

Detecting Corrosion in Existing Structures Using Time Domain Reflectometry

by

Robert G. Hunsperger

Jian Li

Wei Liu

Department of Electrical and Computer Engineering

Michael J. Chajes

**Department of Civil and Environmental Engineering
University of Delaware**

January 2003

DELAWARE CENTER FOR TRANSPORTATION

**University of Delaware
355 DuPont Hall
Newark, Delaware 19716
(302) 831-1446**

Detecting Corrosion in Existing Structures Using Time Domain Reflectometry

by

**ROBERT G. HUNSPERGER
JIAN LI
WEI LIU**

Department of Electrical and Computer Engineering

MICHAEL J. CHAJES

**Department of Civil and Environmental Engineering
University of Delaware
Newark, Delaware 19716**

**DELAWARE CENTER FOR TRANSPORTATION
University of Delaware
Newark, Delaware 19716**

This work was sponsored by the Delaware Center for Transportation and was prepared in cooperation with the Delaware Department of Transportation. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Delaware Center for Transportation or the Delaware Department of Transportation at the time of publication. This report does not constitute a standard, specification, or regulation.

The Delaware Center for Transportation is a university-wide multi-disciplinary research unit reporting to the Chair of the Department of Civil and Environmental Engineering, and is co-sponsored by the University of Delaware and the Delaware Department of Transportation.

DCT Staff

Ardeshir Faghri
Director

Jerome Lewis
Associate Director

Wanda L. Taylor
Assistant to the Director

Lawrence H. Klepner
T² Program Coordinator

DCT Policy Council

Carolann Wicks, Co-Chair
Acting Chief Engineer, Delaware Department of Transportation

Eric Kaler, Co-Chair
Dean, College of Engineering

Timothy K. Barnekov
Acting Dean, College of Human Resources, Education and Public Policy

The Honorable Timothy Boulden
Chair, Delaware House of Representatives Transportation Committee

Michael J. Chajes
Chair, Civil and Environmental Engineering

Kevin Coyle
Representative of the Secretary of the Delaware Department of Natural Resources and Environmental Control

The Honorable Tony DeLuca
Chair, Delaware Senate Transportation Committee

Raymond C. Miller
Director, Delaware Transit Corporation

Donna Murray
Representative of the Director of the Delaware Development Office

Ralph A. Reeb
Director of Planning, Delaware Department of Transportation

*Delaware Center for Transportation
University of Delaware
Newark, DE 19716
(302) 831-1446*

(Draft Final Report)

**Detecting Corrosion in Existing Structures
Using Time Domain Reflectometry**

by

Robert G. Hunsperger , Jian Li, Wei Liu

Department of Electrical & Computer Engineering

Michael J. Chajes

Department of Civil and Environmental Engineering

DELAWARE CENTER for TRANSPORTATION

University of Delaware

Newark, DE 19716

This work was sponsored by the Delaware Center for Transportation and was prepared in cooperation with the Delaware Department of Transportation. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Delaware Transportation Institute or the Delaware Department of Transportation at the time of publication. This report does not constitute a standard, specification, or regulation.

January 2003

TABLE OF CONTENTS

<u>Introduction</u>	3
<u>Basic TDR theory</u>	3
<u>Corrosion detection geometry analysis</u>	4
<u>Another steel cable nearby</u>	5
<u>Metal shielding (if any) of a bridge cable</u>	5
<u>An external sensor wire running outside the grout</u>	5
<u>Analysis of factors affecting corrosion detection</u>	5
<u>Energy loss</u>	6
<u>Sensitivity to extent of corrosion</u>	6
<u>Relative position of sensor wire to the strand</u>	6
<u>Pulse strength enhancement simulation</u>	7
<u>Analysis of factors affecting void detection</u>	8
<u>Void detection geometry analysis</u>	10
<u>External void detection results</u>	11
<u>Conclusions</u>	11
<u>Future work</u>	12
<u>References</u>	12

