

# **Evaluating Corrosion of Steel Strands Using Time Domain Reflectometry**

by

**Robert G. Hunsperger  
Wei Liu  
Jian Li**

**Department of Electrical and Computer Engineering  
University of Delaware**

**June 2002**

**DELAWARE CENTER FOR TRANSPORTATION**

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

# Evaluating Corrosion of Steel Strands Using Time Domain Reflectometry

by

ROBERT G. HUNSPERGER

and

WEI LIU

JIAN LI

Department of Electrical and Computer Engineering  
University of Delaware  
Newark, Delaware 19716

DELAWARE CENTER FOR TRANSPORTATION

University of Delaware  
Newark, Delaware 19716

*This work was sponsored by the Delaware Transportation Institute 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.*

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*

**DCT Policy Council**

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

Eric Kaler, Co-Chair  
*Dean, College of Engineering*

Timothy K. Barmekov  
*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*

Phil Cherry  
*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*

## TABLE OF CONTENTS

Introduction.....	3
Two-wire Transmission Line Model for Bridge Cables.....	3
TDR Measurement Accuracy.....	5
Distance.....	5
Relative Position.....	5
Rise Time.....	5
Attenuation.....	5
Differential TDR.....	6
Field Demonstration -- Bridge 8F Experimental Program.....	7
History and Details of Bridge 8F.....	7
TDR Instrumentation.....	8
Experimental Results.....	9
Implementation Plan.....	12
Installation Procedure.....	12
Measurement Procedure.....	12
Conclusions.....	12
Future Works.....	13
References.....	13

## List of Figures and Tables

Figure 1. Distributed parameter equivalent circuit for the steel cable transmission line. ....	4
Table 1. Distributed parameters of the steel cable transmission line.....	3
Figure 2. TDR reading of 1-meter seven-wire strand specimen.....	6
Figure 3. TDR reading of the same specimen before it was damaged, which is used as baseline. The differential comparison of current TDR reading with the baseline reveals the damage site. ....	7
Figure 4. TDR instrumentation. The monitoring wire was held in place with cable ties. It was connected to a section of coaxial cable that provided electrical access. ....	8
Figure 5. TDR return from strand No.2 of beam B7(4) on October 4, 1999.....	9
Figure 6. TDR return from strand No.2 of beam B7(4) while the beam was stored in the concrete plant. ....	10
Figure 7. Corrosion monitoring of strand No.4 of beam B7(4) while Bridge 8F is in service. ....	11

## Acknowledgement

This work was sponsored by the Delaware Transportation Institute 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.

## INTRODUCTION

The continuing deterioration of the aging infrastructure, particularly the corrosion of metallic reinforcement of highway bridges, is a problem of great importance, which has received intensive attention recently. The Federal Highway Administration (FHWA) estimated that sixteen percent of the 582,969 bridges in the United States are structurally deficient as of June 1998 (FHWA 1998). In fiscal year 1999, FHWA spent 3.2 billion dollars on bridge replacement and rehabilitation.

Reinforced, prestressed, and post-tensioned concrete structures have all suffered significantly from corrosion damage, especially in aggressive environments. The high-strength steel used in these structures is very sensitive to corrosion. While visual inspection is a very effective corrosion detection method, it cannot be used for embedded or encased steel cables. Several indirect electromagnetic nondestructive corrosion detection methods have been developed. Electromagnetic methods are based on the fact that the high-strength steel cables are very good electrical conductors. Mechanical damage to the cable will change its electrical properties. One can use resistance measurement, potential measurement, or magnetic inductance scanning to detect corrosion. To date, these methods have had varying degrees of success in detecting the presence of corrosion, but all have disadvantages, and many are uneconomical. One common drawback to these methods is that the location and nature of the corrosion is very difficult to determine.

A nondestructive evaluation technique for corrosion detection using time domain reflectometry (TDR) has been developed and demonstrated through this project and a preceding project titled "Detecting Corrosion of Steel Strands Using Time Domain Reflectometry".

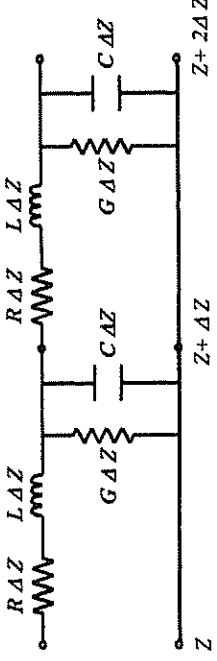
Time domain reflectometry is an electrical measurement technique that has been used since the 1940s to determine the spatial location and nature of faults in transmission lines (Hewlett-Packard 1988). It involves sending an electrical pulse along a transmission line and using an oscilloscope to observe the echoes returning back from the device under test. Any discontinuity will cause a reflection. From the transit time, magnitude, and polarity of the reflection, it is possible to determine the spatial location and nature of the discontinuity. TDR has also been used in some other fields such as geotechnical engineering and mining. Typical applications of TDR include soil moisture measurements, water level changes, and rock mass deformation.

