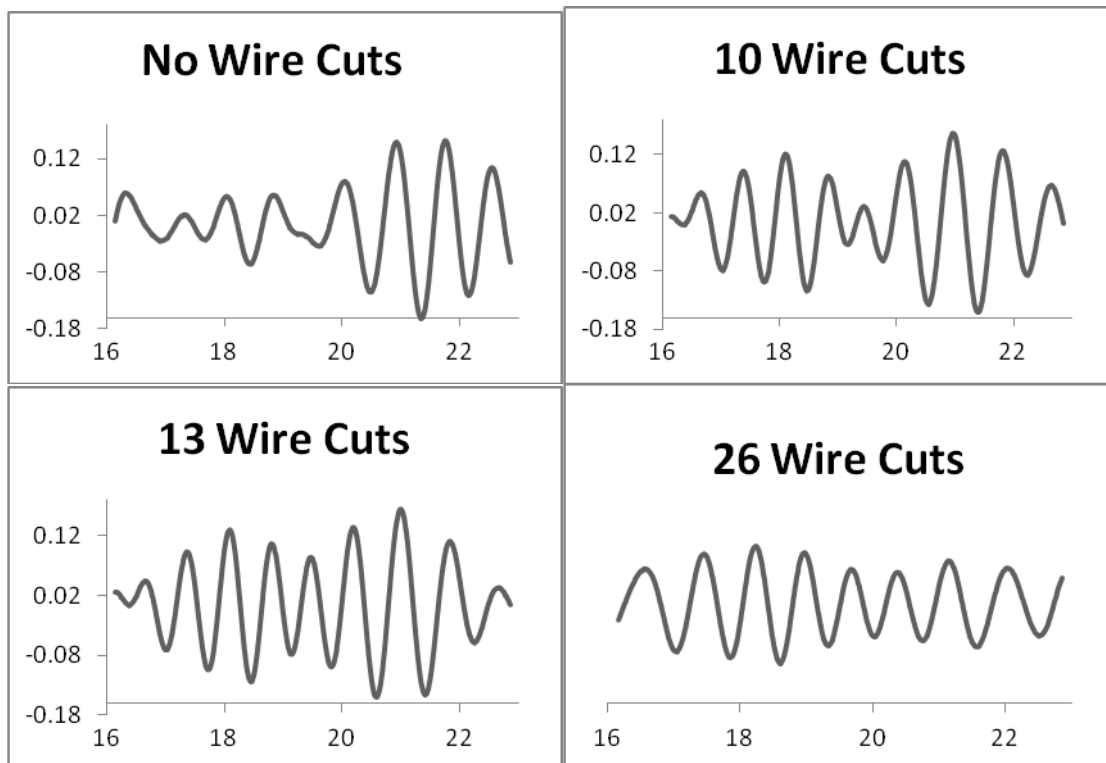


FIGURE 15 Baseline and CSA loss data from double legged suspender rope

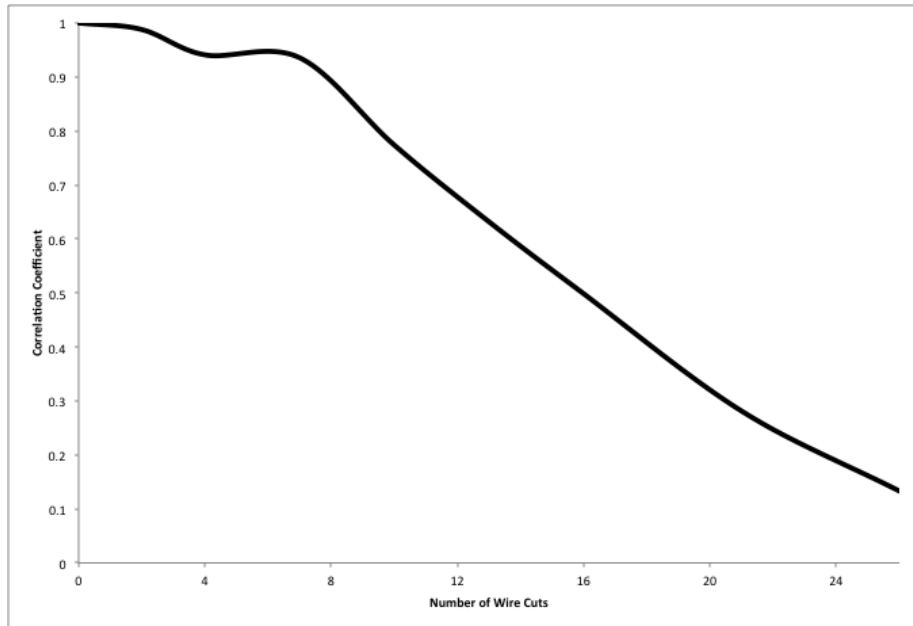


FIGURE 16 Double legged suspender rope correlation coefficient with increasing number of wire cuts.