INTRODUCTION

The effectiveness of corrosion evaluation of steel strands using time domain reflectometry (TDR) has been established both theoretically and experimentally in our previous work¹⁻³. A two-wire transmission line model has been established. The relationship between model geometry and impedance has been under thorough investigation and corresponding experimental results have been obtained. These results have proved its feasibility. TDR instrumentation has been successfully installed in a newly built bridge and periodic data are being collected and studied. It has been proved that for a new structure, if a sensor wire is applied along side the strand/rebar in the process of construction, the future corrosion that could occur on the strand/rebar can be effectively detected and the damage to the strand can be estimated.

However detecting corrosion in existing structures, in which sensor wires were not applied when the structures were built, is more difficult. External detection methods must be employed instead of internal methods. The theory of time domain reflectometry still applies, but factors such as the non-existence of built-in sensor wires, the presence of concrete layers (which are strong dielectrics and contain non-uniformities) and the distance from the strand to the sensor wire must be considered. They begin to exert strong influence on the TDR results and methods of distinguishing and evaluating their effects have to be found.

This project, titled "Detecting Corrosion in Existing Structures Using Time Domain Reflectometry" has been directed at solving these problems. Possible geometries that can be applied to externally detect steel strand corrosion and factors that influence signal returns from corrosion have been thoroughly studied during the project period.

Besides external steel strand corrosion detection, voids are another issue. It is believed that steel strands buried in concrete structures are inclined to incur corrosion in voids where moisture is easily gathered and thus steel is more vulnerable to corrosion. Corrosion will have less chance to happen if voids are detected and a remedy is implemented in time. In this project, void detection and the influence of voids on the observed signal of corrosion were studied. Different void and corrosion combinations and the effect of different void contents have been evaluated.

BASIC TDR THEORY

TDR is a traditional technology widely used for detecting discontinuities in transmission lines such as telephone lines. When electromagnetic waves are propagated from the source down the transmission lines, a part or all of them will be reflected back when the site of a discontinuity is encountered. If there is a detector at the place of the source, this reflected signal can be detected and recorded in the time domain. By analyzing the time domain reflection signal charts, we can know the nature and position of the discontinuities.

Corrosion detection in existing structures using TDR employs the same principles. The transmission line can be composed of a strand/rebar and a sensor wire, or it could be a geometry that involves two conductors laid in a certain way. The discontinuities that appear as signal "bumps" in the time domain can be the result of physical discontinuities of the transmission line, such as corrosion occurring on the strand, or they also could be from an inhomogeneous site in the surrounding environment such as a voids in the concrete.

Figure 1 shows an experimental sample. Before measurements are made the whole sample is encased in concrete like that typically used with steel strands or rebar. When an electromagnetic

field is propagated down the strand and sensor wire, it is reflected back by the ball that simulates a void. The reflection then is recorded as a function of time. Figure 2 is the signal record for the propagation and reflection process. A signal bump representing the man-made void is clearly seen at the time of 13 ns. The bump at 9 ns is due to reflection from the input connector at the end of the sample.

