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Detection of Multiple Flaws in Concrete Bridge Decks Using Ultrasonic Wave Propagation

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NEBRASKA
DEPARTMENT OF TRANSPORTATION

Project Title

Detection of Multiple Flaws in Concrete Bridge Decks Using Ultrasonic Wave Propagation

Project Number:

M066

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Contents

List of Notations and Abbreviations

AASHTO: American Association of State Highway and Transportation Officials (AASHTO)

GPR: Ground Penetrating Radar

GW: guided wave

HCP: half-cell potential

NaCl: Sodium chloride, also known as “salt”

NDOT: Nebraska Department of Transportation

NDT: Nondestructive Testing

SHM: Structural Health Monitoring

TAC: Technical Advisory Committee

1. Introduction

In this section, the motivation and significance, goals and objectives, and project scope and limitations will be presented.

1.1. Background, Motivation, and Significance

This research is motivated by the increased demand for structural health monitoring systems for the rapidly aging U.S. infrastructure. It is estimated that $8 trillion of the U.S. infrastructure is concrete based *(Poston 2008)*. Most of these concrete structures, such as buildings, bridges, and parking structures are reinforced with steel. Reinforced concrete structures are prone to serious structural issues caused by corrosion, delamination, and cracking, which may compromise the integrity of the composite structure. Reinforced concrete bridge decks are arguably one of the most susceptible structures to corrosion and delamination due to the harsh conditions that bridge decks commonly experience: freeze-thaw cycles, de-icing salts, continuous impact from heavy traffic, and exposure to water. It has been estimated that the annual corrosion related repair costs for highway bridges is around $8.3 billion, which includes $2 billion just for bridge decks *(Arndt et al 2011)*, with corrosion and delamination accounting for approximately 40% of all bridge deck repair costs *(Yunovich et al 2001)*.

Currently, there are no global inspection tools for structural health monitoring or diagnostic testing with the sensitivity to detect the ***onset*** of deterioration for bridge decks. Further, there is no single Nondestructive Testing (NDT) method that can identify corrosion, delamination, and cracks; examining steel-concrete interface, steel, and concrete, at the same time with the same set-up. Finally, there are no standardized ultrasonic testing (UT) methods that use energy-based measurements. Currently standardized UT methods, such as ASTM E494, uses velocity measurements in the time domain instead of amplitude measurements in the frequency domain (ASTM 2015).

Therefore, the ***significance*** of this project is twofold:

1. This method has shown promise to detect a variety of flaws in reinforced concrete bridge decks ***earlier than*** any other NDT method (NDOT Report M029).
2. Such early detection, along with the continuous monitoring of the progression of flaws can lead to the ***development of deterioration models*** for new, as well as recently repaired, bridge decks in the future.

1.2. Goals and Objectives

Given the research and application needs stated in the previous section, this project proposes to bridge these gaps. **The ultimate goal of this project is to develop a novel continuous health monitoring system to identify the onset, type, and location of multiple types of flaws (corrosion, delamination, and cracking) in reinforced concrete bridge decks.** This project will be building upon the progress made in the previous project (M029) to provide improvements to the proposed continuous health monitoring method and develop a diagnostic testing tool for reinforced concrete bridge decks. It is also intended to make the proposed method more practical for implementation in real life by identifying the limitations in the propagation distances and optimal sensor arrays.

To achieve these objectives, four specific objectives are identified.

1. To identify and monitor the onset of corrosion product on the rebar in reinforced concrete bridge decks
2. To identify and monitor the onset of cracking of concrete in reinforced concrete bridge decks utilizing the same equipment
3. and same set-up.
4. To examine the influence of directional and multiple layers of reinforcement on the ability of the UGWL arrangement to identify existing, and to monitor the onset of, multiple types of early-stage flaws.
5. To determine the capabilities of this testing method as a diagnostic tool for overall interior deterioration of concrete bridge decks.
6. To perform a pilot bridge implementation trial

1.3. Scope and Limitations

While this project attempts to make improvements with respect to the practicality of the process, development of new sensors or methods of attachment between the sensors and rebars are out of the scope of this particular contract. For this method to be actually adopted by the NDOT, these further developments will be necessary.

1.4. Technical Advisory Committee

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2. Project Tasks

Table 1 summarizes the project tasks as initially proposed. The methodology and results chapters will provide further detail on the actual tasks as they were performed throughout the project.

Task	Description
1	Design of experiments and Kickoff Meeting
2	Laboratory Experiments- Specimen Set 1
3	Laboratory Experiments- Specimen Set 2
4	Laboratory Experiments- Specimen Set 3
5	Development of Diagnostics Tool and Benchmarking
6	In-situ Bridge Deck Pilot Implementation
7	Dissemination, TAC Meetings and Technological Transfer

3. Methodology

The novel methodology developed in the previous project (M029) is briefly reiterated here.

There are two unique aspects of the method utilized:
1) Utilization of the leakage from the ultrasonic guided waves (referred to as Ultrasonic Guided Wave Leakage, or UGWL) by taking advantage of the locations of the transmitter (on steel rebar) and receivers (on concrete surface).
2) Utilization of the amplitude change (in frequency domain) as flaws progress instead of using velocity measurements used in typical ultrasonic measurements.

The UGWL test arrangement investigated, illustrated in Figure 1, transmits a guided wave through a steel reinforcing bar and detects the bulk waves leaked into the surrounding material. This test arrangement monitors the ultrasonic guided wave leakage, theoretically allowing the steel reinforcement, the steel-concrete interface, and the concrete to be inspected with one system. Two sets of equipment was used in this project:

1. The NDE 360 platform from Olson Instruments
2. Pulsonic Iltrasonic Pulse Analyzer 58-E4900 from Controls Group

The experimental set-up (Figure 1) includes a transmitter (T), which is a standard 54 kHZ transducer. For receivers (R), we used either a 2-inch diameter transducer, a 1-inch diameter transducer, or pinducers (miniature transducer) from CTS Valpey corporation. A low noise preamplifier was used to amplify the signals detected by pinducers. However, despite the amplifier, signals were too low and coupling was too problematic.

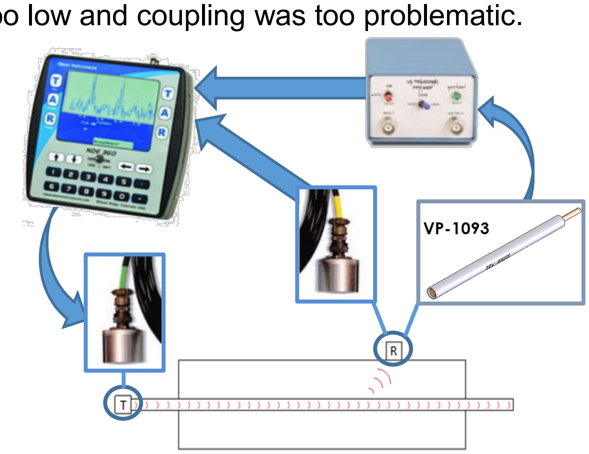

Figure 1 - Ultrasonic experimental set-up

Specific tasks in this project will entail three sets of laboratory experiments, a field implementation, an attempt at a standardized diagnostic tool, and development of technology transfer tools.

3.1. Laboratory Experiments

Three separate sets of specimens were cast to accomplish the objectives of this research. For all specimens, the concrete mix design used was Mix 47BD, designated by the Nebraska Department of Transportation (NDOT). The Technical Advisory Committee stated that this concrete mix design is commonly used on their bridge decks and also meets the criteria set out by the *American Association of State Highway and Transportation Officials* (AASHTO) for concrete bridge decks. Further, all specimens were cast to be 5 inches in thickness, so that the steel bars have a 2.5 inch cover, as typically found in Nebraska bridge decks.

Laboratory Experiments– Specimen Set 1

Specimen Set 1 comprised of two different investigations, designated as Set 1A and 1B.