4 FIELD TESTING ON SUSPENDER ROPES

WINS performed LRUT inspection on five of the 1-13/16" diameter suspender ropes on the C-truss of the Manhattan Bridge. The ropes varied in length from 105' to 190'. The ropes are coated with a white paint over a lead-based primer. The purpose of this examination was to identify the presence and extent of any defects occurring on the internal or external surface of the ropes.



FIGURE 17 Manhattan bridge, Manhattan in the background

The inspection was performed from one location on each rope, as shown in Figure 18. The inspection range was sufficient to inspect the entire length of one leg in one shot. In total 620 feet of suspender rope was inspected. Of the 620 feet of suspender rope inspected, there were five ultrasonic reflectors observed. These reflections ranged from approximately 1% - 12% Cross Sectional Area (CSA). One of the reflectors was visually verified as pack-rust while four of the reflectors were visually confirmed as areas with multiple wire breaks. Example data for one rope is shown in Figure 19. Two reflectors could not be visually verified and were subjected to follow-up visual inspection after the cables were removed from the bridge. Follow-up inspection on the out-of-service rope did not confirm Indication # 4, possibly do to its size of 1% CSA loss. An area of +/- 12 inches centered about the estimated location Indication # 4 was visually inspected and no observable CSA loss was observed. Follow-up inspection of Indication # 5 identified a 5-15 % CSA loss in that area confirming the data obtained on the rope while it was in-service on the Manhattan Bridge.

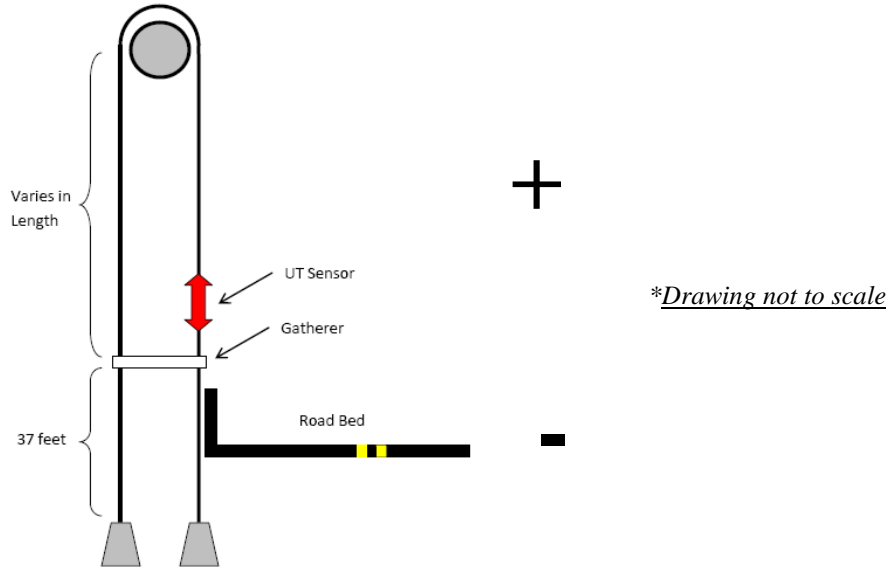


FIGURE 18 Suspender rope schematic with inspection location identified.

