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GROUND PENETRATING RADAR APPLIED TO REBAR CORROSION INSPECTION

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ABSTRACT. In this paper we investigate the use of ground penetrating radar (GPR) to detect corrosion-induced thinning of rebar in concrete bridge structures. We consider a simple pulse/echo amplitude-based inspection, positing that the backscattered response from a thinned rebar will be smaller than the similar response from a fully-intact rebar. Using a commercial 1600-MHz GPR system we demonstrate that, for laboratory specimens, backscattered amplitude measurements can detect a thinning loss of 50% in rebar diameter over a short length. GPR inspections on a highway bridge then identify several rebar with unexpectedly low amplitudes, possibly signaling thinning. To field a practical amplitude-based system for detecting thinned rebar, one must be able to quantify and assess the many factors that can potentially contribute to GPR signal amplitude variations. These include variability arising from the rebar itself (e.g., thinning) and from other factors (concrete properties, antenna orientation and liftoff, etc.). We report on early efforts to model the GPR instrument and the inspection process so as to assess such variability and to optimize inspections. This includes efforts to map the antenna radiation pattern, to predict how backscattered responses will vary with rebar size and location, and to assess detectability improvements via synthetic aperture focusing techniques (SAFT).

Keywords: Ground Penetrating Radar, Concrete, Rebar, Corrosion, Bridge Inspection

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INTRODUCTION AND BACKGROUND

Ground penetrating radar (GPR) is routinely used to locate and map steel reinforcing bars (rebar) in concrete structures. Detecting damage to embedded rebar is a much more difficult challenge. The specific problem being addressed is illustrated in Figure 1. On highway bridges vertical rebar are used to anchor the concrete retaining wall to the road deck. Typically the concrete for the road deck is poured first and partially embeds a series of vertical rebar located near the road deck edges. The vertical retaining walls, which are poured later, then complete the enclosure of these rebar. Water infiltration at the "cold joint" between the road deck and the bottom of the wall can cause corrosion of the rebar. Over time, this can lead to rebar thinning and failure. In this paper we report on efforts to develop a GPR approach to quantifying corrosion-induced rebar thinning in concrete. Our goals are twofold: (1) to assess amplitude-based GPR as a technique for detecting rebar thinning; and (2) to use the bridge inspection problem as a vehicle for developing tools to enhance and quantify GPR inspections in general.
FEASIBILITY STUDY USING LABORATORY SPECIMENS

The equipment used in our measurements is shown in Figure 1b. It is a commercially-available, portable, battery operated GPR unit manufactured by Geophysical Survey Systems, Inc. (GSSI). Our rebar inspection is analogous to a pulse/echo ultrasonic inspection, with an electromagnetic (EM) pulse replacing the sonic pulse. The pulser portion of the pulser/receiver sends a voltage spike to the antenna, causing the antenna to radiate a short-duration EM pulse. Some of this radiated energy penetrates into the concrete, strikes an embedded rebar and is reflected back toward the antenna now acting as a receiver. The resulting output voltage signal is amplified by the receiver electronics and displayed on a computer monitor.

For a one-dimensional scan of the antenna above an embedded rebar (Figure 1c), a standard GPR display is referred to as a "B-scan" with an example shown in Figure 1d. The horizontal axis indicates the antenna position, while the vertical axis displays either signal arrival time or inferred penetration depth. The gray-scale image then depicts echo strength, with white indicating a strong positive voltage value and black indicating a strong negative voltage. For the standard 1600-MHz antenna we are using, the EM radiation is in the microwave band. The wave speed and wavelength in concrete depend on the dielectric constant of the concrete which varies somewhat for different grades of material. Typically the wavelength in concrete is on the order of a few inches, and the rebar diameter is smaller than either the EM wavelength or the broadcast envelope (radiation pattern size) of the antenna. When the antenna is scanned across a concrete fixture containing a rebar, the rebar is "sensed" at many different antenna positions. The arrival time of the rebar echo depends on the distance between antenna and the rebar, being smallest when the antenna is directly above the rebar. Because of the dependence of echo arrival time on antenna position, regions of high reflected amplitude in B-scans have a hyperbola-like shape as illustrated in Figure 1d. A measurement of the slope of the hyperbola asymptote can be used to estimate the wave speed in concrete, and hence the dielectric constant on which it depends.