A. ***Specimen Set 1A: Two 18inch x 12inch x 5 inch concrete slabs*** with a No.5 steel reinforcing bar embedded at the center (Figure 2): The purpose of these specimens were to put them under conditions to simulate corrosion and monitor the capabilities of the proposed UGWL method to detect the onset and the progression of corrosion. As such, the specimens were cast using 5% NaCl solution to accelerate corrosion. These specimens were also placed in a covered tub with water during curing such that the water was at a level that partially submerged the specimens, i.e. just below the reinforcing bar.

Figure 2 – Specimen Set 1A: Corrosion Specimens (left) and Corrosion product build-up over time (right)

B. ***Specimen Set 1B: One 60inch x 48 inch x 5 inch concrete slab*** with three No.5 steel reinforcing bars spaced at 12inches (Figure 3): The purpose of this specimen was to: 1) investigate whether it is possible to detect the onset of corrosion in a larger and more complex specimen, 2) Whether it is possible to detect corrosion and delamination simultaneously. Certain regions of the slab were cast using 5% NaCl solution (salt water) rather than regular water to localize the corrosive environment. Further, to accelerate the corrosion in these regions, concrete basins of 12 inches x 3 inches x 2 inches were cast in those regions above the reinforcing bar (Figure 3). These were filled with 5% NaCl solution to accelerate the corrosion process. The solution inevitably gets absorbed and evaporates, so the basin was refilled with water every six days. The third steel reinforcing bar in this specimen was used to monitor simultaneous development of corrosion and delamination. This test is referred to as the “corrosion-delamination test”. The bar was exposed to corrosive conditions for 24 days, while simultaneously delaminated slowly over the same time period.

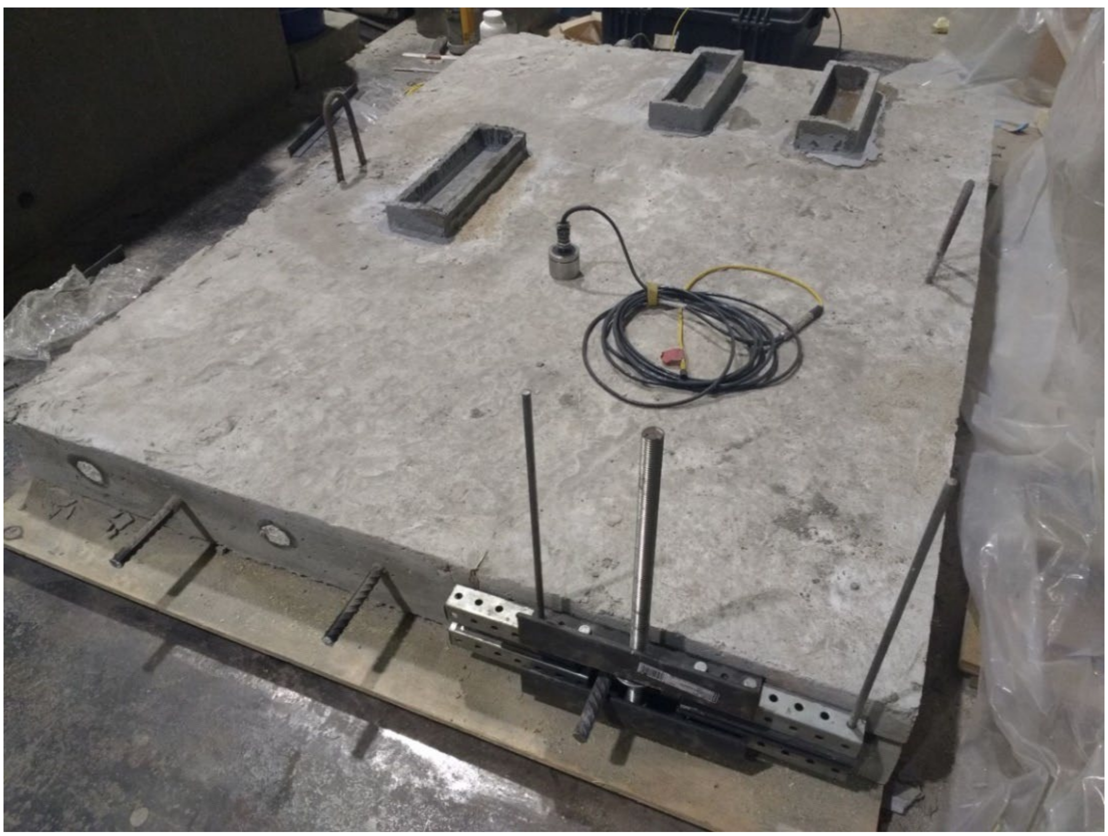

Figure 3- Specimen Set 1B (Corrosion-delamination Specimens)

Laboratory Experiments– Specimen Set 2

Specimen Set 2 comprised of two concrete test specimens with the dimensions of 18 inch x 18 inch x 5 inch, which were cast with a No.5 steel reinforcing bar embedded at the center height and three inches away from one edge of the cross-section. The purpose of this set of specimens was to look at the ability of using the UGWL method to identify the onset of cracks in concrete independent from rebar delamination (rebar delamination was studied in previous project M029). As such, an initial crack was created in the specimen and gradually opened further mechanically, as shown in Figure 4.

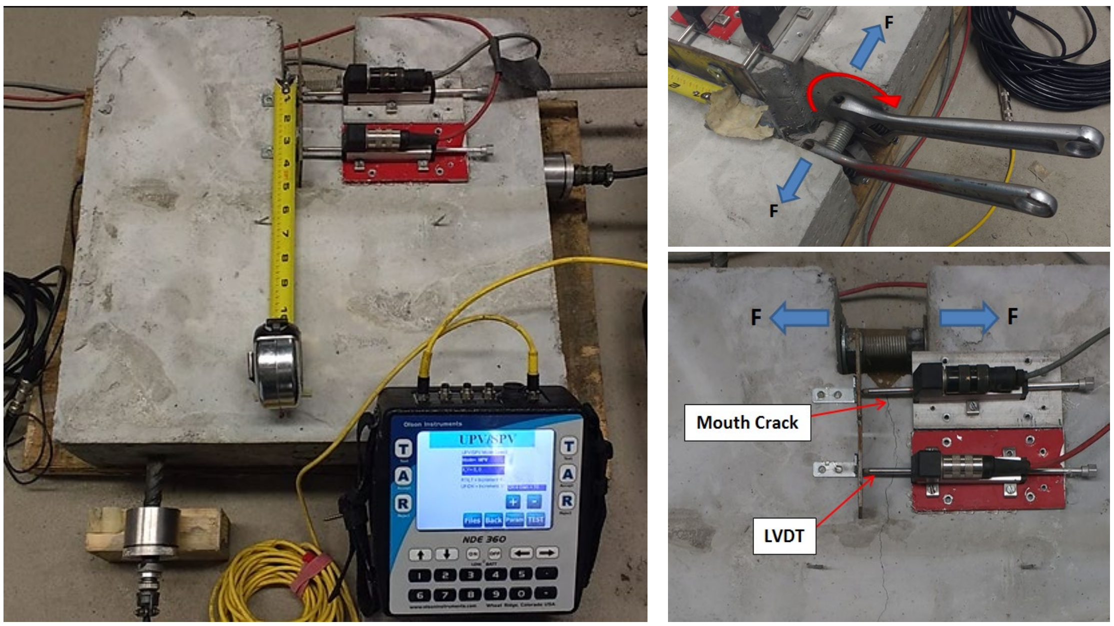

Figure 4 – Specimen Set 2: Cracking Specimen and the detail of the cracking mechanism

Laboratory Experiments– Specimen Set 3

Specimen set 3 was a larger reinforced concrete slab (10 feet long, 4 feet wide, and 8 inches thick), which was cast to examine the influence of multiple layers and direction of reinforcement on the UGWL method, as well to test farther distances between the transmitter and receivers than we tested before (Figure 5). Each layer of reinforcement had a cover of 2.5 inch and, consequently, 3 inches between them. The specimen contained known areas with delamination, corrosion and cracks as shown in Figure 6. An array of sensor locations were marked on the side of the slab as shown in Figure 7.