There are obvious similarities between bridge cables and transmission lines. The bridge cable can be modeled as an asymmetric, twin-conductor transmission line by applying a sensor wire along with the cable (Bhatia et al. 1998). Physical defects of the bridge cable, such as abrupt pitting corrosion, general surface corrosion, and voids in the grout, will change the electromagnetic properties of the line. These defects, which can be modeled as different kinds of discontinuities, can be detected by TDR.

## TWO-WIRE TRANSMISSION LINE MODEL FOR BRIDGE CABLES

An embedded steel cable is a good conductor enclosed in a dielectric (grout). In order to utilize time domain reflectometry to detect corrosion damage, the steel cable must be a part of a transmission line. No less than two conductors must be presented to support the transverse electromagnetic (TEM) wave. Therefore, another conductor running parallel to the steel cable under test is necessary.

By applying a sensor wire along side of the steel cable, an asymmetric two-conductor transmission line is obtained. A distributed parameter model is used to study the wave propagation in this transmission line. Wave propagation is described in terms of voltage and current by utilizing the equivalent circuit shown in Figure 1.



**Figure 1. Distributed parameter equivalent circuit for the steel cable transmission line.**

The four distributed parameters of the steel cable transmission line are calculated from the geometry and material parameters of the cable and are given in Table 1.

**Table 1. Distributed parameters of the steel cable transmission line.**

Distributed Parameters	Two-wire Transmission Line
shunt capacitance $C$	$C = \frac{2\pi\epsilon}{\cosh^{-1}\left(\frac{d^2 - a^2 - b^2}{2ab}\right)}$
series inductance $L$	$L = \frac{\mu}{2\pi} \cosh^{-1}\left(\frac{d^2 - a^2 - b^2}{2ab}\right)$
series resistance $R$	$R = \sqrt{\frac{f\mu}{4\pi}} \left( \frac{1}{a\sqrt{\sigma_a}} + \frac{1}{b\sqrt{\sigma_b}} \right)$
shunt conductance $G$	$G$ is negligible for insulated sensor wire in dry grout

At very high frequencies  $R$  increases as the square root of  $f$ , whereas  $\omega L$  increases directly as  $f$ , and the ratio  $R/\omega L$  decreases as the square root of  $f$ . It will be useful to consider the case of a single seven-wire prestressing strand ( $\sigma=0.635\text{cm}$ ), the sensor wire being used ( $b=0.05\text{cm}$ ), and a typical distance between them ( $d=3.175\text{cm}$ ). At  $f=50\text{MHz}$ , the ratio  $R/\omega L$  is  $1.08 \times 10^{-2}$ , which is negligible compared with unity, it will clearly become still more negligible at higher frequencies. This result, which is based on reasonably realistic data, shows that series resistance can be neglected in the frequency range of TDR operation. For grout with low water content, the conductance is quite small. Additionally, there is an isolating layer of plastic insulation around the sensor wire. Therefore, the conductance  $G$  can be considered to be zero, and  $G/\omega C$  will therefore be approximately zero. Under these circumstances the characteristic impedance is given to a high degree of accuracy by the simplified expression

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \approx \sqrt{\frac{L}{C}}$$

On substituting for  $C$  and  $L$  the following expression for  $Z_0$  results

$$Z_0 = \frac{1}{2\pi} \sqrt{\frac{\mu}{\epsilon}} \cosh^{-1}\left(\frac{d^2 - a^2 - b^2}{2ab}\right)$$

Note that the characteristic impedance of the line depends on the radius of steel cable. Therefore, any physical damage to the steel cable will change the impedance. This change can be detected with TDR.

## TDR MEASUREMENT ACCURACY

The sensitivity and accuracy of TDR measurement depends on several parameters. A parametric study has been conducted and the following parameters have been identified:

- diameter of the sensor wire,
- distance between sensor wire and steel cable,
- relative position of the sensor wire and damage site,
- system rise time, which describes how fast the signal of the measuring system is,
- water content of the surrounding grout.

### Distance

The TDR measurement sensitivity depends on the distance between the sensor wire and steel cable. Basically, TDR detects impedance changes. When  $b \ll d$ ,

$$\frac{dZ_0}{da} \approx -\frac{1}{2\pi} \sqrt{\frac{\mu}{\epsilon}} \frac{1}{a} \sqrt{\frac{1}{d^2} + a^2}$$

The magnitude of  $\frac{dZ_0}{da}$  is mainly determined by  $\frac{1}{a} \sqrt{\frac{1}{d^2} + a^2}$ . When the sensor wire is close to the steel cable,  $d^2 \ll a^2$  is small, and  $dZ_0/da$  has a relatively large value. In this case, the characteristic impedance will increase rapidly if  $a$  decreases, and hence the TDR method will be more sensitive. On the other hand, when serious corrosion reduces  $a$  to a very small value,  $1/a$  becomes the dominant factor. The characteristic impedance will once again respond to any change of dimension vigorously.

