AN OVERVIEW OF CORROSION DAMAGE DETECTION IN STEEL BRIDGE STRANDS USING TDR

By

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ABSTRACT

The corrosion of metallic reinforcement is a major threat to aging infrastructure. Prestressed structures such as the bridges built in the early 1950's and 1960's are showing signs of deterioration. The current corrosion detection methods for embedded or encased steel reinforcement suffer from several significant drawbacks. A nondestructive evaluation technique has been developed that is capable of determining the location and severity of corrosion of embedded or encased steel rebar and strands. This technique utilizes time domain reflectometry (TDR). By applying a sensor wire alongside of steel reinforcement (such as a prestressing strand), a transmission line is created. Physical defects of the reinforcement will change the electromagnetic properties of the line. Both analytical models and small-scale laboratory tests have shown that TDR can be effectively utilized to detect, locate and identify the extent of damage in steel reinforcement in this manner. Currently, the TDR method is being used as a permanent corrosion monitoring method for Bridge 8F, a prestressed high-performance concrete adjacent box beam bridge in Fredrica, Delaware. Differential TDR measurements are used to monitor serious damage due to corrosion of the steel. Experimental results from both small-scale laboratory tests and field implementation will be reported.

INTRODUCTION

The corrosion of metallic reinforcement represents one of the leading causes of durability problems affecting aging civil infrastructure. The high-strength steel used for the cables of suspension and cable-stayed bridges is very sensitive to corrosion, and failure of cables is a serious problem due to the limited degree of redundancy in the structure. A reliable, accurate, and economical method for detecting the existence, location, and severity of corrosion-induced damage will lead to increased levels of safety for civil infrastructure, and may enable significant savings to the public by reducing maintenance costs through early corrosion detection.

Historically, visual inspection has been the most effective method of corrosion detection. However, it cannot be used for embedded or encased steel strands. Several indirect nondestructive corrosion

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detection methods have been developed. They can be grouped into two main categories: mechanical methods and electromagnetic methods. Mechanical methods use force measurement. The tension force in a bridge cable is measured either directly by pulling on the cable or indirectly by observing its free damped vibrations. The vibration frequency reveals the tension in the cable. Electromagnetic methods are based on the fact that the high-strength steel cables are very good electrical conductors. Damage to the cable will change its electrical properties. One can use resistance measurement, potential measurement (utilizing electrochemical reaction due to active corrosion) (Wietek and Kunz 1995), or magnetic inductance scanning to detect corrosion (Zahn and Bitterli 1995). 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.

In this paper, a nondestructive evaluation technique for detecting damage in steel strands and rebars using time domain reflectometry (TDR) is described. The method being developed has the advantage over existing methods in that it can detect, locate, and identify the extent of corrosion.

TDR is a well-established technique in the field of electrical engineering that has been used for many years to detect faults in transmission lines (Hewlett-Packard 1988). 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 steel strand, 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.

ANALYTICAL MODELS

Modeling Bridge Cables

Time domain reflectometry is traditionally used in the field of electrical engineering to detect discontinuities in a transmission line. A bridge cable is a good conductor embedded in a dielectric (concrete). By applying a sensor wire along side of the steel cable, the twin-conductor transmission line geometry is obtained (see Figure 1). However, there are still some important differences between this system and the classic transmission line. First, the two conductors have different diameters. Next, they are embedded in grout and encased in a tube; this imposes a complicated boundary condition. However, if the dimension of the grout is much larger than the dimension of the steel cable and the sensor wire, one can assume these two conductors are in a uniform concrete medium, i.e., the influence of the tube is neglected. This simplification will not appreciably affect the analysis since the electromagnetic field is concentrated between the two conductors and does not significantly extend through the grout to the tube.