Figure 5- Specimen Set 3 formwork and bars before casting (left) and final specimen (right)

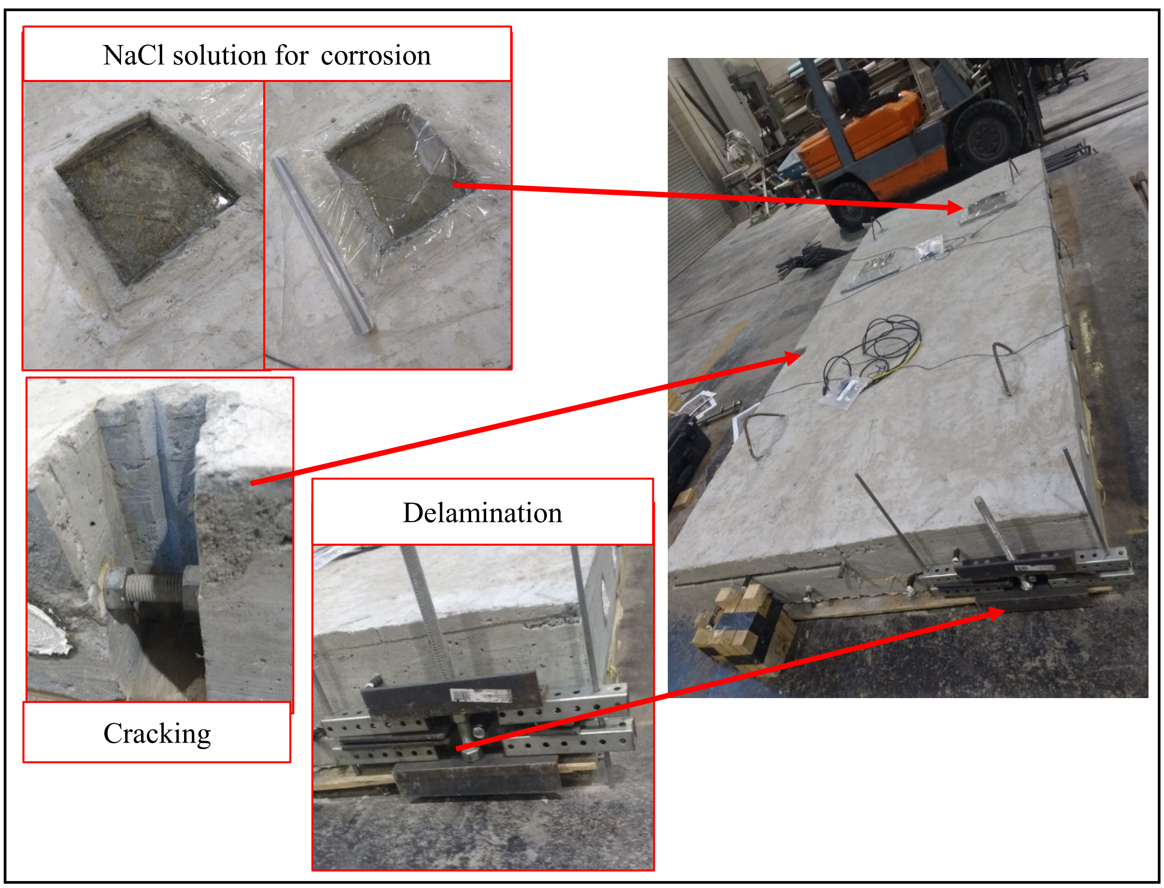

Figure 6- Specimen Set 3 and various areas of artificially introduced flaws

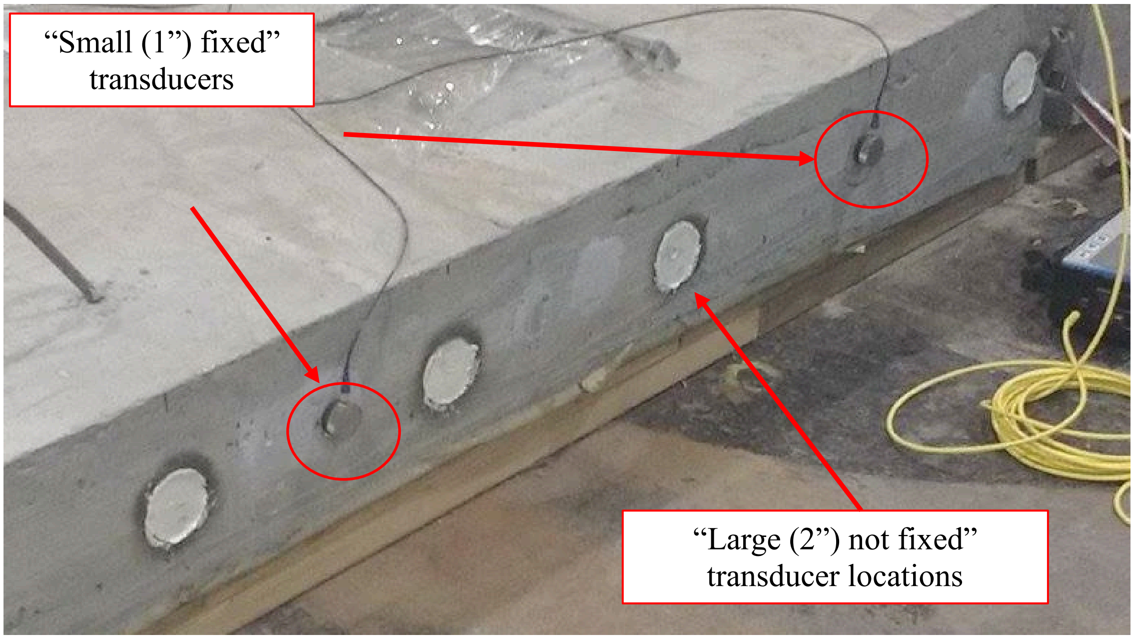

Figure 7- Specimen Set 3 Sensor locations

3.2. Development of a Diagnostic Tool and Benchmarking

While the main potential of the original idea is to develop a new structural health monitoring (SHM) or continuous monitoring technique, through our discussions with the TAC; we decided to also investigate whether it is possible to develop a diagnostic tool that can give valuable instantaneous information on the health of an existing bridge deck. This requires a database and analysis of data to determine relationships over a long period and field data sets that are otherwise validated. It may also be achieved by combining the method with other methods.

For benchmarking purposes, Ground Penetrating Radar (GPR) and half-cell potential (HCP) techniques will be utilized in order to see if they can detect corrosion as clearly as the proposed UGWL method.

3.3. In-situ Bridge Deck Pilot Implementation

One pilot bridge deck implementation took place toward the end of the project. The pilot test was conducted on bridge numbered S006 30574, located near the town of Emerald, and referred to as the "Emerald Bridge".

3.4. Technology Transfer

One of the goals of this project is to develop a method that can eventually be adopted by the NDOT staff. For this purpose, our team implemented lab visits and developed videos to make the method easier to understand for the NDOT staff. Technical publications were also prepared from the findings of this project to share our findings with the larger community and get external feedback.

4. Results

Results of the project are presented in this section, in the order that the tasks are explained in the previous section.

4.1. Results of Lab Experiments

Laboratory Experiments– Specimen Set 1

Specimen Set 1A comprised of two 18inch x 12inch x 5 inch concrete slabs with a No.5 steel reinforcing bar embedded at the center level (Figure 2). The purpose of the experiment was to investigate whether the proposed method can detect the start of corrosion. Figure 8 shows the velocity measurement results (time domain) on top and the amplitude measurement results (frequency domain) on the bottom. As discussed before, velocity measurements represent the current industry standard, while amplitude measurement is part of the methodology proposed by our team. Figure 9 shows a larger view of the peak amplitudes in frequency domain that clearly shows the change in amplitude as the corrosion progressed; while it is more difficult to see this change by velocity measurements (Figure 8). These figures represent the average of five measurements each. Figure 10 shows mean and standard deviation of each data set in a plot of percent change in energy (or peak amplitude) versus days (or progression of corrosion).