### Relative Position

When two parallel conductors are close together, the magnetic fields from each conductor affect the current flow in the other, resulting in a non-uniform current distribution. The current density is increased in adjacent parts of parallel conductors with oppositely directed currents and is decreased at more remote parts. The damage occurring in the adjacent parts are more likely to be detected since the current distribution around the damage sites changes significantly.

### Rise Time

A very important characteristic of a time domain reflectometer is its rise time. The rise time,  $T_r$ , is the time required for the excitation signal to change from a specified low value to a specified high value. Typically, these values are 10% and 90% of the signal amplitude.

When the time constant associated with the reactive components is much greater than the system rise time  $T_r$ , i.e., the inductance or capacitance is large, the system can be considered as perfect with a zero rise time. The TDR return in this case will be very similar to the ideal TDR response. By measuring the time constant, one can obtain the value of the inductance or capacitance.

When the time constant is of the same order of magnitude as the TDR system rise time, a different TDR return will be observed. The inductance and capacitance can be calculated through some good empirical formulas.

If the time constant of the reactive component is much less than the TDR system rise time, no visible reflections will occur. Therefore, small mismatches may not be measured unless a TDR system with shorter rise time is used.

### Attenuation

The signal in a transmission line will be attenuated as it passes down the line and back. Attenuation in a transmission line consists of two parts that can be associated with dielectric losses and conductor losses. The dielectric loss is mainly determined by the water content of surrounding concrete. For dry grout, this type of loss is not significant. The conductor loss is related to the resistance of the two conductors involved, which is affected by the skin effect. Since skin depth varies as  $1/f$ , the attenuation increases with increasing  $f$ .



Attenuation is frequency dependent. Although a high frequency signal can give much better resolution, it can be rapidly attenuated. It can only be used for short samples and is not suitable for long bridge cables. On the contrary, low frequency signals can travel very long distance. However, one can only detect a damage site when its dimension is comparable to the signal wavelength. It means that frequency cannot be too low.

## DIFFERENTIAL TDR

In field applications for more complex structures like an actual bridge, noise, energy loss, and wave dispersion can be problematic for TDR measurements. Testing of prestressed girders in the field has indicated that energy loss and wave dispersion are not significant.

Whether in the lab, or in the field, small amounts of random noise will be present. To deal with this, one can repeat measurements and average the results to effectively mask the noise. Another kind of noise in the signal can be created by

- electric field disturbance caused by steel components near the cable being tested,
- variations in  $d$ , the distance between the steel cable and the sensing wire, since the characteristic impedance depends on  $d$ .

This kind of noise is inevitable due to the complexity of a real structure and the difficulty of maintaining constant spacing. The noise magnitude can be relatively large. However, once the concrete element is instrumented, the location of the steel components causing noise, and the steel cable-to-sensing wire spacing will remain unchanged. Therefore, the noise will be repeatable. Differential TDR measurement can be used to effectively distinguish corrosion sites from repeatable noise. If several TDR measurements are made for the same cable over a long time period, the later TDR results should be identical to the former ones except for the corrosion sites. A differential comparison of stored signals with newly measured ones can reveal corrosion that occurred between the two measurements.

The differential TDR method has been tested experimentally. Figure 2 shows TDR results obtained from a 1-meter seven-wire strand sample. This sample has two severed wires over a 4.0cm length, 48cm from the front end of the sample. From Figure 2 it is hard to tell whether or not the sample is damaged and where the damage is. However, if this waveform is differentially compared with Figure 3, which is the TDR return obtained from the same sample when it did not have any electrical discontinuities, the damage site can be easily identified.