For a thorough analysis of the wave propagation in this transmission line, one needs to solve Maxwell's equations with boundary conditions imposed by the physical nature of the bridge cable and surrounding grout. It is also possible to represent the line by distributed parameter equivalent circuit and discuss wave propagation in terms of voltage and current. The distributed parameter equivalent circuit is shown in Figure 2. It possesses a uniformly distributed series resistance R, series inductance L, shunt capacitance C, and shunt conductance G. (R, L, C, and G are defined per unit length.) By studying this equivalent circuit, several characteristics of the transmission line can be determined.

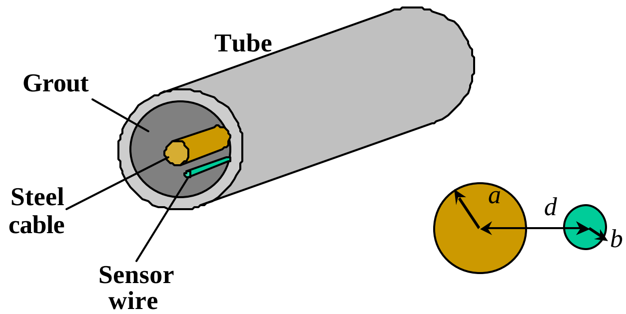


Figure 1. Twin-conductor transmission line geometry of a bridge cable with sensor wire, where *a* is the radius of the steel cable, *b* is the radius of the sensor wire, and *d* is the center-to-center distance between the cable and wire.

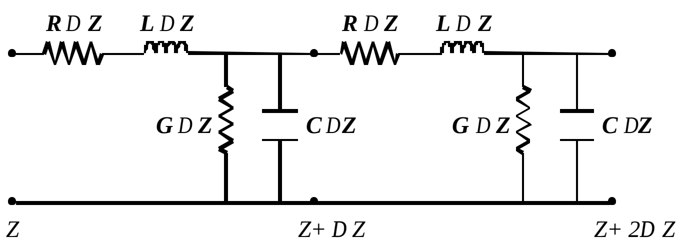


Figure 2. Distributed parameter equivalent circuit of a transmission line.

The propagation constant, γ, defines the phase shift β and attenuation α per unit length. It is given by

$$g = a + jb = \sqrt{(R + jwL)(G + jwC)}$$

The velocity at which the voltage travels down the line can be defined in terms of β:

$$v_p = {}^{w}\!/_{b}$$

The characteristic impedance, Z_0 , defines the relationship between voltage and current in the line. It is given by

$$Z_0 = \sqrt{\frac{R + jwL}{G + jwC}}$$

Distributed Parameters

To study the electrical properties of the cable, it is desirable to obtain the distributed parameters associated with the cable. The capacitance per unit length is calculated by considering the electric field of two parallel infinitely long straight line charges of equal and opposite uniform charge densities. The equipotential surfaces are cylinders with axes parallel to the line charges. If a perfectly conducting cylinder is placed in any equipotential surface, the electric field will not be disturbed. By placing the two conductors in two equipotential surfaces, and calculating the potential difference, the capacitance per unit length of the line is obtained to be (Liu 1998)

$$C = \frac{2\pi\varepsilon}{\cosh^{-1}\left(\frac{d^2 - a^2 - b^2}{2ab}\right)}$$

Since L and C are related by $LC=\mu\varepsilon$ (the product of permeability and permittivity), one can get inductance per unit length from the expression

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

The resistance per unit length R has two parts, R_a and R_b, which are the resistance of the bridge cable and sensor wire respectively. To calculate the resistance at high frequency, skin effects must be taken into account. When the operating frequency is f, the resistance of the transmission line is

$$R = R_a + R_b = \sqrt{\frac{f\mu}{4\pi}}\left(\frac{1}{a\sqrt{\sigma_a}} + \frac{1}{b\sqrt{\sigma_b}}\right)$$

where, σ is the conductivity of the conductor.