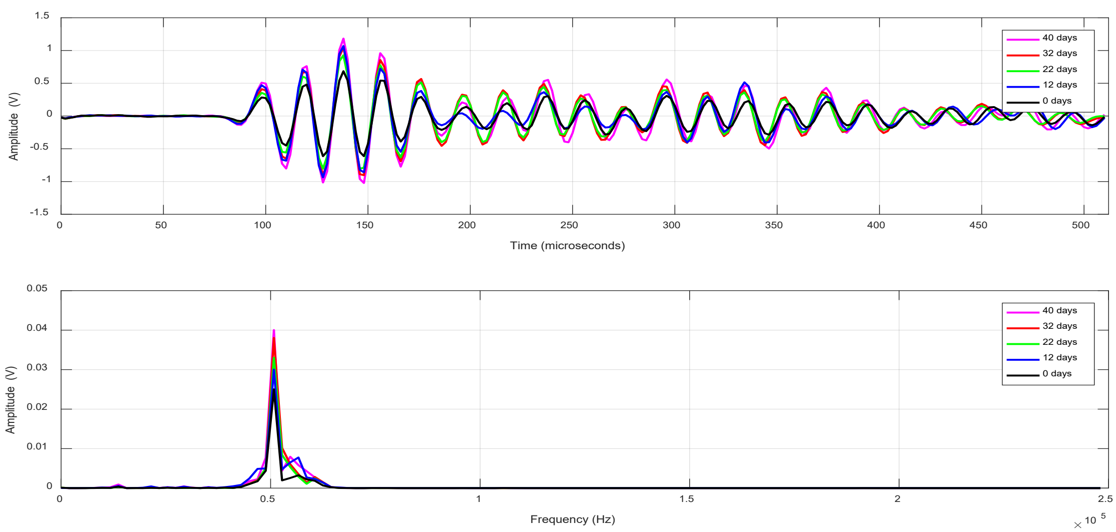

Figure 8- Velocity (top) and Amplitude (bottom) readings as the corrosion progressed up to 40 days

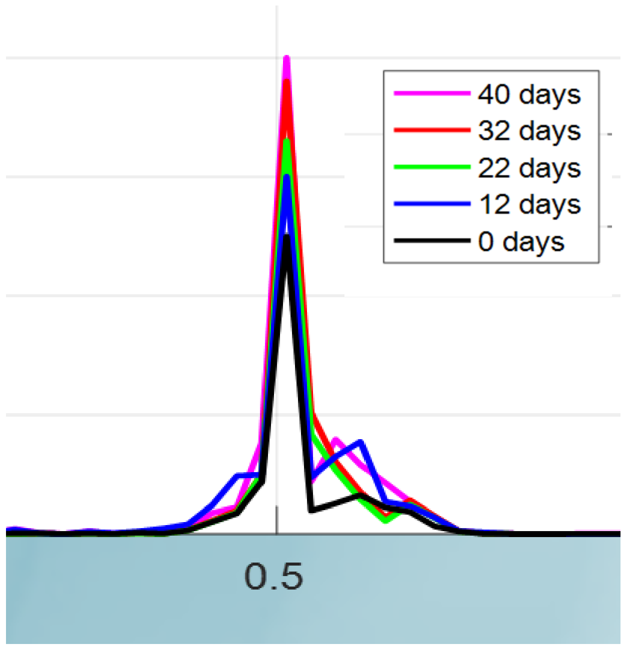

Figure 9- Larger view of the peak amplitude readings as the corrosion progressed in the specimens up to 40 days

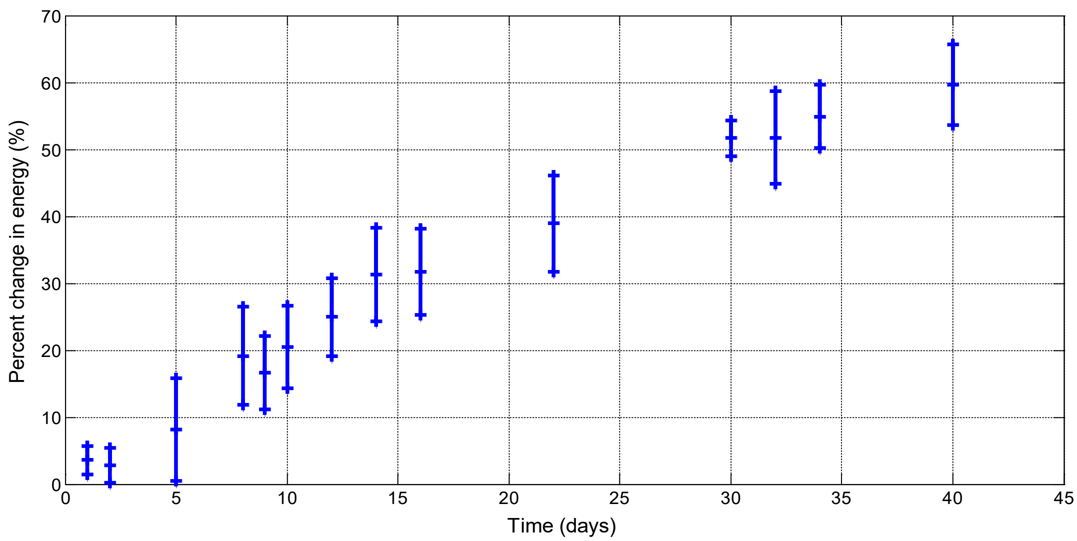

Figure 10- Mean and standard deviation of each data set

It can be concluded from this set of experiments that onset of corrosion, even as early as 5 days, is detectable with this method; and the percent difference increases as the corrosion builds up.

Specimen Set 1B comprised of one 60 inch x 48 inch x 5 inch concrete slab with three No.5 steel reinforcing bars spaced at 12inches (Figure 4). Figure 11 shows the amplitude of leaked waves detected from the array of sensors located along the edge of the concrete slab at the beginning and after 24 days of corrosion progression. In this test, the transmitter is on bar 1a (shown in Figure 12), and sensors are located on the near edge of the slab, i.e. 1 foot away from the bar (denoted by the red line in Figure 12). As expected, the energy attenuates as the sensors are farther away from the transmitter location at the end of the rebar. Further, while the no-corrosion data (0 days) follows an exponential curve as expected from theoretical equations after 24 days, the sensors corresponding to the corrosion region show an increase in amplitude. Finally, based on the leakage angles demonstrated in Figure 13, it is expected to have the exponential decay of the amplitude start around 13.5 inches.

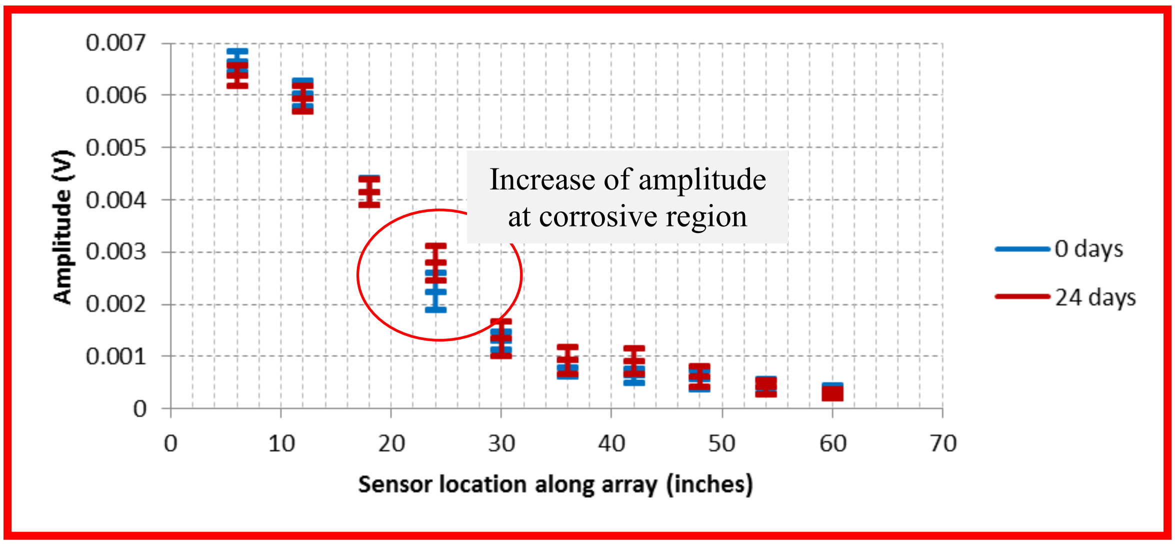

Figure 11- Amplitude of leaked waves versus sensor location plot for Specimen 1B, Transmitter on corroded bar (bar 1a) and Receivers 1 foot away from the bar