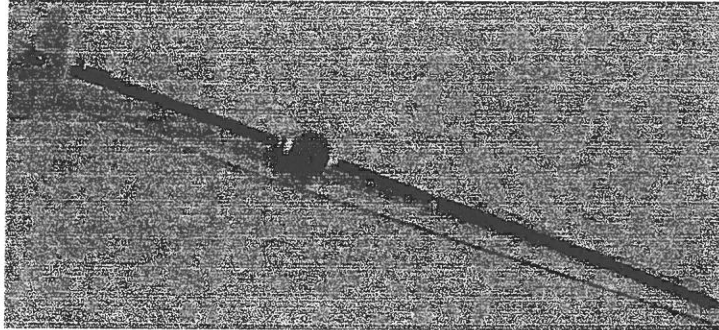


Figure 1. experimental sample for void detection

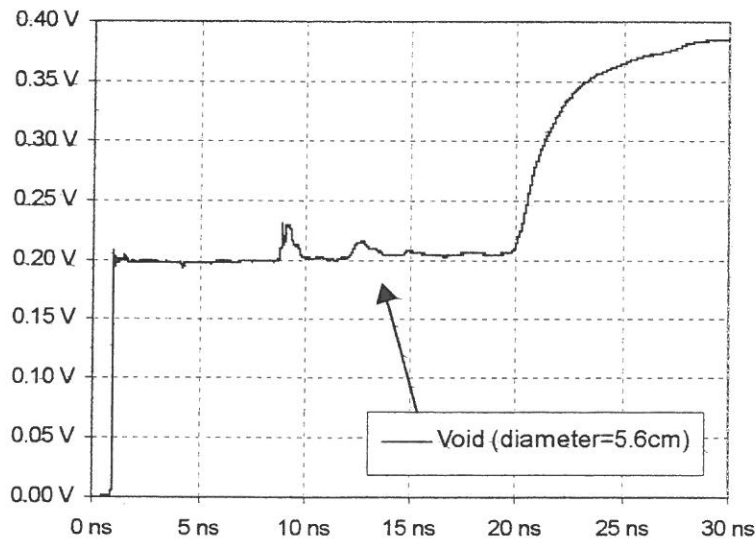


Figure 2. TDR return for the sample in Figure 1

CORROSION DETECTION GEOMETRY ANALYSIS

Time domain reflectometry employs a transmission line model in which two electrical conductors, in a variety of possible configurations, compose a medium that carries electromagnetic waves from the end where the waves are generated to the other end. The propagation properties are decided by the impedance of materials surrounding the transmission lines, as well as that of the conductors, and therefore there will be some reflections when the waves are propagated to the points where impedance discontinuities occur. The reflections will

then propagate back and be recorded in the time domain by the oscilloscope located where the waves are originally generated. By studying the time domain reflection signal plot, the nature and seriousness of these impedance changes can be understood. In existing structures, the steel strand itself, which is usually buried in concrete, composes one conductor of the transmission line. The other part of the transmission line is created either by installing a second conductor external to the concrete or by making use of a nearby conductor that is already installed.

Several possibilities that could satisfy this objective are the following:

- Another steel cable nearby
- Metal shielding (if any) of a bridge cable
- An external sensor wire running outside the grout

Another steel cable nearby

The strands are usually arranged in grids or parallel to each other in existing structures and this provides us the chance to use another neighboring steel cable as a sensor wire to detect corrosion on the cable under monitoring. Preliminary experiments were carried out in air and a corrosion site on one strand could be detected by this two-strand transmission line model, although the signal magnitudes decreased when the spacing between the two strands was increased. Results from further experiments in which both the strand under test and the sensing strand were buried in concrete show that the corrosion site is detectable but the signal is very small due to the lossy properties of the grout. Further study using larger input pulse magnitude is called for.

Metal shielding (if any) of a bridge cable

During the reporting period, the possibility of using the metal shielding of a bridge cable as a monitoring conductor for defect detection was systematically studied. Wave propagation and attenuation were studied for this coaxial transmission line geometry. If the diameter of the metal shielding is too big compared to the diameter of the strand, undesirable wave propagation modes may exist in the transmission line causing energy losses. Coaxial transmission line discontinuities were also studied. The irregularity of the center conductor (steel strand) caused by corrosion can be analyzed accurately.

An external sensor wire running outside the grout

The method of using an external sensor wire to detect corrosion is the most flexible one among all of the three. It is known from the theory of TDR that the geometry is not exclusive and there exist many choices of geometry. The external sensor wire can be arranged according to the factors existing in the local environment, and thus this method can be more accurate and sensitive (although it is more complex and environment-dependent) than the former two methods. This method is applicable to external void detection, as well as corrosion detection.