Characteristic Impedance

Since at very high frequencies R increases as the square root of f, whereas ωL increases directly as f, the ratio $R/\omega L$ decreases as the square root of f. Let us consider the case of a single 7-wire prestressing strand (a=0.635cm), the sensor wire being used (b=0.05cm), and a typical distance between them (d=3.175cm). At f=50MHz, the ratio $R/\omega L$ is 1.08×10^{-2}, which is negligible compared with unity; it will clearly become still more negligible at higher frequencies. For concrete 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. $G/\omega C$ will therefore be approximately zero. Under these circumstances the characteristic impedance is given to a high degree of accuracy by the simplified expression

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

Upon substituting for *C* and *L* the following expression for Z_0 results

$$Z_0 = \frac{1}{2p}\sqrt{\frac{m}{e}}\cosh^{-1}\left(\frac{d^2 - a^2 - b^2}{2ab}\right)$$

The characteristic impedance of the line is a function of *a*, *b*, and *d*. Note that *b* is much smaller than *a* and *d* (see Figure 1), and it remains the same value along the line. However, the radius of the steel cable, *a*, may be changed if corrosion occurs.

When $b << d$,

$$\frac{dZ_0}{da} \approx -\frac{1}{2p}\sqrt{\frac{m}{e}}\,\frac{1}{a}\,\frac{d^2 + a^2}{d^2 - a^2}$$

This expression has a negative value. This means that the characteristic impedance will increase for a small decrease of *a*. Since radius *a* always decreases at a corrosion site, corrosion will cause higher characteristic impedance. This change of impedance can be detected by time domain reflectometry.

It is also noticed that dZ_0/da depends on the value of d^2-a^2. When the sensor wire is close to the steel cable, d^2-a^2 is small, and dZ_0/da is large. In this case, the characteristic impedance will have a greater change for the same decrease of *a*, and hence the TDR method will be more sensitive.

Modeling different types of corrosion

In order to utilize TDR to detect corrosion, the damage sites of a bridge cable need to be modeled as electrical discontinuities in a transmission line. Several physical defects are of great interest when considering the durability of bridge cables. Among them are abrupt pitting corrosion, general surface corrosion, and voids in the grout.

- Pitting corrosion

Abrupt pitting corrosion is a severe localized damage. It greatly reduces the cross-sectional area of the steel cable. Its length is small compared to the wavelength of the excitation signal. Therefore, it is modeled as an inductor in series with the line. The localized impedance should increase abruptly if pitting corrosion occurs. In TDR measurement, a positive reflection from the site of pitting corrosion is expected. The location of the corrosion site is obtained from the transit time. The reflection amplitude indicates the magnitude of the damage.

- Surface corrosion

Surface corrosion tends to reduce the radius of the cable on the order of a few percent over a part of length of the line. Its length is longer than the wavelength of the excitation signal. Therefore, it can be modeled as a section of transmission line with different characteristic impedance. The extent and length of the corrosion can be determined from the magnitude and duration of the reflection, respectively.

- Voids in grout

Although a void in the grout will not change the strength of the reinforcing cable, it leaves a section of the cable vulnerable to corrosion. The characteristic impedance also depends on ε, which is the dielectric constant of the system. A void in the grout will change this dielectric constant since the contents of the void, usually air and some water, have different electrical properties. Voids tend to reduce the dielectric constant and therefore increase the characteristic impedance. Also, voids will also change the velocity of propagation in the transmission line.

Validation of Transmission Line Model

The bridge cable/wire system is different from traditional transmission lines in many aspects, such as material, geometry, and dimension. The system is not embedded in a uniform medium. For this reason it cannot support pure TEM wave, since the phase velocities in different media would be different. Inside, the propagation mode is quasi-TEM mode. In other words, the fields are essentially the same as those of the static case with only minor differences. Thus, expressions for propagation constant and characteristic impedance (obtained from static solutions) are good approximations.