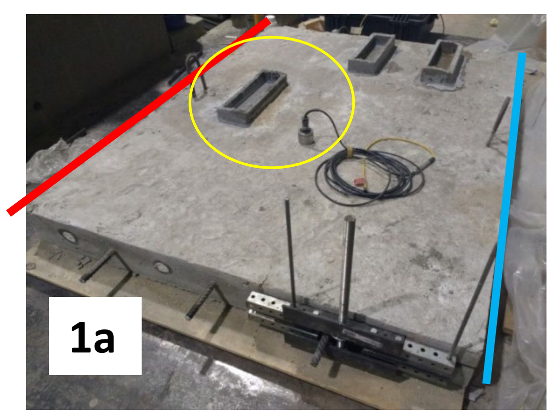

Figure 12- Red line denotes the sensor array for data displayed in Figure 11, and blue line denotes the sensor array for data displayed in Figure 14.

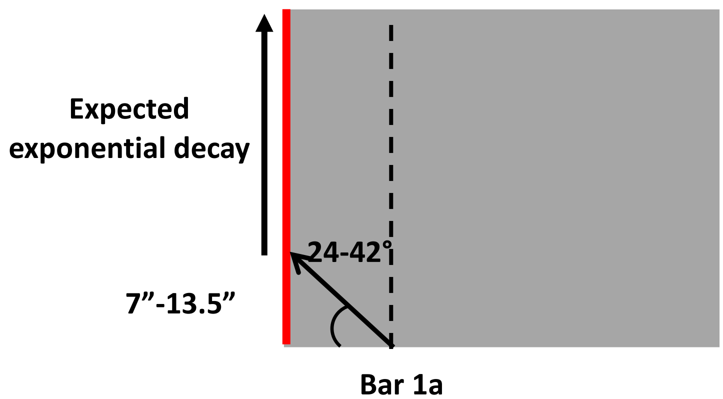

Figure 13- Schematic illustration of leakage angles with respect to the location of the sensor array shown in red line (1 foot away from bar 1a)

Figure 14 shows data from the sensor array on the other edge of the specimen (blue line in Figure 12) and Figure 15 illustrates the consequences of the leakage angle in this case.

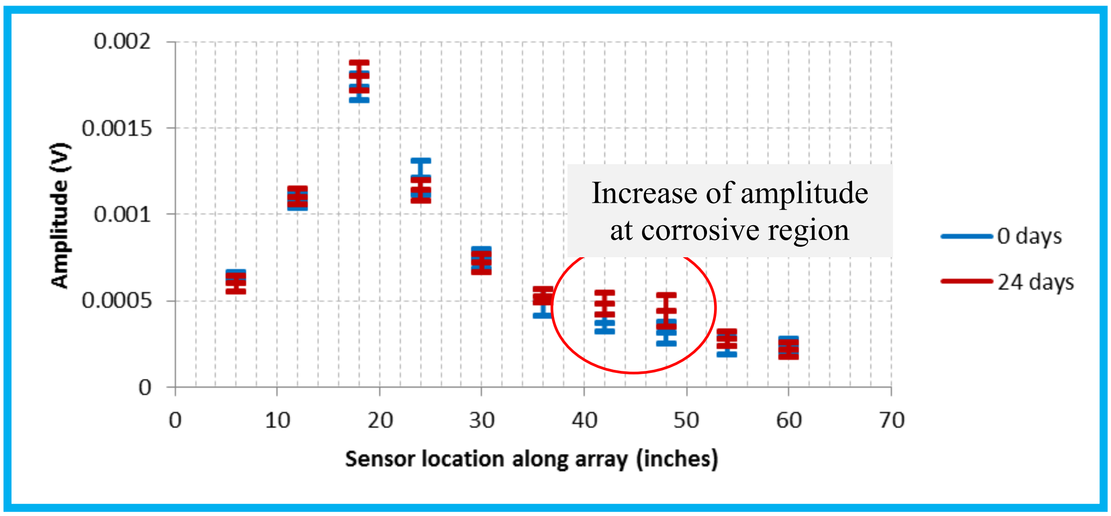

Figure 14- Amplitude of leaked waves versus sensor location plot for Specimen 1B, Transmitter on corroded bar (bar 1a) and Receivers 3 foot away from the bar (blue line)

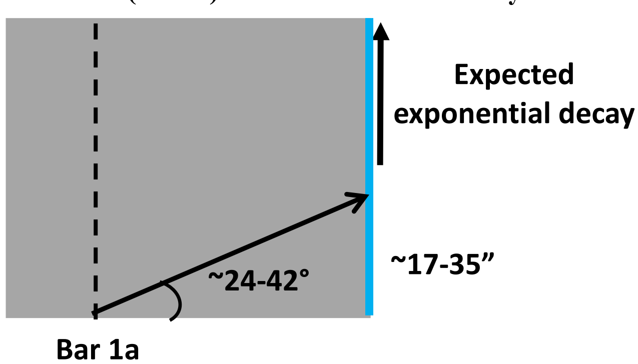

Figure 15- Schematic illustration of leakage angles with respect to the location of the sensor array shown with blue line (3 feet away from bar 1a)

As expected, sensors located closer to the corroded bar with signals transmitted through this wave guide detect stronger signals/higher amplitudes compared to an array located farther out. However, whether tested at 1 foot or 3 feet away from the corroded bar, the onset of corrosion could be detected as early as 5 days.

It should also be noted that the corrosion is detected as an increase in the amplitude of the leaked signals in either case (Figures 11 and 14). The initial stages of corrosion improves the bond between steel and concrete until the delamination occurs, increasing the amount of energy absorbed into concrete.

Finally, it should be noted that, when interpreting test results, leakage angle should be considered in order to calculate the location of the flaw.

Laboratory Experiments– Specimen Set 2

The purpose of this specimen was to test the ability of the proposed method in detecting cracking in concrete, independent of delaminations between steel and concrete. Specimen Set 2 comprised of ***two*** concrete test specimens with the dimensions of 18 inch x 18 inch x 5 inch, which were cast with a No.5 steel reinforcing bar embedded at the center height and three inches away from one edge of the cross-section.

In one of these specimens, the crack was created parallel to the steel rebar that was used as the wave guide with direction of wave crossing the crack nearly perpendicular (see Figure 16). This results in the amplitude graphs shown in Figure 17, as the as the crack in concrete progressed from not existent to 11.6 inches long. The drop in the amplitude is very clear when these graphs are inspected together, indicating a flaw that is getting worse.

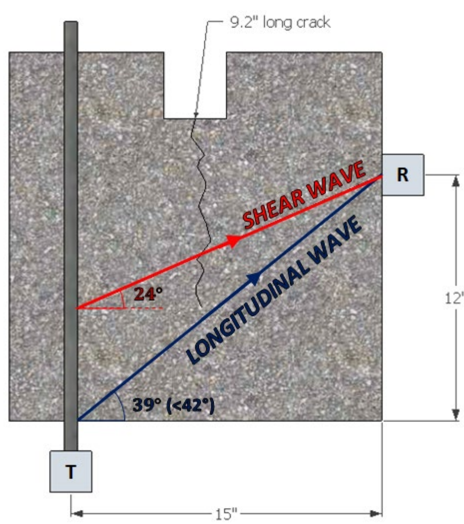

Figure 16- Plan view of the relationship between the transmitter, the receiver, and the cracking in concrete for the first specimen in Set 2.