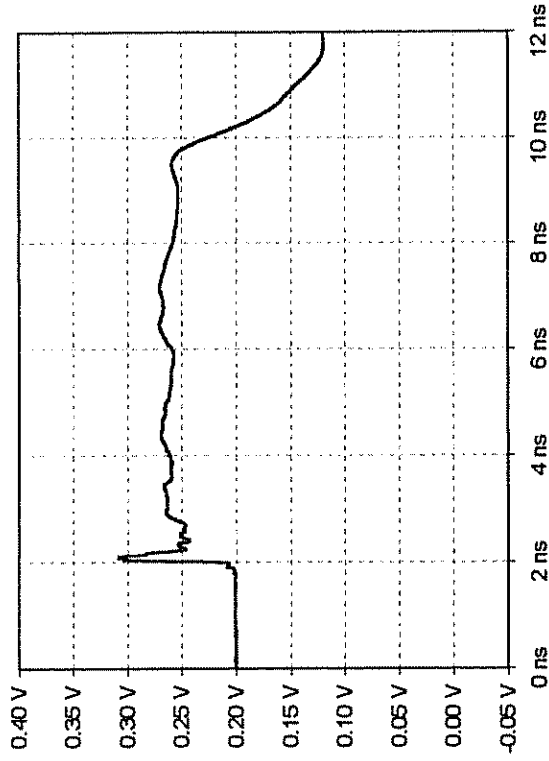
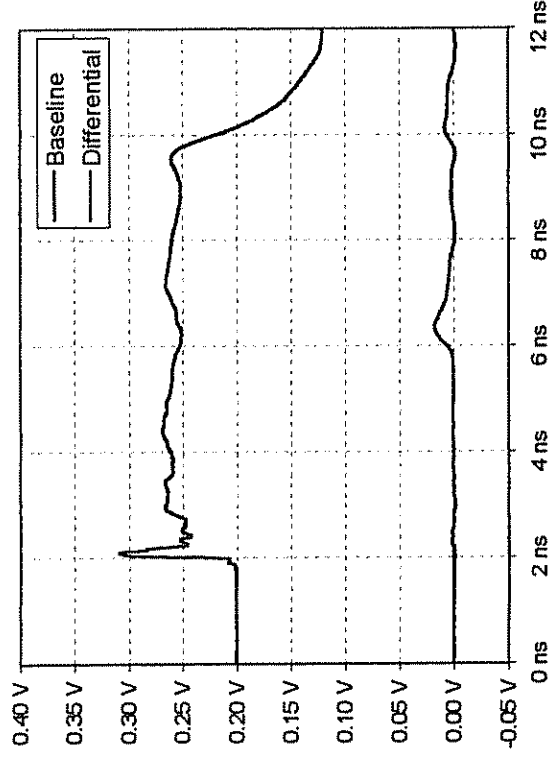


Figure 2. TDR reading of 1-meter seven-wire strand specimen.



**Figure 3. TDR reading of the same specimen before it was damaged, which is used as baseline. The differential comparison of current TDR reading with the baseline reveals the damage site.**

Differential TDR comparison can be effectively used to detect physical damage. One may notice that the comparison waveform in Figure 3 is perfectly flat before the damage site. However, it becomes a little bumpy afterwards. The reason is that the damage site introduces multiple reflections. With this method, the first damage site can be easily detected. For the case of multiple damage sites, one needs to distinguish new damage sites from multiple reflections. This can be done mathematically.

## FIELD DEMONSTRATION -- BRIDGE 8F EXPERIMENTAL PROGRAM

The effectiveness of the TDR corrosion detection method has been proven through both analytical models and laboratory tests. In order to ready this technology for field implementation, full-scale experiments and field demonstrations are necessary. Bridge 8F is the first field demonstration of the TDR corrosion monitoring technology (Liu et al. 2001). The primary purpose of the demonstration was to show that the TDR system was robust enough to survive the fabrication and erection process, and to show that usable signals could be achieved.

Bridge 8F is a two-span, prestressed, adjacent box beam high-performance concrete (HPC) bridge. HPC is concrete that is optimized for a specific application and often possesses qualities such as high strength, low permeability, good workability, and excellent long-term durability.

The complete experimental program involving Bridge 8F consists of two parts. First, a material testing program has been initiated to determine the properties of the HPC used for the bridge beams. This program involves a series of material tests conducted over a one-year period. Next, the performance of the HPC beams is being evaluated through long-term monitoring. One of the many aspects of long-term monitoring is corrosion detection using differential TDR. Corrosion monitoring with TDR began at the time of fabrication, and is continuing now that the bridge is in service.

## History and Details of Bridge 8F

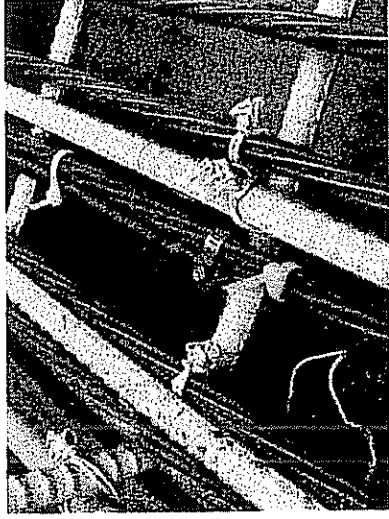
In 1999, the Delaware Department of Transportation (DelDOT) received funds through the Federal Highway Administration's Innovative Bridge Research and Construction Program (IBRC) to design and construct a high-performance concrete bridge in Fredricka, Delaware. A two-span, prestressed concrete, adjacent box beam bridge utilizing HPC in both the beams and deck was designed. Bridge 8F, which replaced a deteriorated four-span structure, was completed in October 2000.