To test if losses were occurring due to radiative modes of the samples, a 1-meter control sample was checked for electromagnetic radiation using a vector network analyzer. The intensity of the radiative electric and magnetic fields was measured along the length of the sample when an input waveform was applied. It was found that over a range of frequencies from 500 MHz to 20 GHz, the electric field radiated power was more than 60 dB down from the input power. Also, the magnetic field radiated power was 40 dB down from the input power over the range from 50 MHz to 20 GHz (Bhatia et al. 1998). Thus, very little of the energy being sent down the cable is being radiated away as electric or magnetic fields. Therefore, the bridge cable/wire system can be treated as a transmission line.

Existing Structures

While it is true that the model being described here will be applicable only to new structures fabricated with the monitoring wire, the methodology is extendible to various kinds of existing structures.

For detecting corrosion in existing structures, a monitoring wire can be placed outside the grout as long as the wire is parallel to the steel cable and the distance d is not too large. This method is very easy to use. However, the biggest disadvantage of the external sensor wire is that the TDR measurement is less sensitive. The characteristic impedance is less sensitive to the change of the radius a when the sensor wire is far away from the steel cable (i.e. d^2-a^2 is large), since dZ_0/da is inversely proportional to the product of a and d^2-a^2, as mentioned above. However, the corrosion detection will become sensitive when a is small, as in the cases of serious damages. It means that the external sensor wire can be used to detect serious corrosion as well as the internal wire. This fact is of great significance because it allows the evaluation of existing structures.

Theoretically, it is possible to use the metal shielding of a bridge cable as a monitoring wire for defect detection. For existing structures having a metal duct, the metal duct and the embedded steel strand form a coaxial transmission line. The wave propagation, attenuation, and discontinuities in coaxial transmission lines are well studied. 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. A mode is a wave propagation pattern with unique spatial distribution of electromagnetic energy. The TEM mode is the only desirable and allowed mode in most transmission lines. However, a coaxial cable may support TE and TM modes at very high frequencies. In practice, it is important to be aware of the cutoff frequency of the lowest order non-TEM modes to avoid some deleterious effects, such as superposition of two or more propagating modes with different velocity. The presence of TE or TM modes will make TDR measurement difficult since it is equivalent to sending several different signals down the line simultaneously.

EXPERIMENTAL PROGRAM

Small-scale Laboratory TDR Tests

Small-scale laboratory tests have been conducted to verify the effectiveness of TDR in locating and characterizing simulated corrosion sites. Several 1-meter and 3-meter specimens, made from standard rebar and seven-wire strand, with built-in defects were used to study the ability of TDR to detect damage sites. TDR tests were performed on both grouted and ungrouted specimens. Preliminary testing indicated that damage detection for the ungrouted specimens was very similar to that of grouted specimens. According to the analytical model, both propagation constant and characteristic impedance depend on ε_r, the dielectric constant of the surrounding material. Since $\varepsilon_{r\_concrete} > \varepsilon_{r\_air}$, grouted sample will have smaller impedance and smaller propagation velocity. The grout should not introduce significant energy loss over a short length since the monitoring wire is fully insulated. Different grout mixes may have slightly different dielectric constants. However, it will not affect TDR measurements. Because the researchers have access to the damage site when measuring specimens that are not embedded in concrete, such specimens are more convenient to use to study the electromagnetic properties of the simulated corrosion. As a result, bare specimens were mainly used in small-scale TDR tests.

The specimens were connected to the time domain reflectometer through standard 50Ω coaxial cables. The far end of the specimen was connected to a terminating resistive load. A pulse was then sent down the sample and the reflections shown on the oscilloscope. The terminating load was changed from an open to a short to determine where the end of the sample was. The propagation velocity was then calculated.