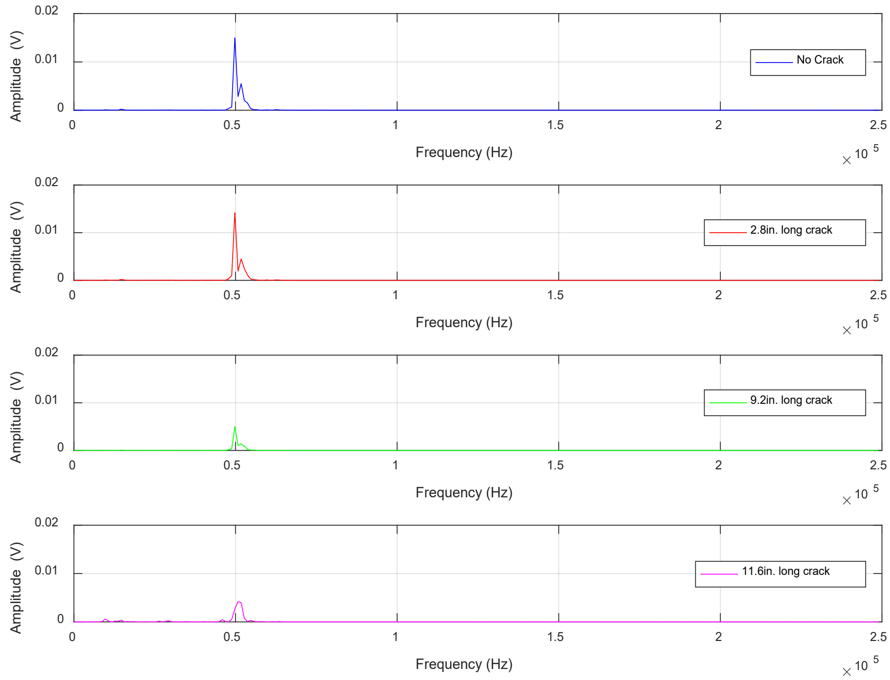

Figure 17- Amplitude of the leaked energy measured as shown in Figure 16.

Figure 18 shows the other specimen in plan view, with the location of the crack, transmitter (on bar), and receiver (on concrete). As can be seen, in this case, the direction of the wave crossing the crack is nearly parallel. Figure 19 shows the amplitude graphs for this specimen, as the crack in concrete progressed from not existent to 11.9 inches long. It should be noted that there is still a drop in the amplitude and it is noticeable, but as not clear as the previous case. As the crack disturbs the travel of the leaked waves, the amplitude of the energy received decreases, but because the crack is nearly parallel to the wave, the decrease is smaller.

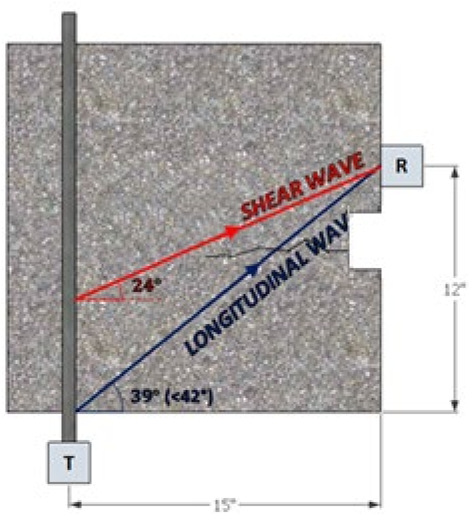

Figure 18- Plan view of the relationship between the transmitter, the receiver, and the cracking in concrete for the 2nd specimen in Set 2.

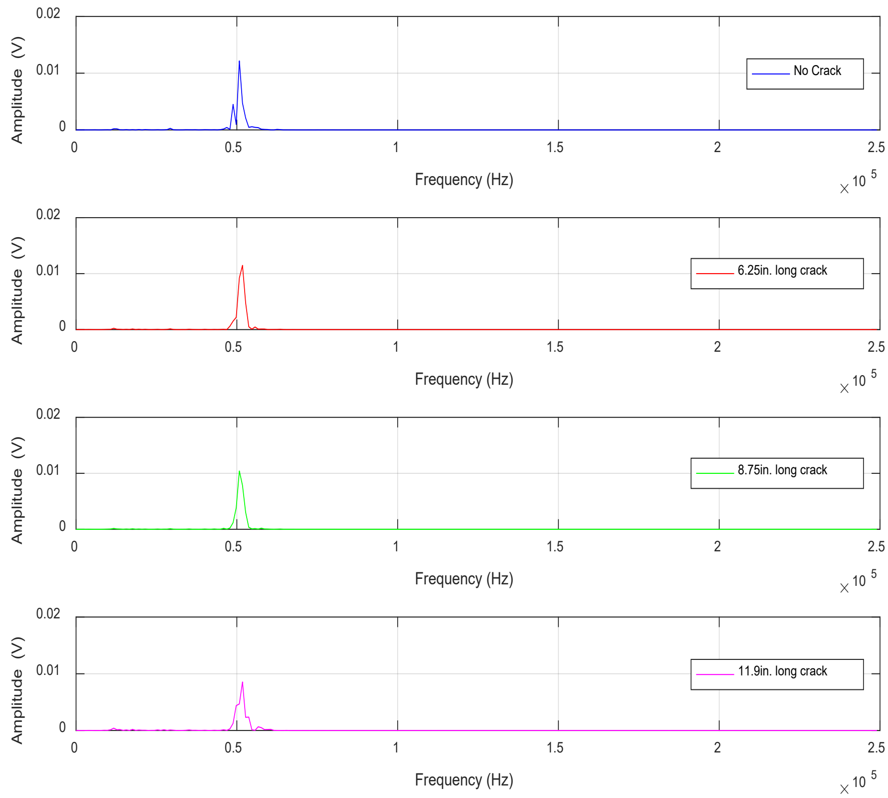

Figure 19- Amplitude of the leaked energy measured as shown in Figure 18.

Laboratory Experiments– Specimen Set 3

The purpose of this larger specimen was to examine the influence of multiple layers and direction of reinforcement on the UGWL method, as well to test farther distances between the transmitter and receivers (Figure 5). Several investigations were carried out on this specimen:

First, a delamination is introduced around some parts of the bars with laminates placed around while casting and the existence of this flaw was detected by several sensors along the length of the specimen as shown in Figure 20. The results in this test (Figure 21) showed that the amplitude of the leaked wave increased after the delamination region as expected.

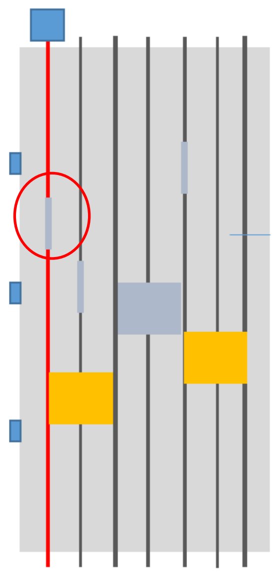

Figure 20- Schematic of the setup for the testing for delamination around the bar (see circled area of inserted delamination)