ANALYSIS OF FACTORS AFFECTING CORROSION DETECTION

Corrosion detection with an internal sensor wire has been under thorough study and positive results show that internally measured corrosion detection signals are relatively stable. This is because in internal corrosion detection the sensor wire runs along side the strand or rebar. The tiny spacing between the sensor wire and the strand or rebar constrains the change of environmental parameters and thus signals can remain stable even in a changing environment. External corrosion detection, on the other hand, faces a more unfavorable situation. In external corrosion detection, the strands under detection are buried in concrete, the thickness of which could vary from inches to tens of inches. This layer of concrete makes the strands physically

inaccessible and brings uncertainties into the signal. These uncertainties mainly concentrate in following aspects:

- Energy loss
- Sensitivity to extent of corrosion
- Relative position of sensor wire to the strand

Energy loss

Energy loss is the main impediment to external corrosion detection. Concrete is a lossy medium that attenuates the magnitude of the electromagnetic field propagating through it. In internal corrosion detection, the sensor wire is very close to the strand/rebar and the attenuation effect is relatively small compared to the bump signal from the corrosion site. In external corrosion detection, however, the size of the corrosion site is small compared to the thickness of the concrete layer that exists between the external sensor wire and the strand/rebar. Experimental data shows that reflections from the corrosion site are relatively small but they can be detected through concrete thickness up to 1 meter with our present instruments. It is likely that a more powerful pulse generator would increase this distance.

Sensitivity to extent of corrosion

Sensitivity to the size of the corrosion site is another concern. Internal and external corrosion detection mainly depend on a change of geometry of the strand/rebar that is translated into a change of dielectric constant. When this change is small compared to the environment, it is hard to distinguish. Background noise is inevitable and it masks the reflections of small corrosion sites. To be distinguished, a corrosion site must reach certain severity and this condition prevents the possibility of detection of the start of corrosion.

Relative position of sensor wire to the strand

Among the factors that influence corrosion signals is the relative position of the sensor wire to the strand. The position where the corrosion site resides is not necessarily on the path through which the sensor wire runs and this raises a question of whether the relative position of corrosion to the sensor wire will affect signals. Experiments show that the relative position does influence the signals. To estimate the situation more easily, we chose to first test it in air on a bare strand with a sensor wire running along side the strand in its groove. Figure 3 shows the data obtained from 3 sensor wires that were laid in different positions on the strand.

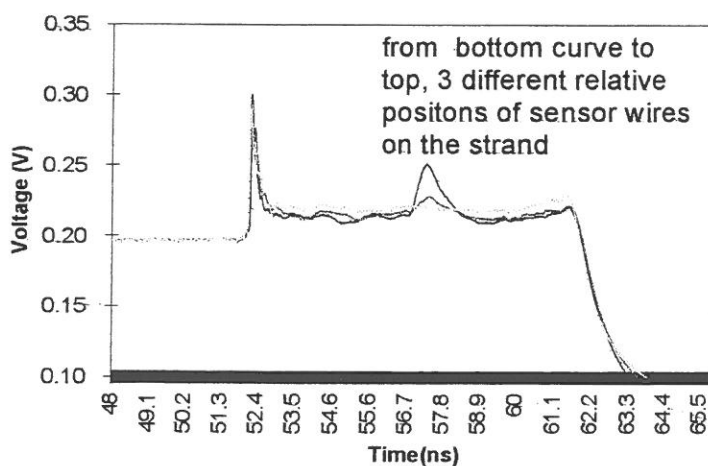


Figure 3. Effect of relative position of sensor wire to the strand

In the plot the signals change dramatically because of the position of the wires. The ratio between the most favorable position (the corrosion occurring right under the sensor wire) and the most unfavorable position could be more than 5:1. Although in practice moisture tends to penetrate around the strand and make the corrosion occur more symmetrically, this effect cannot be ignored.