Table 2: Location of all ultrasonic reflectors

Indication #	Indication Location	Indication Size	Visual Confirmation
1	56C-NW Brooklyn +20.9' from Socket	7% CSA	Wire Breaks
2	56C-NW Brooklyn + 32.8 ' from Socket	12% CSA	Pack Rust
3	56C-SW Brooklyn +16.5' from Socket	5% CSA	Wire Breaks
4	56C-SW Brooklyn +41.8' from Socket	1% CSA	Post-inspection Nothing Observable
5	55C-NW Manhattan +27.2' from Socket	5% CSA	Post-inspection Wire Breaks
	55C-SW Manhattan +25.8' from Socket	6% CSA	Wire Breaks

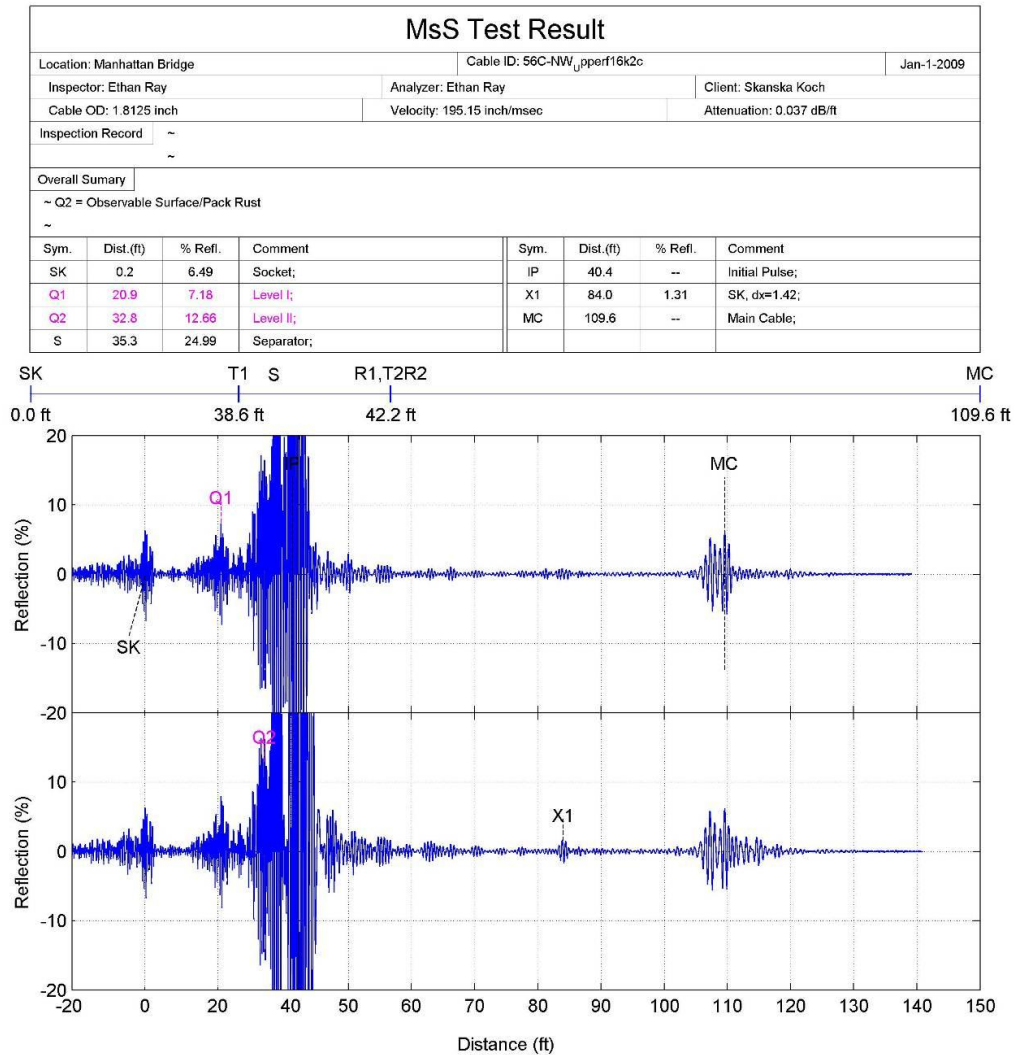


FIGURE 19 Example guided wave data from rope 56C-NW (Brooklyn) ultrasonic data

5 FIELD TESTING ON CABLE STAY BRIDGE

The main cable was inspected on the Hydro Quebec Bridge in Beauharnois, Quebec using ultrasonic guided wave technology. The main cable was opened in the two locations shown in Figure 20. At these locations, ultrasonic sensors were installed on the individual strands. The individual strands were then inspected in the *forward* and *backward* directions.