The HPC replacement bridge consists of two 19.0 m (62 ft. 4 in) spans consisting of adjacent prestressed concrete box beams with a concrete deck to make the structure continuous for live load. HPC is being used throughout the bridge with low permeability limits to reduce the amount of salt penetrating the concrete over the life of the structure and high strength to optimize structural members and stretch span lengths.

Each of the 22 adjacent prestressed concrete box beams is 19.0 m (62 ft. 4 in) long and 0.686 m (27 in) deep. The beams were fabricated by Concrete Building Systems (CBS) in Delmar, Delaware, and were all produced in the same bed. The test program focused on three beams, which were labeled B5, B7(4), and B7(8). Each beam was prestressed using 12.7 mm (0.5 in) diameter, Grade 270 (1863 MPa), seven-wire low relaxation strands. Beams B5, B7(4), and B7(8) have 16, 18, and 18 straight strands respectively. The strands were jacked to an initial tensile force of 138 kN (31 kips). After approximately 18-hours after curing, the strands for each beam were released. Beam B5 was cast on August 30, 1999, while beams B7(4) and B7(8) were cast on October 4, 1999 and October 14, 1999, respectively. Prior to casting, long-term monitoring instrumentation was installed in each beam. TDR corrosion monitoring began at the time of fabrication, and is continuing now that the bridge is in-service. While no corrosion is anticipated in the new HPC bridge in the near future, the repeatability of the signals over time will help to validate the technology and confirm the performance of the HPC.

### TDR Instrumentation

TDR monitoring wires have been installed alongside a total of five strands in beams B5, B7(4), and B7(8). The wire is fully insulated, silver-coated copper wire, which is commercially available. Both silver and copper are more corrosion resistive than steel. Therefore, the corrosion of steel strands will occur well before the corrosion of the monitoring wire. Corrosion monitoring wires were wound loosely around the strands. Since the TDR signal wavelengths are much shorter than the twisting length, this did not affect the transmission line geometry. The monitoring wires were held in place with cable ties, as shown in Figure 4.



**Figure 4. TDR instrumentation. The monitoring wire was held in place with cable ties. It was connected to a section of coaxial cable that provided electrical access.**

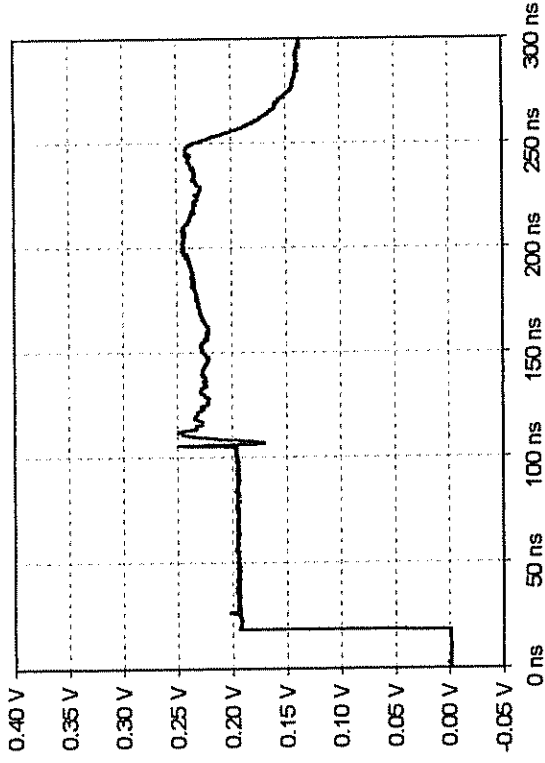
A section of coaxial cable was used for each strand to provide electrical access to the strand/wire system. Initially the connecting coaxial cable was about 8.5 m in length, which is longer than necessary and allows for installation variances. To minimize noise, the coaxial cable to strand/wire connection was made inside the concrete beam and was covered by insulating tape. A standard BNC connector was installed on the other end of the coaxial cable. An HP54750A digitizing oscilloscope was used to take TDR measurements, which is capable of generating a fast rising step wave with rise time less than 100 picoseconds.

Energy loss can be a major concern when TDR is applied to long samples. Fully insulated monitoring wire is used to reduce energy loss. At high frequencies, even the standard coaxial cable used to connect the measuring system and the steel cable will introduce considerable energy loss. Therefore, the coaxial cable should be as short as possible to reduce energy loss and improve the sensitivity of TDR measurements. Upon the completion of the bridge construction, the connecting coaxial cable was cut to the shortest length allowable.