PULSE STRENGTH ENHANCEMENT SIMULATION

All of the previously mentioned factors significantly reduce the visibility of corrosion sites beneath concrete layers in existing structures. One solution to this problem is to use bigger pulses. The TDR equipment in our lab is an HP oscilloscope that provides both the pulse generator and the detector. The maximum pulse magnitude that can be generated is 200 mV. The reflections from the corrosion site are in the magnitude of mV and they are easily mixed with the background noises of the same magnitude. When the pulses increase, if the background noise also increases proportionally, the increased corrosion signals are still mixed with increased noise and cannot be distinguished. Preliminary experimental data shows that this is not the fact, and thus supports the promising solution of using a stronger pulse generator.

Some results have been obtained from void detection using an attenuator to simulate smaller pulses and make a comparison possible. The maximum pulse magnitude is 200 mV in our equipment and an attenuator was used to get smaller pulses. Figures 4 and 5 show the data obtained both without the attenuator and with it:

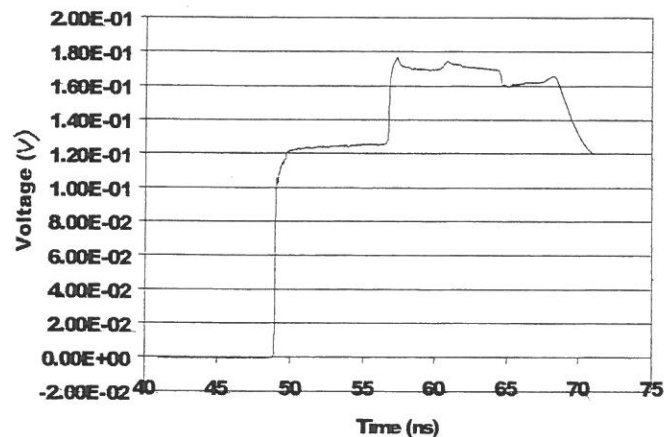


Figure 4. TDR return without the attenuator

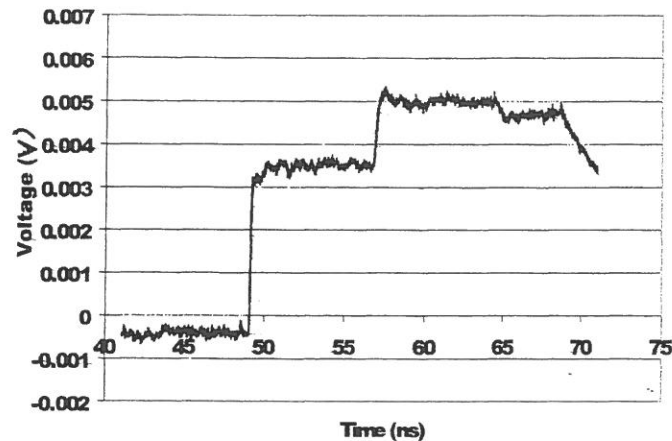


Figure 5. TDR return with the attenuator

By comparison it can be seen that the shape of the curves before and after the attenuator was applied remains the same. The noise level still remains less than 1 mV after attenuation and it does not change with the signal. This means if the pulses generated by the generator get stronger, the reflections from the corrosion site or void will increase proportionally while the noise level remains unchanged thus minor signals can be detected and smaller corrosion sites or voids can be found.

ANALYSIS OF FACTORS AFFECTING VOID DETECTION

Voids are another big issue in corrosion detection. It is believed that corrosion is more likely to happen where voids form. Voids can form in the process of pouring concrete during construction or later along with the fluctuation of the weather. Moisture and salt are more inclined to gather within voids and thus electrochemical batteries tend to form and corrosion begins. If voids can be found easily in existing structures and corrective measures can be implemented, the probability of occurrence of corrosion will be greatly lowered and the structures will last longer. In addition, voids are usually found in concurrence with corrosion and they are larger in size and will be the first to be detected. Thus void detection has become a preventive method for existing structures.