Figure 3 shows the TDR reflection from a 3-meter steel rebar sample. This sample has 50% pitting corrosion in the middle (1.55m from the front end). Pitting corrosion was simulated by locally grooving the rebar specimens. The TDR measurement was made on a bare specimen. The first step in the waveform corresponds to the generation of the step wave (point A). The wave is launched into a coaxial cable, which is used to connect the sample to the measuring system. The characteristic impedance of this coaxial cable is 50Ω. However, the sample has higher impedance. As a result, there is a positive reflection at the beginning of the sample (point B). The wave travels down the line at v_p, the velocity of propagation. At every point that the excitation signal crosses, the transmission line equations must be obeyed. However, there is a simulated corrosion site at point C. The physical damage changes its electromagnetic properties. Therefore, the transmission line equations are not satisfied and a reflection is generated at this point. The reflected wave is separated from the incident wave in time. This time, $T = T_C - T_B$, is the transit time from point B to the mismatch and back again. At the end of the sample, the wave goes up because the line is terminated by an open circuit (point D). The time interval between points B and D is 23.0ns, which gives a propagation velocity of 2.61×10^8 m/s, i.e. about 87% of the speed of light. The location of the damage site is determined as 1.58m from point B since $T_C - T_B$ =12.1ns, which is the correct location.

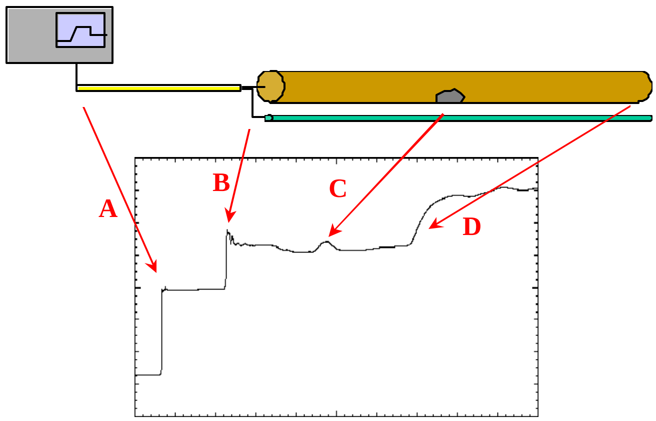
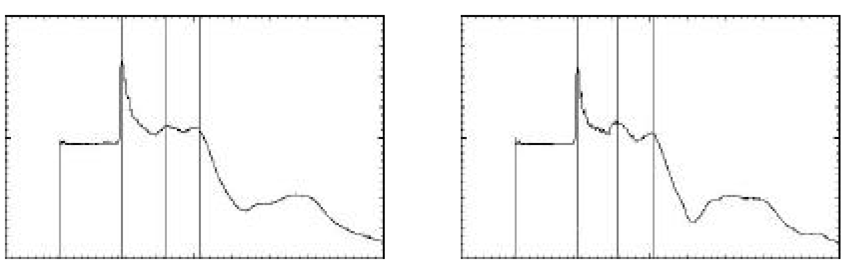


Figure 3. TDR return of a 3-meter rebar specimen. The sample has 50% pitting corrosion in the middle.

TDR can not only locate the corrosion, but also reveal the severity of corrosion. Figure 4 shows TDR returns from two seven-wire steel strand samples. The strands are 0.95m long and each strand is 1.27cm (1/2 inch) in diameter. Corrosion was simulated by severing several wires of the strand specimen. The damage was produced over a 7.5cm length, 44cm from the end of the sample. The first marker indicates the initial reflection from the front of sample, and the third marker indicates the reflection from the end of sample 9.94ns later. The propagation velocity is 1.91×10^8 m/s. The initial reflection is positive, which shows that the characteristic impedance of the sample is larger than 50Ω. The impedance is measured as 56Ω. It is close to 52Ω, which is predicated by the analytical model. Because the sample was terminated by a short circuit, the reflection from the end of the sample is negative. The second marker indicates the reflection from the simulated corrosion site. Note that an accurate location is identified. Experimental results indicate that the magnitude of the reflection depends on the severity of the damage. The sample on the right has severe damage in which six strands are severed, while the other sample has two severed strands.