For example, during the data acquisition the sensor first focuses the majority of the ultrasonic wave in the forward direction but a small percentage is also directed in the backward direction. During the next step, the data is focused in the backward direction with a small percentage of the ultrasonic wave directed in the forward direction. Since directional cancellation is not 100%, reflectors located on one side of the sensor may be observed on the opposite side.

A detailed analysis of the data on strand E-7 between saddle 17 and 18 in Figure 20 is provided here. The sensor position is shown at approximately 55 feet from collar 3B. To the right of the sensor is the forward direction. To the left of this position is the backward direction. In the forward direction, 4 evenly spaced collars (Collar 1F to 4F) are observed at 20 foot increments. To the left, 3 (Collar 1B to 3B) evenly spaced collars are observed at 20 foot increments. Collars 1B and 2B are also observed on the forward side. The same inspection and interpretation method was used for each cable inspection and are presented in Table 3. There were no unexplained reflectors in the data acquired.

The attenuation at the collars was calculated using the guided wave data from each cable. The attenuation coefficients for both forward and backwards directions in dB/feet are provided in Table 3.

5.2 Implementing Cable Stay Bridge Inspection

The work described in this section was the first of its kind that applied LRUT to cable stay bridges. The following critical milestones were demonstrated relative to the future development of the technology for stay cables.

- It is possible to separate individual cables for LRUT sensor installation**
- Ultrasonic wave attenuation is not a major factor**
- Inspection range is significant at distances up to 160 feet**

The inspection sensitivity to CSA loss for stay cables, however, is still unknown. A separate research project would be required to study LRUT sensitivity to CSA loss in single strands, but more importantly to CSA loss in the single strands of installed stay cables. In this work, the research undertaken in this project would be applied similarly to stay cables. A series of CSA losses would be inserted over a range of distances to the sensor. The minimum CSA loss sensitivity would be determined as a function of distance, and also attenuation, for the specific stay cable tested.