The research on void detection by TDR began from internal void detection and many experiments were carried out to find the relationship between void signals and surrounding situations. Factors that mainly affect the signal returns from the voids and thus jointly contribute to the visibility of the defect sites are as follows:

- Corrosion
- Sand (or other solid)
- Water (from rain or snow)
- Moisture (may fluctuate with weather)

Among these factors positive and negative effects coexist. Signal returns from defect sites where voids reside can be enlarged or reduced due to the presence of one or several factors. Corrosion severity plays an important role on the signal returns. Figure 6 shows how increasing corrosion affects the total look of the signal.

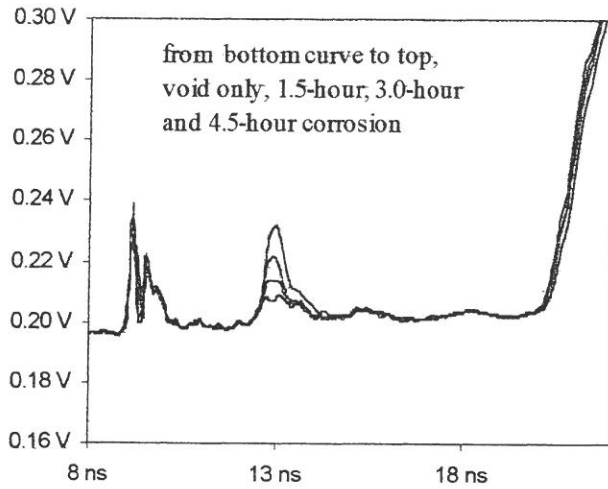


Figure 6. TDR returns with progressive corrosion

In this experiment, electrochemical corrosion was used to expedite the speed of corrosion and shorten the experimental period. The time represents the corrosion time that strand/rebar experienced. Time length of 4.5 hours roughly equals 20% loss of the cross sectional area of the strand/rebar. From the plot it is seen that the severity of corrosion does affect the signal. Besides corrosion, several other factors also affect the signal return such as water (rain or melted snow), moisture (may fluctuate with the weather), and sand (or corrosion product or similar material). Experiments were also done on these issues and their relative influences were analyzed and compared. Figure 7 shows the comparison data derived from the experimental data obtained from various conditions simulating water, moisture, sand etc.

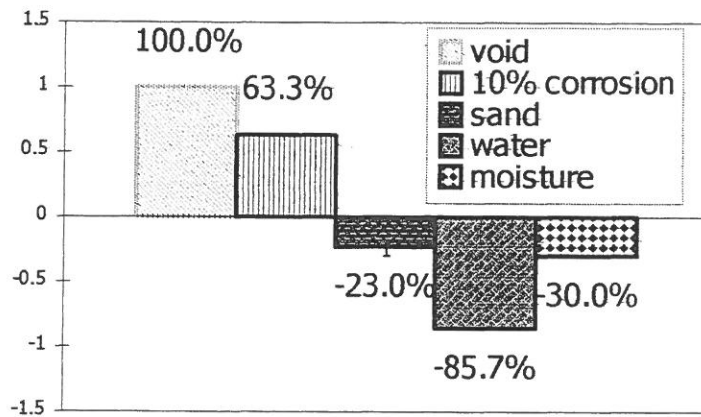


Figure 7. Relative strength comparison of different factors

The different conditions are compared in the plot and the relative strength of influence the conditions exert on TDR returns are roughly estimated. Full magnitude of the void signal is used as 100% and magnitudes of the influences are estimated relative to it. Corrosion plays a very

important role in increasing the signal return while water, moisture and sand contribute various negative influences, reducing it.

With understanding of the nature and the degree to which different factors influence signal returns, it can be deduced that external void detection is promising, but there still exist some problems that must be solved before it can be applied practically.