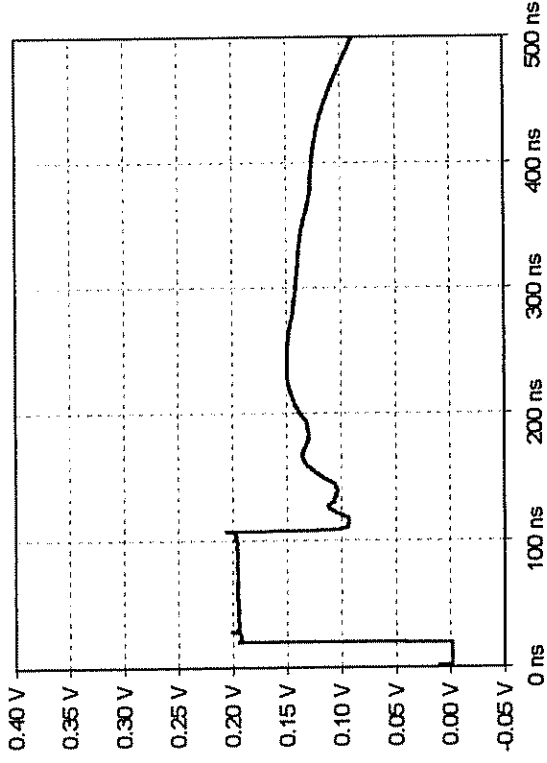
Differential TDR is used for long term corrosion monitoring

## Experimental Results

Corrosion monitoring began at the time of fabrication. During the fabrication of each beam TDR measurements were taken before and immediately after the concrete pour. Since then, TDR readings were taken on each of the 5 strands on roughly a monthly basis. All TDR results were converted and stored digitally for future comparisons.



a. before pour (bare strand)



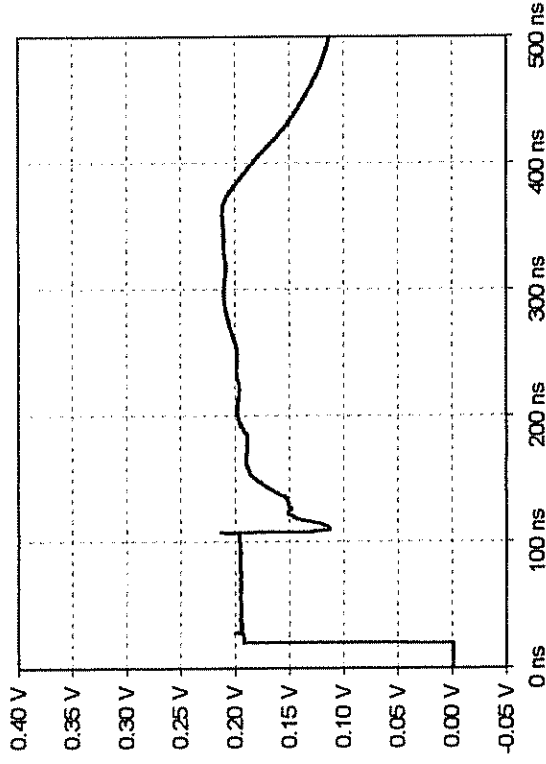
b. immediately after pour

Figure 5. TDR return from strand No.2 of beam B7(4) on October 4, 1999.

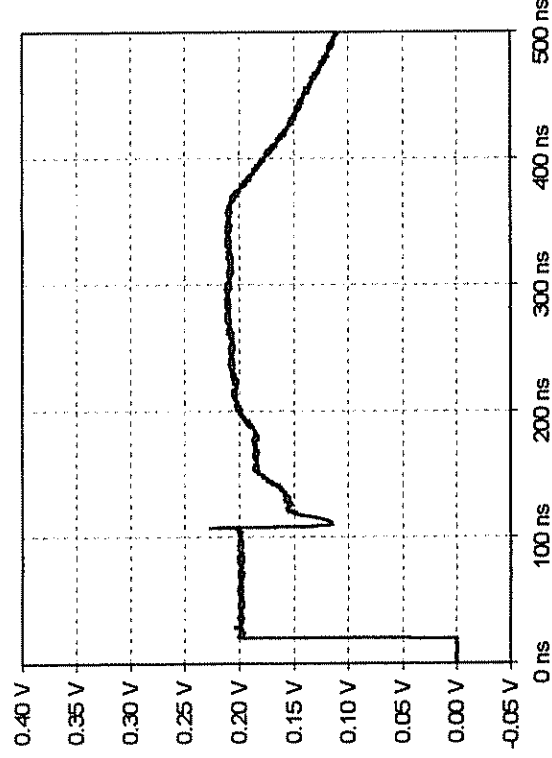
Figure 5a shows the TDR return from stand No.2 of beam B7(4) before the pour. The sample is terminated with a short circuit (electrical contact between strand and sensor wire). A voltage drop marks the end of the sample. The electrical length is 142.7 nanoseconds. The signal is noisy due to the presence of other electrically connected conductors. Note that the time scale used in Figure 5a is different from the one used in other figures.

Figure 5b shows the TDR return from the same sample immediately after the pour. Theoretical analysis shows that both characteristic impedance and propagation velocity depends on the dielectric constant of concrete. When the water content of concrete is high, energy loss is significant because of the conductance between steel strand and sensor wire. Another consequence of the high water content is that the characteristic impedance is small. From Figure 5b, it is hard to tell where the sample ends.