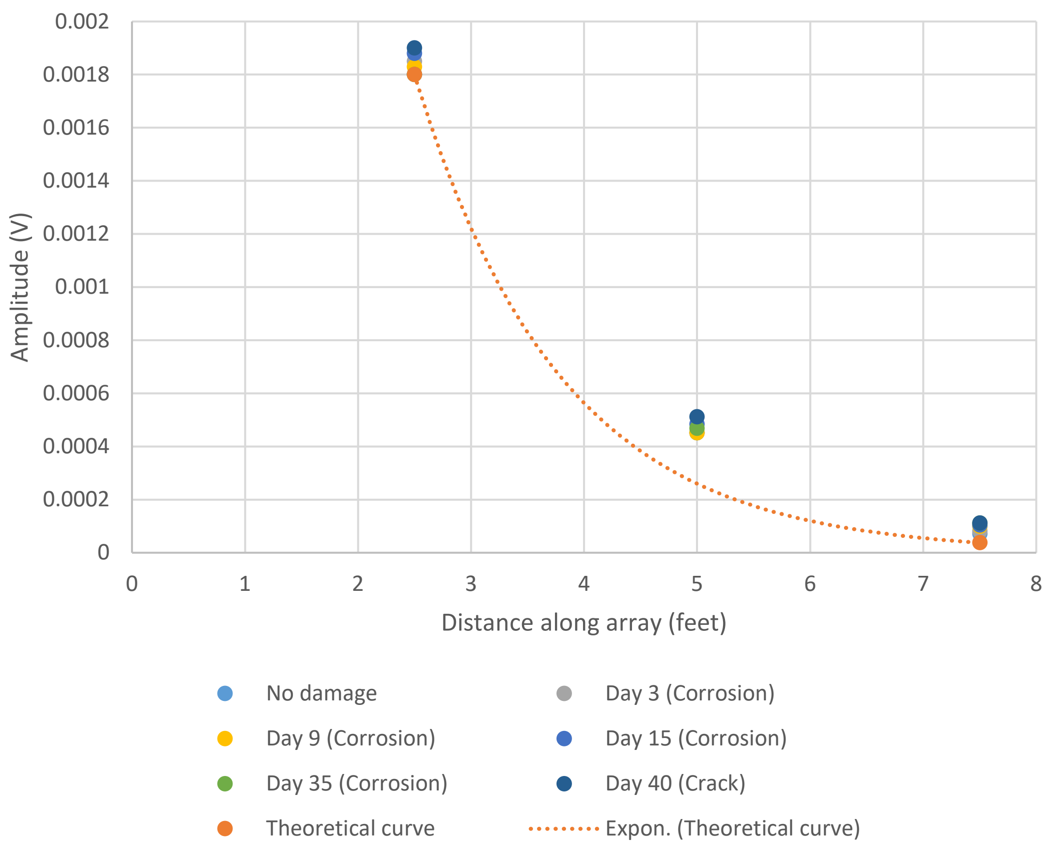

Figure 21- Amplitude versus distance plot for Specimen 3, 1st bar (as shown in Figure 20).

In the second test, the second bar (shown in red on Figure 22), was the one where the signals were transmitted and the purpose was to detect the corrosion. As shown in Figure 23, the amplitude increases after the corrosion zone.

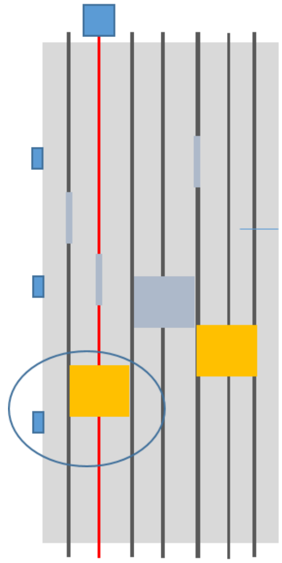

Figure 22- Schematic of the setup for the testing for corrosion around the second bar (see circled area of corrosion)

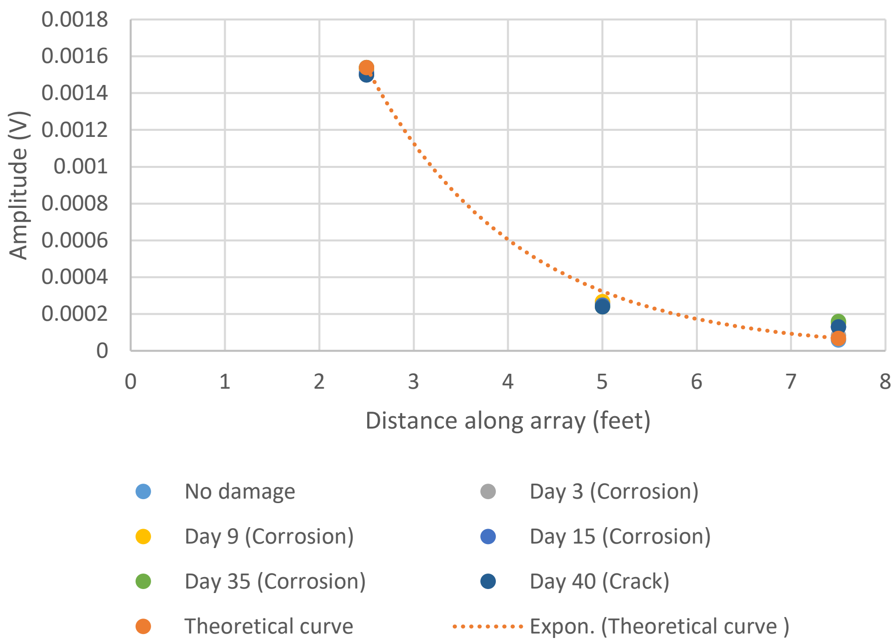

Figure 23- Amplitude versus distance plot for Specimen 3, 2nd bar (as shown in Figure 22).

The manual delamination and cracking attempts for this specimen were unsuccessful because, with two layers of reinforcement, the slab was too strong for cracking or delaminating manually. However, all in all, the main goal of this specimen was achieved: we could detect two types of flaws (delaminations inserted around bars and corrosion on bars) with two layers of reinforcement and up to 10 feet away from the transmitter location.

4.2. Results of Benchmarking and Diagnostics Tool Development

We used Specimen Set 3 to benchmark with GPR and HCP to compare the competencies of our method to these well known methods, specifically for corrosion detection. Figures 24 and 25 show a course scan and a finer scan with the HCP, respectively. This confirms, as expected, that the HCP can also detect the corrosion once it is formed at the same locations as our method. On hindsight, we realized that we should have tested with HCP continuously from the start in order to compare sensitivities of the two methods to very early corrosion detection and to quantify the amount of corrosion.

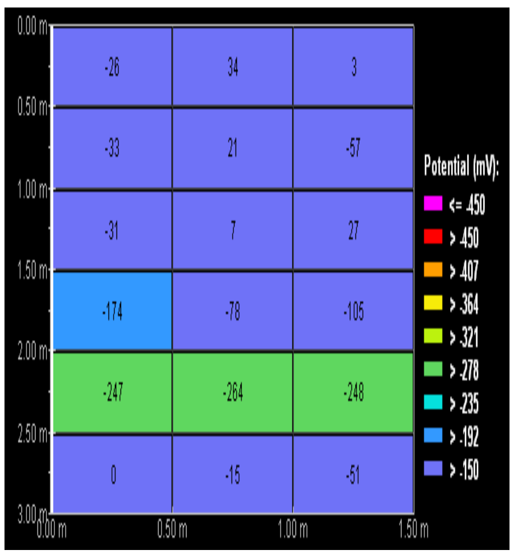

Figure 24- Course half-cell potential scan of the test slab for corrosion

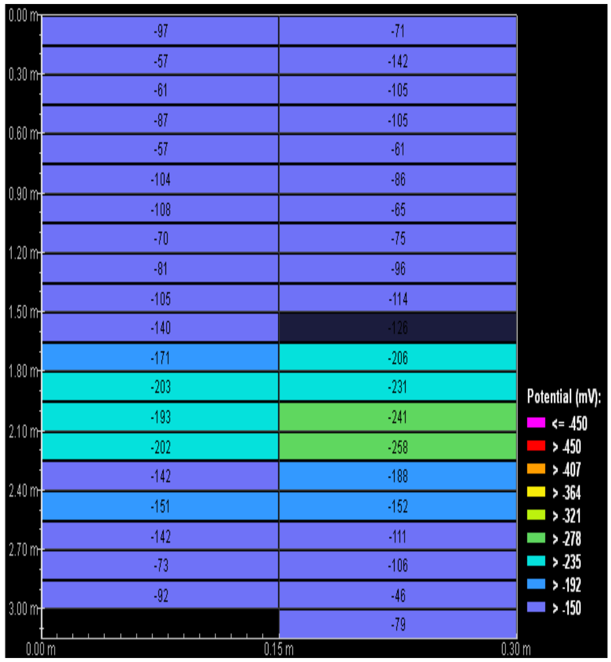

Figure 25- Fine HCP scan of the slab for corrosion detection

Finally, we also scanned the slab with GPR, and the results are shown in Figure 26. However, the results are inconclusive from GPR as expected. There seems to be a slight change in the hyperbolas indicating anomalies in the rebar reflections at the locations of corrosion, but they are not too different from reflections from the clean rebar regions. On the field, this type of result would be considered inconclusive and subject to a final call based on the operator's judgment and expertise.