VOID DETECTION GEOMETRY ANALYSIS

Due to the various difficulties presented by the traditional strand and sensor wire geometry in external void detection, a transmission line model with a different geometry should be considered and perhaps employed to enhance the sensitivity and usability. Some traditional transmission lines which are intended for other applications than void detection are under consideration for use, such as lamp cord and TV cable. These transmission lines share some common features that traditional strand and sensor wire geometry or strand-strand/rebar-rebar geometry do not have, and thus they have certain advantages. Transmission lines such as lamp cord and TV cable have a perfectly homogeneous geometry that can avoid the background noise signal generated in the strand-sensor wire geometry due to inhomogeneous spacing. They are more flexible for application without the support of a strand and can be applied anywhere voids are suspected to occur without the presence of a strand or rebar.

Although lamp cord or TV cable may appear to be slightly more awkward, they must be under consideration when accuracy, sensitivity and feasibility of void detection become the major issues that hamper current void detection technique development.

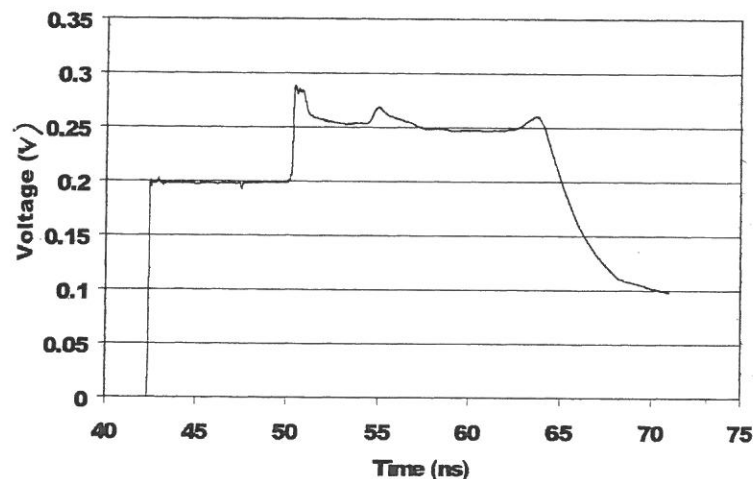


Figure 8. TDR return for voids using lamp cord as sensor wires

Figure 8 shows the data obtained from a lamp cord that runs through a racquetball used to simulate a void in concrete. The curve appears smoother than that obtained with the strand-sensor wire geometry and the signal bump caused by the ball is also sharper. It can be expected that lamp cord or TV cable has favorable performance and their independent geometry can be used to detect voids externally without the support of a strand or rebar.

EXTERNAL VOID DETECTION RESULTS

Efforts that address the problem of external detection of corrosion or voids have proved its feasibility. Various factors that could influence the signal return have been investigated and characterized. Further laboratory experiments were carried out to detect voids externally in situations that simulated field conditions. Figure 9 shows the data we collected from one sample.

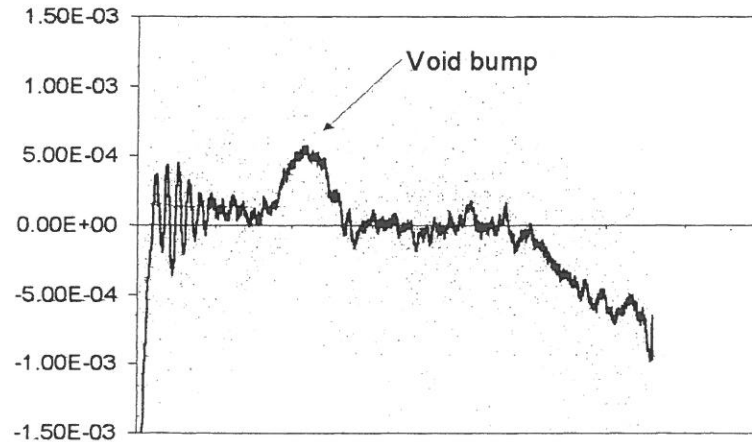


Figure 9. External TDR return for voids

The curve shown is the result obtained from a concrete-encased void measured with an external sensing transmission line using differential TDR. The void signal bump is evident.