The prior results indicate that with proper calibration, it may be possible to measure the moisture content of the concrete through TDR measurements. TDR monitoring of the beams indicated that water content changed most significantly in the first day after the concrete was poured.



a. October 13, 1999



b. March 29, 2000

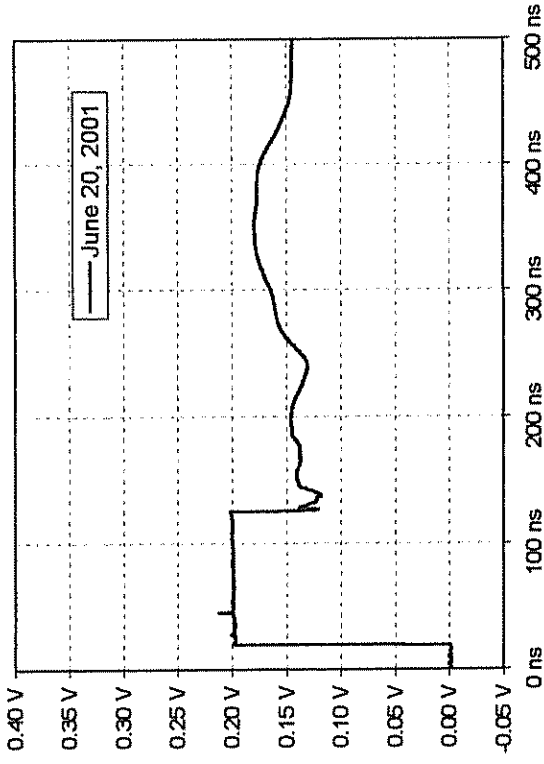
Figure 6. TDR return from strand No.2 of beam B7(4) while the beam was stored in the concrete plant.

The data of Figure 6 are TDR readings taken while the beam was stored in the concrete plant in Delmar, Delaware. The end of the sample can be easily identified indicating that energy losses for the embedded transmission line are

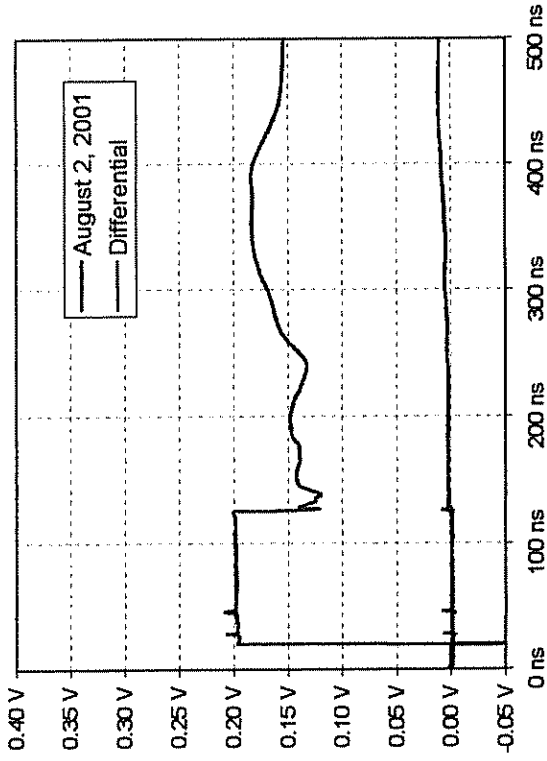
not a problem. The electrical length of the sample is measured to be 266 nanoseconds, which is significantly longer than the one without concrete.

TDR returns from this strand were repeatable with minor changes likely due to the small changes in the concrete's water content. Furthermore, the beams had been moved around in the fabricator's yard during the monitoring process. This change in the environment also can cause minor changes in the waveform. The repeatability of the TDR returns demonstrates the effectiveness of differential comparison.

As discussed previously, electrical connections were remade upon beam installation to reduce energy loss. As expected, there were changes on TDR reflections due to the change of environment and connecting coaxial cables. Initial measurements were taken after the bridge construction was finished. These results are used as new baselines.



a. June 20, 2001



b. August 2, 2001

Figure 7. Corrosion monitoring of strand No.4 of beam B7(4) while Bridge 8F is in service.

Figure 7 shows two TDR readings from stand No.4 of B7(4) while the bridge is in service. The signal repeatability, demonstrated by the differential comparison, indicated that no detectable corrosion damage had occurred. If the steel strand is corroded in the future, a differential comparison of newly measured signals to the baseline should reveal the corrosion damage site.

Since Bridge 8F is a new HPC bridge, corrosion is not likely to occur within the next 20 to 50 years. However, the purpose of this Bridge 8F experimental program is to transit TDR technology from laboratory to the field. Even with standard concrete, a new bridge is not likely to corrode within the first 10 years, which is much longer than the lifetime of a typical research project. However, it has been demonstrated that TDR systems can be implemented and made operational. Furthermore, the stability of the signal over a long time period will provide useful validation regarding the integrity of the system, and of the HPC.