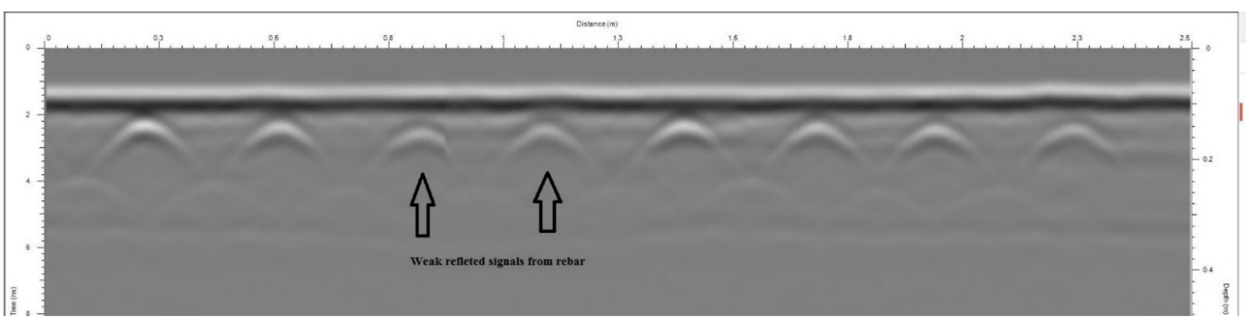

Figure 26- GPR results from the attempt to detect the corrosion areas on the rebar

In terms of the development of a diagnostic tool, while we think there is promise, there is more work to be done. If the concrete strength and bar diameter is known, a theoretical exponential curve can be drawn, which would in turn lead to some comparison of detected signals versus the theoretical curve to detect the flaws. However, there are many factors affecting the field testing, such as the history of the deck and its repairs, coupling issues with sensors, etc.... We believe these issues need to be resolved and more data need to be collected for comparisons to be able to develop a robust diagnostic tool.

4.3. Results of Pilot Field Implementation

A pilot test was conducted on Bridge S006 30574 near the town of Emerald. This bridge will be henceforth referred to as the Emerald Bridge. There were two testing locations: one in north lane and one in south lane; each right on a rebar. At each location, with the help of NDOT staff, we drilled down to the top rebar and grinded the surface of the rebar to create a smooth and flat surface for better coupling. We used both a 1-inch diameter sensor and a 2-inch diameter sensor. 2-inch diameter sensor is shown in Figure 27.

Figure 27- Images from pilot field work

Lessons learned from this field implementation include the following:

- 1 inch sensor was not strong enough to detect signals on the field, even though it had worked in the lab
- 2 inch sensor could collect data up to 14 feet away from the transmitter, which is greater than the largest distance we have achieved in the lab (due to specimen size).
- Placing sensors directly aligned with the bar was better than setting them up on an offset, which is another deviation from the lab setup. While signals were stronger in this case, we know that all of the transmitted energy does not go into the rebar in this layout. In the future, a mechanism that directs the signal to a direction close to parallel to the rebar needs to be invented.

4.4. Technology Transfer

The Technical Advisory Committee (TAC) was invited to the structural lab in Omaha to observe a demonstration of the method. Further, two videos were prepared to explain the methodology and use of each equipment. These videos were submitted to NDOT along with the final presentations in digital format. Peer-reviewed Publications from this study are as follows:

1. Garcia, E.[3]; Erdogmus, E.; Schuller, M; Harvey, D (2017). *"*A Novel Method for the Detection of Onset of Delamination in Reinforced Concrete Bridge Decks*," ASCE Journal of Performance of Constructed Facilities, 31 (6),* DOI: 10.1061/(ASCE)CF.1943-5509.0001093.
2. Garcia, E.*, Erdogmus, E; Schuller, M., Harvey, D. Detecting the Onset of Different Types of Flaws in Reinforced Concrete, *Accepted for publication in the ACI Materials Journal, print date TBD.*

5. Conclusions and Recommendations for Future Work

The lab experiments and pilot field study resulted in valuable findings as well as new issues to be resolved with future work. The following sections detail these findings.

5.1. Conclusions

Following conclusions are drawn from this study:

1. The proposed ultrasonic testing method is a powerful and novel method in detecting the following:
    - Onset of delamination right from the beginning with delamination widths as small as 0.008 inches
    - Start of corrosion as early as 5 days
    - Individual cracks in concrete
    - Flaws in complex slabs with bidirectional reinforcement
2. At this time, this method is more promising as an SHM tool than a diagnostic tool.
3. To improve the practicality and success as an SHM tool, we need to develop better sensor-rebar attachment methods to improve coupling
4. To improve practicality and success as a diagnostic tool, we need a larger data pool of data with variety of conditions and material properties
5. Epoxy coating should be considered in future work:
    - Our tests showed epoxy coated bars still work with wave propagation in a similar manner as uncoated, which presents an area of superiority to HCP in corrosion detection.
    - However, grinding the bar is needed for better attachment. This removes the protective epoxy coating from the bar. Precautions should be taken to maintain the method as nondestructive and avoid causing means for future corrosion.
6. Based on our current knowledge, the ideal testing setup on a bridge would use the following information.
    - Up to 14 ft of detection range: We were able to detect strong signals up to 10 ft in the lab and 14 ft in the field.
    - If relatively accurate location of flaws is desired, a grid of sensors located at every 6 inch is recommended. Therefore, each grid around a rebar can be 14 feet long and 3 feet wide, based on limits tested thus far.
    - On the field, sensors right on top of the rebar along its length are recommended; but if possible, the direction of the signal should not be perpendicular to the bar

with the use of an inclined sensor-to-bar attachment. Otherwise, based on lab results, it is also predicted that sensing from the edge of slab near the tested bar could give larger amplitudes.

7. Two key ***significant/long term potential*** of this method compared to other NDT are:
    - ***Very*** early detection of flaws
    - The ability to identify the speed and patterns of deterioration in bridge decks from the first sign of corrosion to a detrimental level of delamination (i.e. the level where there would be a need for deck replacement). With such a *bridge deck deterioration model*, NDOT may save funds from unnecessarily overlaying healthy bridge decks and/or extend the 10 year benchmark of overlays in the future.

5.2. Recommendations for Future Work

While the method has been found to be successful in the laboratory settings on idealized specimens, there are still impediments before the practical application of this method on the field on a regular basis.

First, as stated before, on the field, sensors right on top of the rebar along its length are recommended; but if possible, the direction of the signal should not be perpendicular to the bar with the use of an inclined sensor-to-bar attachment. Currently, there are no commercial options for such sensors. Further, while the pilot field study showed that drilling down to the rebar in a few locations and holding the sensor on the bar works to some extent, it also causes major coupling issues depending on the quality of the grinded surface. Therefore, to obtain more reliable data, special sensors or sensor attachments need to be developed.

Second, the method was successful in detecting the progression of corrosion as early as 5 days and the corrosion built-up was benchmarked with the well-known half-cell potential (HCP) at the end. However, no periodic measurements were taken by (HCP) to quantify the amount of corrosion detected. Only the last stage (40 days) were confirmed by HCP. This limitation should be remedied by future work.

Finally, with the solution of the two issues mentioned above as well as long term data from several successful field implementations, a bridge deck deterioration model should be developed for new and recently repaired bridge decks.

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