The reflected signal from an embedded object depends in part on the size of the object relative to the EM field that is incident upon it. Other things being equal, smaller objects will return smaller reflected signals than larger objects. Thus the peak amplitude observed in a scanned measurement (i.e., the amplitude at the top of the hyperbola in the B-scan image) is expected to depend on the size of the embedded object. Our approach to rebar inspection is a
straightforward measurement of peak reflected amplitude. The assumption here is that a rebar containing a thinned region (i.e., presenting a smaller physical target to the incoming microwave pulse) will reflect more weakly than an unthinned rebar, thus resulting in a smaller peak amplitude.

A feasibility study was conducted using 5 rebar-in-concrete specimens (Figure 2), supplied by the Iowa Dept. of Transportation and designed to simulate rebar thinning at a road-deck/retaining-wall joint. Three of the specimens contained “standard black” 0.5"-diameter steel rebar. Of these, one was fully intact and two had metal removed from a small region to simulate thinning. The diameter reductions were 0%, 25%, and 50% respectively relative to undamaged rebar. The remaining two specimens contained 0.75"-diameter epoxy-coated rebar, with one specimen intact (0% reduction), and one having a 50% diameter reduction. One difficulty in using GPR here is illustrated in Figure 2a. For the GPR system to operate correctly, the antenna carriage must be rolled along a surface, with the carriage wheels turning properly and sending accurate position information to the computer. In our case the antenna carriage is rolled along the near-vertical retaining-wall surface just above the simulated joint. In this orientation the center of the antenna is aimed above the thinned region of the rebar, and thus the thinned region is not illuminated with the strongest portion of the broadcast microwave field. Nonetheless, some of the microwave radiation does strike the thinned region and is reflected back to the antenna. So, although the setup is not optimal, there is still an opportunity to search for signal amplitude differences arising from rebar thinning.

Measurements were made to determine whether the amplitude of GPR reflected signals could distinguish the various rebar in the test specimens. The five specimens were aligned as shown in Figure 6b so that the antenna carriage could be scanned across them in a continuous fashion. Two measurement trials were made, one in which the antenna carriage rolled right-to-left (trial J004) and one in which it rolled left-to-right (J005). The B-scan image for the second trial is shown in Figure 6c. There the reflection from the air/concrete interface appears as the horizontal band near the top of the image. Note the perturbation of this band near the far right-hand edge; this is a consequence of the change in the "liftoff" between the bottom of the antenna housing and the concrete surface. Such liftoff variations can occur when a carriage wheel slips off of a surface or rolls over an obstacle. To a lesser extent lift-off can also change due to unevenness of the rolling surface, or to compression of the carriage wheels when the hand-applied pressure varies while scanning. In this particular case, the liftoff change occurred when the front wheels of the carriage rolled off of the right-most concrete block, causing the antenna to tilt slightly.

The processing of the GPR data is summarized in Figure 3. A plot of signal-voltage-versus-arrival-time plot observed at any fixed antenna position is called a "wiggle plot" or A-
scan, with an example shown in Figure 3a. One A-scan essentially represents one vertical line of data in a B-scan. To quantify a rebar response for a given test specimen, we first located the A-scan (near the top of the hyperbola) where the rebar response was largest in amplitude. As a measure of amplitude we used the peak-to-peak response, i.e., the difference between the highest positive voltage and the lowest negative voltage in the A-scan signal (Figure 2b). The maximal peak-to-peak amplitudes of the 5 test specimens are compared in Figure 2c. These may be regarded as the “raw” or uncorrected amplitudes. Note that for our test specimens the echo from the rebar partially overlaps the earlier-arriving echo from the air/concrete interface immediately below the antenna. One can "subtract" the air/concrete echo (acquired at a location not near a rebar), resulting in a "rebar only" signal. When doing this, one can also partially correct for minor liftoff and antenna-tilt differences, which are indicated by shifts in the arrival times and amplitudes of the earliest arriving portion of the A-scan (i.e., the first peak in the air/concrete interface echo). For the “corrected” peak-to-peak amplitudes of Figure 3d we have: (1) rescaled and shifted each A-scan such that the leading positive peaks have the same arrival time and amplitude; and (2) subtracted an air/concrete “reference” signal from each measured rebar signal to obtain a “rebar only” A-scan; and (3) reported the peak-to-peak amplitude of the result. The reference signal was obtained by scanning the antenna across the back sides of the test blocks where the physical distance to the rebar targets is larger, and the rebar responses consequently are seen later in time. The early-time portion of the reference signal was then used to represent the air/concrete interface response when no rebar was present.