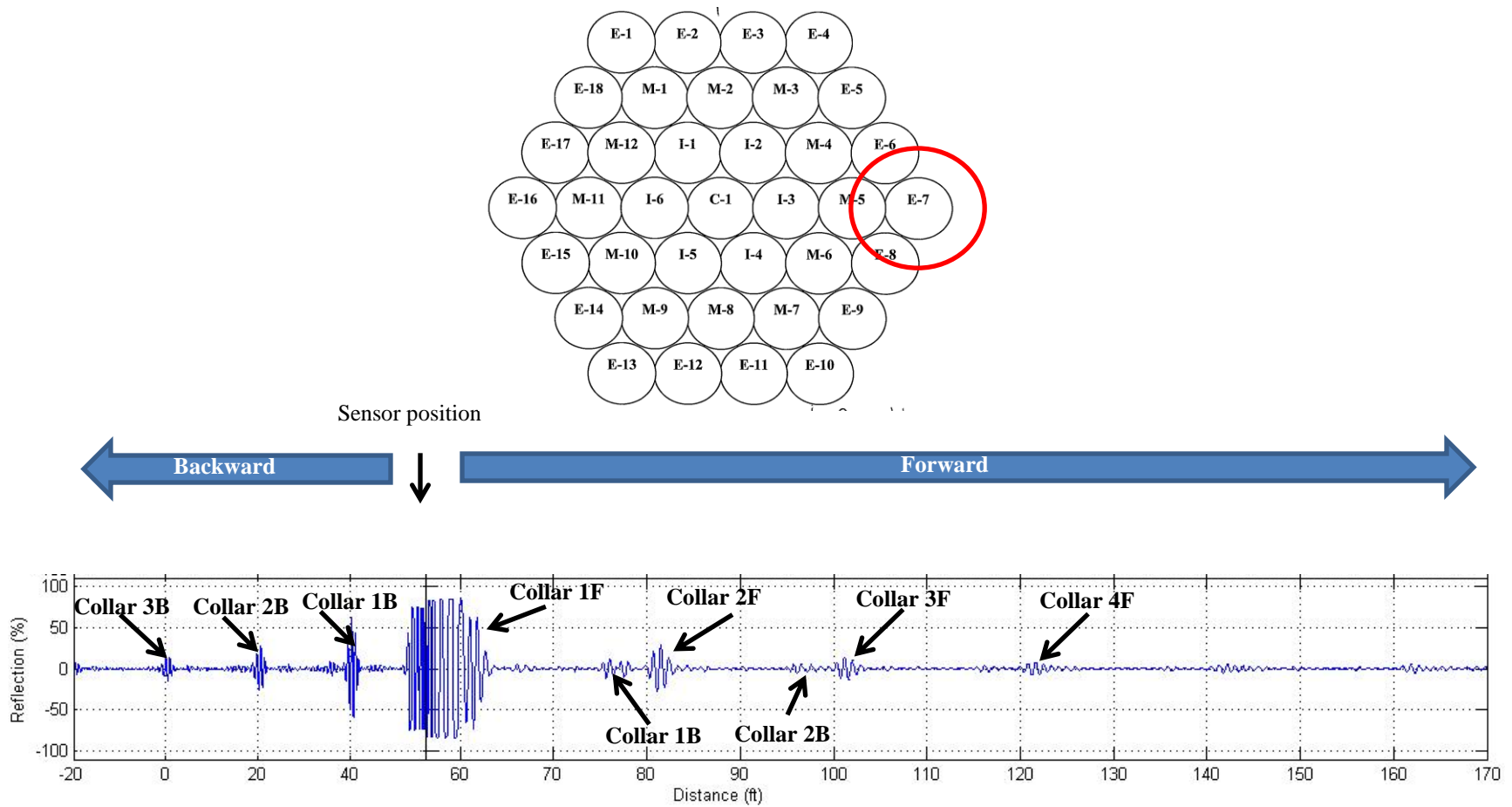


FIGURE 21 Ultrasonic guided wave data acquired on strand E-7 between saddle 17 and 18.

Table 3: Summary of inspection range, defects observed, and attenuation at each sensor position.

Position	Forward range (feet)	Backward range (feet)	Total range (feet)	Major defects	Attenuation Positive	Attenuation Negative
E-7 between saddle 17 and 18	60	60	120	No	0.27	0.30
E-18 between saddle 17 and 18	60	60	120	No	0.21	0.25
E-1 between saddle 14 and 15	60	60	120	No	0.27	0.25
E-7 between saddle 14 and 15	60	60	120	No	0.32	0.30

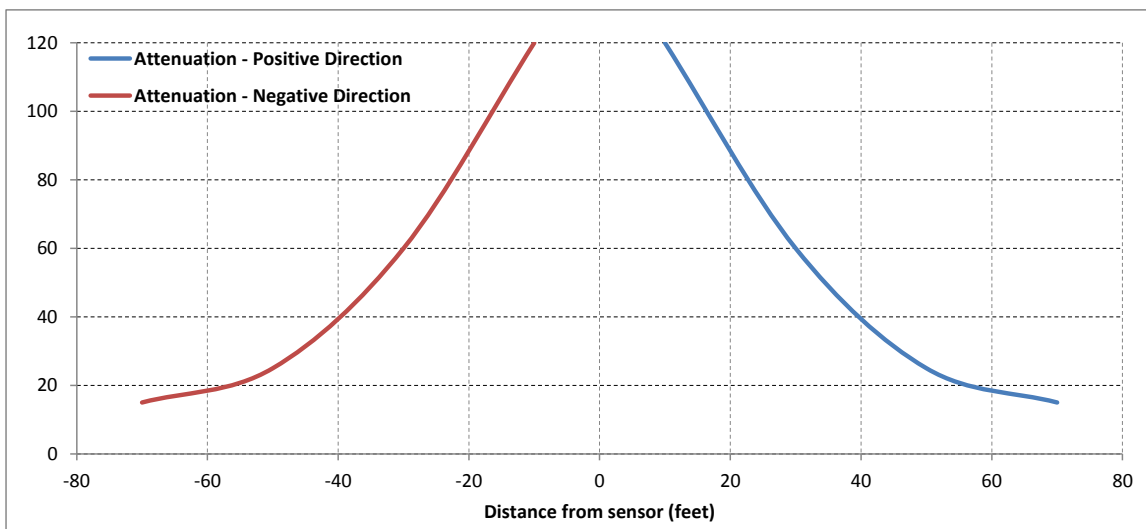


FIGURE 22 Attenuation profile for strand E-7 between saddle 14 and 15.