## **IMPLEMENTATION PLAN**

As proved through the Bridge 8F experimental program, TDR is a robust, practical, and economical corrosion monitoring method for field implementation. This technique can be implemented to any new structures. The general installation and measurement procedures are listed as follows:

### **Installation Procedure**

- Apply an insulated sensor wire to the bridge cable section (post-tensioned strands, stay cables, or prestressed strands. The wire should be parallel, and as close as possible to the strands for better measurement accuracy and sensitivity. The sensor wire can be applied outside of an existing grouted duct in both a post-tensioned or stay cable situation. While this will not be as sensitive as if the sensor wire is installed initially within the duct directly next to the strands, it is still a functional TDR detection system.
- Terminate one end with a short circuit, i.e. electrical contact must be made between the strand and sensor wire.
- Use a section of standard coaxial cable to provide electrical access to the bridge cable/wire system. The inner and outer conductors of the coaxial cable need to be connected to bridge cable and monitoring wire, respectively.
- Seal the connections.
- Adjust the length of the leading coaxial cable if necessary.

### **Measurement Procedure**

- Connect the leading coaxial cable to a TDR tester.
- Take an initial reading that is used as a baseline and also evaluated for voids in grout or significant defects.
- Take readings over time and subtract from initial reading to get differential readings. Changes in strand condition (defects) will be evaluated from the differential readings.

The TDR corrosion detection technique can also be applied to existing structures. This is the focus of the ongoing research.

## **CONCLUSIONS**

A TDR parametric study has been conducted. The sensitivity and accuracy of TDR measurement depends on several parameters, including conductor spacing, relative position, rise time, and water content. Basic requirements for measurement apparatus were determined.

A method of differential TDR measurement was developed to cancel some deleterious effects such as noise. Initial TDR measurements were taken on undamaged specimens and used as baselines. Differential comparisons of newly measured signals to the baseline readings can reveal damage to the steel reinforcement.

Bridge 8F is the first field demonstration of the TDR corrosion detection method. TDR instrumentation has been successfully installed alongside a total of five strands in three beams. The differential TDR method is being used as

a permanent corrosion monitoring technique. The nature and repeatability of initial measurements have demonstrated that the method is viable for actual field use.

Based on the experimental results, two papers have been published. One paper, entitled **Nondestructive Corrosion Monitoring of Prestressed HPC Bridge Beams Using Time Domain Reflectometry**, was presented at the TRB 80th Annual Meeting, in Washington, DC. The other paper, entitled **An Overview of Corrosion Damage Detection in Steel Bridge Strands using TDR**, was presented at the 2nd International Symposium on TDR for Innovative Applications, in Evanston, Illinois. The papers attracted attention and encouragement from specialists in the NDE field.

## FUTURE WORKS

TDR corrosion detection can be applied to both new and existing structures. However, every existing structure is different. Therefore, TDR for each existing structure needs to be uniquely analyzed and designed. Additional research is necessary to standardize the TDR technique for some typical kinds of structures.

Currently some steel manufacturers produce epoxy-coated strands. Since each strand consists of seven twisted wires, it is desirable to insulate one wire (preferably one of the six outer wires) from the others. In this case, each strand has two electrically isolated parts. It is a transmission line by itself and ready to be evaluated with TDR. It may be possible to produce this new type of strand by slightly altering the manufacturing process. Instead of the whole strand, just one wire is coated with suitable insulating materials and twisted with six bare wires. Initial tests have been conducted on this type of strand. Usable TDR signals can be obtained, although the characteristic impedance is relatively small due to close spacing. It will be of great importance if the steel strands with two electrically isolated parts can be mass-produced. Corrosion detection with TDR could become an industrial standard and routine practice for this type of strand.

## REFERENCES

- Bhatia, S. K., Hunsperger, R. G., and Chajes, M. J. (1998). "Modeling Electromagnetic Properties of Bridge Cables for Non-destructive Evaluation." *Proc. of Int. Conference on Corrosion and Rehabilitation of Reinforced Concrete Structures*, Orlando, Florida.
- "Our Nation's Highways - Selected Facts and Figures" (1998). Federal Highway Administration, U.S. Department of Transportation, Publication No. FHWA-PL-00-014
- "Time Domain Reflectometry Theory" (1998). *Hewlett-Packard Application Note 1304-2*, Hewlett-Packard Company, Palo Alto, Calif.
- Liu, W., Hunsperger, R. G., Chajes, M. J., Li, D., and Kunz, E. (2001). "Nondestructive Corrosion Monitoring of Prestressed HPC Bridge Beams Using Time Domain Reflectometry", *Proc. of TRB 80th Annual Meeting*, Washington, DC.



**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).