As can be seen in Figure 3c-d, for standard “black” rebar (white ovals) the GPR amplitude measurements could readily distinguish a localized diameter thinning of 50% (i.e. Black50% vs. Black0%), but not a thinning of 25% (Black25% vs. Black0%). The two types of Epoxy-coated rebar could also be distinguished from each other, but there the thinned rebar returned a higher response than the unthinned one. For the two Epoxy-coated rebar (unlike for the black rebar) there was a substantial difference between the arrival times of the rebar echoes, indicating that the unthinned rebar was deeper within its concrete block. This depth difference is believed to be responsible for the amplitude difference in Figure 3, pointing to the need to
FIELD TRIAL AT A HIGHWAY BRIDGE

As illustrated in Figure 4, GPR measurements on embedded rebar were made along the bridge in central Iowa where Iowa Highway 210 passes above Interstate 35. The overpass spans about 200 feet and five 6-foot-long sections were selected for study, some near the crown of the overpass where water drains quickly, and some near the ends where water tends to collect. For the laboratory test blocks discussed earlier we knew (by design specifications) the degree of rebar thinning in each block. For the bridge trials no such information was available. All of the rebar studied may have been sound or all or some may have been corroded. As a possible way to distinguish the presence of thinning at the road deck, the following strategy was adopted. Each section of road deck was scanned in two ways: (1) with the antenna carriage flush with the road deck; and (2) with a (nominal) 2" x 4" wooden spacer placed between the antenna carriage and the road deck. The wooden spacer served to elevate the antenna approximately an additional 1.5" above the road deck, and hence 1.5 inches further from the thinned rebar zone if thinning was present. It was hypothesized that the difference in signal amplitudes (between a flush-with-road-deck measurement and an elevated measurement) would be larger for thinned rebar than for sound rebar. Each scanning trial was repeated four times: twice with left-to-right antenna movement and twice with right-to-left movement. Thus a total of 40 GPR datasets were collected: (5 sites) x (once with spacer, once without spacer) x (2 left-to-right scans and 2 right-to-left scans).

GPR data for one of the trials is shown in Figure 4b. In this case the region scanned...
was located at the crown of the bridge and the antenna carriage was flush with the road deck (no spacer used). Within the white-outlined box on the B-scan one can identify responses from 8 rebar, and the peak positive amplitude of each response was measured. As shown in Figure 4*, these responses ranged from about 25% to 40% of full-screen-height at the gain setting used. The peak positive value occurs within the dominant white crest seen in the B-scan. This was far enough removed from the air/concrete interface echo that it was not necessary to subtract the interface echo from the rebar signal when tabulating amplitudes.

Figure 4c compares GPR B-scans for a different section, located at the east end of the bridge. The white-circled areas identify cases where the rebar response increased significantly when the antenna was elevated above the road deck. Figure 4d compares the measured peak rebar amplitudes for the eastern section of the bridge. For a given rebar there are 8 plotted values: four with the antenna carriage flush with the road deck, and four with the antenna carriage elevated by the spacer. Generally speaking, as can be seen in Figure 4d, the measured amplitudes were larger when the antenna was elevated than when it was flush with the road deck. This trend is believed to be due to the fact that the lower face of the retaining wall tilts slightly away from vertical, with the angle between the wall surface and the road deck being larger than 90 degrees. Thus if a rebar was embedded perpendicular to the road deck (as designed), the distance from the retaining wall surface to the rebar would decrease slightly as one moved up the wall. Because concrete attenuates EM waves, the measured rebar amplitude depends in part on the thickness of concrete being traversed. Thus, a marked increase in rebar amplitude seen when the antenna is elevated does not necessarily signal a corroded rebar.

To partially account for travel path differences we measured both the peak amplitude of each rebar response and its time of occurrence relative to the air/concrete interface. Figure 4e summarizes the results for three bridge sections that were studied in detail, namely one each in the east, west and central regions. Each point in Figure 4e corresponds to a single rebar with the plotted coordinates based on an average of the measured amplitudes and arrival times for the four measurement trials. One sees a fairly strong correlation between amplitude and arrival time, with all points for the elevated-antenna measurements lying within the banded region shown. Most of the points measured with the antenna carriage flush with the road deck also lie within the banded region. However, there are a handful of “on the road deck” cases where the amplitude is unexpectedly low given the arrival time. One possible explanation for these cases is loss of amplitude due to localized thinning of the rebar near the road deck.