6 PLANS FOR IMPLEMENTATION

This project demonstrated the feasibility of using LRUT to detect flaws in the problem zones of suspender ropes and to a lesser extent stay cables. For suspender ropes, implementation and acceptance of the technology will require an additional stage of sensor development and validation, LRUT performance on a variety of different ropes, and performance of the technology over longer periods of time.

Implementation of LRUT suspender rope and stay cable inspection will require studying the procedures used currently in other industries. LRUT is used across many industries as a screening technology. For example, LRUT pipeline inspection is performed by installing a sensor and “shooting” ultrasound in the upstream and downstream directions. The inspection range is comparable at distances exceed 200 feet from one sensor location. All LRUT indications are followed up with a visual and/or ultrasonic inspection method for accurate sizing. This follow-up requirement positions the technology as a “screening” technology meaning that it inspects significant distances for changes in cross-sectional area but does size the CSA loss accurately enough to be used on load and/or remaining life calculations. Therefore during the early stages of implementations, the technology would be introduced to the bridge owners and maintainers as screening technology and to gage the market for this inspection approach. In this stage, the end users would be educated on the advantages and limitations on the technology which include:

- Entire suspender ropes may be screened rapidly and economically from one sensor position.
- Qualitative versus quantitative CSA loss characterization
- Permanent sensor installation will be required for monitoring critical areas like sockets, gatherers, etc.

Feedback from potential end users would be solicited during this stage and used to guide the development commercial equipment, technology installation, frequency of inspections, and how the data is managed.

6.1 Current Vision for Technology

The technology may be used to prompt visual inspection based on cable condition instead of the regulatory periodic visual inspection. In this scenario, the technology could be retrofitted on to an entire bridge cable system or cables with advanced corrosion or wire breaks. A technician would install the sensor(s) and acquire baseline data. Moving forward, data would be acquired on a weekly, monthly, or annual basis to determine if cable damage has been initiated or if it has advanced by comparing it to the baseline data. Beyond a certain damage tolerance, a follow-up visual inspection would be required. There are numerous cost benefits to the technology that will contribute to the total cost ownership reduction of cable system bridges. These include:

- **Transition to condition based visual inspection to from time-based:** Visual inspection will be performed only on cables that show exceed the allowance tolerance on ultrasonic data. Significantly less bridge inspector time will be required to evaluate the bridge cables over the lifetime of the bridge cable system.

- **Reduction of traffic control required for bridge cable inspection:** Ultrasonic inspections are most commonly performed at walkways where the sensor is installed. Very rarely is traffic control required to assist with the inspection. The same logic applies to reduction of rope access and aerial lift device equipment and personnel costs to support bridge cable inspection.
- **Elimination of subjective and inspector dependent visual inspection results:** The technology provides high quality engineering data over the entire bridge cable system remotely.
- **Cables and suspender ropes are becoming increasingly hard to access:** Due to security concerns and surface coatings, cables systems are becoming increasingly difficult to inspect visually. The ultrasonic technology is an excellent inspection solution for the future bridge cable systems.

6.2 Implementation Steps

As discussed in Section 1, the current design of the magnetostrictive sensor used for LRUT inspection may not be compatible with the long term monitoring solution discussed above. While the sensor performs excellently, it is large and potentially unstable in permanent installations. The existing magnetostrictive sensor must be redesigned to be lower profile while minimizing the small changes that shifts in magnet and coil positions have on the ultrasonic wave generated in the cable. In parallel, new flexible piezopolymer or piezocomposite sensors must be investigated as they show the most potential for low profile and cost while minimizing the effect that transducer performance has on the reproducibility and stability the ultrasonic wave in the suspender rope.

The performance of the selected sensor must be validated over a long period of time to be subjected to the full spectrum of loads , temperature, and weather to demonstrate to potential end users that it is robust enough to survive on the bridge preferably with no maintenance required. This will require partnering with a bridge owner and installing between 5 and 10 sensors on suspender ropes. Baseline data would be acquired after installation. Moving forward, data would be acquired on a monthly basis and compared to previous data. The performance of the sensor shall be evaluated by comparing the reflection from a known reflector such as a socket, gatherer, etc.

Bridge owners will be consulted to determine the most desirable procedure for acquiring and managing data while establishing a threshold for damage that requires visual inspection follow-up. Input will be required to establish the desired inspection frequency (monthly, annually, etc.), who will perform the data acquisition and manage the cable inspection database.

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