CONCLUSIONS

Basic possible transmission line geometries for external void detection have been studied and the most applicable and flexible geometries have been characterized.

Factors that could influence external corrosion detection have been determined and evaluated, and possible resolutions to the problems have been found.

As an important cause of corrosion occurrence, voids have been recognized as a major defect of existing structures. Void detection, thereby, has become a major issue in corrosion detection in existing structures. Experiments were carried out to determine factors that could influence the accuracy of void detection and their relative strengths have been compared quantitatively.

Geometries other than traditional strand-sensor wire, such as lamp cord and TV cable, have been investigated. Their advantages and special uses have been identified and confirmed.

FUTURE WORK

Corrosion detection and void detection in existing structures are important measures to detect defects in a timely manner and thus initiate the remedial process to protect the structures and prolong their life. However, these promising measures still face some difficulty. Existing structures do not embody any features designed for up-to-date TDR implementation and thus a particular method has to be developed to fit the specific conditions found for each structure. Another problem is signal attenuation. External detection cannot avoid the involvement of concrete layers that cause strong attenuation to the signals and this hampers TDR measurements. Larger pulse generators must be employed to enhance the visibility of voids and corrosion sites. At the same time, further research is needed to find more practical geometries of sensing transmission lines that can meet the requirements of field practice.

Implementation Plan

The research conducted has shown that TDR can be effective in identifying the existence of voids in grouted ducts. Furthermore, TDR can be used to detect corrosion of steel tendons. The most effective application of TDR has been when the detection system is installed during construction. Research conducted to evaluate the use of TDR for existing structure has, to date, been less successful.

The research team has successfully installed TDR sensors in a high performance bridge (8F in Frederica, DE), and in full-scale pre-cast beams similar to those used for bridge 712B. In so doing, the team has demonstrated that the technique is field ready. One requirement of the procedure to be aware of is that the user must have access to the appropriate TDR equipment (which is available at UD).

In light of recent problems with voids in grouted ducts in four major bridges in Florida and the resulting corrosion problems, it is recommended that this technique be considered as a QA/QC method during the construction of future post-tensioned or cable-stayed bridges in the state. When in place, the sensor system can be used immediately to detect voids in the grout, and subsequently to detect corrosion. It is further recommended that the additional corrosion sensors be used in conjunction with TDR to allow for further confirmation of damage.

REFERENCES

1. "Evaluating Corrosion of Steel Strands Using Time Domain Reflectometry"(2002). Delaware Center For Transportation.

2. Liu, W., "Electromagnetic Modeling of Embedded Metallic Structures For Nondestructive Evaluation Using Time Domain Reflectometry"(2001). *PHD Dissertation*, University of Delaware, Newark, Delaware.
3. Liu W., Hunsperger, R. G., Chajes, M. J., Folliard, K. J., and Kunz, E. (2002). "Corrosion Detection of Steel Cables Using Time Domain Reflectometry". Volume14, Number3, *Journal of Materials in Civil Engineering*, American Society of Civil Engineers.

**Delaware Center for Transportation
University of Delaware
Newark, Delaware 19716**

AN EQUAL OPPORTUNITY/AFFIRMATIVE ACTION EMPLOYER The University of Delaware is committed to assuring equal opportunity to all persons and does not discriminate on the basis of race, color, gender, religion, ancestry, national origin, sexual orientation, veteran status, age, or disability in its educational programs, activities, admissions, or employment practices as required by Title IX of the Education Amendments of 1972, Title VI of the Civil Rights Act of 1964, the Rehabilitation Act of 1973, the Americans with Disabilities Act, other applicable statutes and University policy. Inquiries concerning these statutes and information regarding campus accessibility should be referred to the Affirmative Action Officer, 305 Hullahen Hall, (302) 831-2835 (voice), (302) 831-4563 (TDD).