**DEVELOPMENT OF GPR ANALYSIS AND MODELING TOOLS**

To field a practical amplitude-based system for detecting thinned rebar, one must be able to quantify and assess the many factors that contribute to GPR signal amplitude changes. These include variability arising from the rebar itself (e.g., rebar location and thinning), and from other factors (concrete properties; antenna position and orientation; equipment characteristics; etc.) The quantification of measured signals itself presents some difficulties. The commercial software which accompanied our GPR Instrument is primarily geared to providing and manipulating B-scan images for visual interpretation by the user. A-scan data could be graphically viewed, but there was no handy way to process individual A-scans and extract numerical values for peak responses and other characteristics. Such numerical values are required to accurately quantify rebar responses and to construct comparative graphs like those shown in Figures 3-4. In the early stages of the rebar research project, it was necessary to develop special-purpose software to read the raw GSSI data files and to analyze that data in various ways. Software development using the C+ language is ongoing with new analysis tools being added as needed. Some software tools are relatively simple in intent, such as the ability to locate the peak response and its corresponding arrival time within a user selected box on a B-scan. Others are more sophisticated, such as the ability to fit a hyperbola to a rebar response crest, and to then determine an effective EM wave speed from the shape of that hyperbola.
Another option recently added to the analysis software allows the use of synthetic-aperture focusing techniques (SAFT) to enhance the responses of weak reflectors. Our GPR antenna is not focused. If it were focused at a particular depth, reflected signals from objects at that depth would be enhanced. SAFT provides a way to improve image quality to that comparable for a focused antenna by combining measurements made at a sequence of lateral positions. The basic idea is illustrated in Figure 5a. The A-scans gathered at different antenna positions (A, B, C) are shifted in time to account for their different travel times to a target point. The shifted A-scan responses are then summed to obtain a new “response value” that is then assigned to the target point. This process is repeated for every possible target point in the image. Figure 5b illustrates the application of SAFT in one case. The original pre-SAFT image was obtained by scanning the antenna across the back-sides of two abutting laboratory test blocks, each containing one rebar target. After SAFT processing the “response hyperbolas” of the two rebar have been greatly compressed in the horizontal direction, resulting in higher-contrast peak responses and more readily identified rebar locations. Our addition of SAFT to image processing is a recent development which is still undergoing testing and refinement. It has not yet been systematically applied to rebar responses from the laboratory test blocks or the bridge inspection data.

In analogy to past ultrasonic modeling efforts, we have also begun work to develop a “measurement model” which can be used to simulate GPR inspections. One eventual goal is a simulation tool to predict how the pulse/echo response from a given rebar depends on the degree of thinning and on the position and orientation of the rebar relative to the antenna. To this end we have performed measurements to “map” the radiation pattern broadcast by our antenna, fit that pattern to a two-parameter antenna model, and used the antenna model as one ingredient in GPR simulation software. The flavor of this ongoing work is captured by Figure 6. Panel (a) shows the field-mapping setup with the antenna being scanned above a steel sphere sitting on a foam support. The response from the sphere was recorded for a variety of scanning passes with different vertical and lateral offsets. Figure 6b shows a preliminary model prediction for the radiation pattern in air at the 1600 MHz center frequency. There, each colored image is 20 x 20 cm in size, with the leftmost image showing the plane containing the antenna scan direction, and the rightmost image showing the plane normal to the scan direction.
The EM field intensity peaks in the “near field” about 6 cm distance from the antenna before diverging at larger distances. Our broadband antenna radiates over a range of frequencies from about 0.8 to 2.4 GHz. The radiated intensity pattern depends on frequency, tending to diverge faster at lower frequencies. Figures 6c-d displays model predictions of how the reflected response from a rebar depends on rebar location and diameter. Two cases are illustrated, namely: (1) the dependence of rebar response on rebar diameter when there is a fixed distance of 3 inches between the antenna and the rebar; and (2) the dependence of rebar response on antenna-to-rebar distance for a fixed rebar diameter (0.5 inches). The model results in Figure 6 are for rebar in air, but we hope to soon extend the model to treat rebar embedded in concrete, including rebar which are thinned in local regions. Reference [1] contains a fuller discussion of our work to develop measurement models for simulating GPR rebar inspections, and more details of the measurements and analyses for the laboratory specimens and the highway bridge.

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REFERENCE