Two Severed Strands Six Severed Strands

Figure 4. TDR returns from 95cm seven-wire strand cable samples. The first and third markers indicate the beginning and the end of the sample, respectively, while the second marker indicates the simulated corrosion site.

TDR is able to detect multiple damage sites. Figure 5 shows the TDR reflection from a 3-meter steel rebar sample. The two markers in Figure 5 indicate the pulse reflections from two simulated damage sites. Both of them are detected through a single measurement. The reflections are small (because the damage extends over only a short length) but are clearly identifiable.

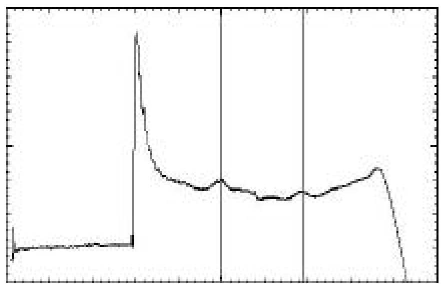


Figure 5. TDR returns from 3-meter reinforcing steel rebar sample.

The sensitivity and accuracy of TDR measurement depends on several other factors. They need to be considered before TDR installation and measurement. Among them are

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

As predicted by the analytical model, TDR measurement is more sensitive when two conductors are close together. However, if two conductors are too close, axial current distribution will be modified by the proximity effect. The density of axial current is increased in adjacent parts of parallel conductors with oppositely directed currents and is decreased at more remote parts. Therefore, corrosion occurring on remote parts is hard to detect. Laboratory experiments also indicate that the TDR measuring system must have a small system rise time to produce acceptable results.

Differential TDR Measurements

In field applications involving complex structures like an actual bridge, noise will be present in the TDR measurements. Other than random noise, undesirable wave reflections 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*.

However, once a concrete girder is instrumented, the location of the steel components causing noise, and the distance *d* between the steel strand and sensing wire will remain constant. While reflections created due to these reasons can be relatively large, they are repeatable. Differential TDR measurement can be used to effectively distinguish corrosion sites from repeatable noise. If several TDR measurements are made for the same strand 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 6 shows TDR results obtained from a 1-meter seven-wire strand bare sample. This sample has two severed strands over a 4.0cm length, 48cm from the front end of the sample. From waveform 1, 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 waveform 2, 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.

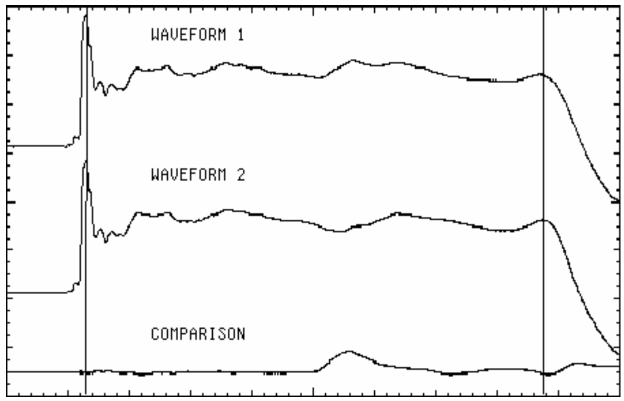


Figure 6. TDR results obtained from a 95cm seven-wire strand sample before (waveform 2) and after (waveform 1) a simulated damage is made to the sample. The differential comparison in the bottom reveals the damage site.

Field Demonstration – Bridge 8F Experimental Program

The effectiveness of the TDR corrosion detection method has been proven through 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.

In 1999, the Delaware Department of Transportation (DelDOT) received funds to design and construct Bridge 8F in Fredrica, Delaware. It is a two-span, prestressed concrete, adjacent box beam bridge utilizing high-performance concrete (HPC) in both the beams and deck. 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. Bridge 8F, which replaced a deteriorated four-span structure, was completed in October 2000.

Bridge 8F consists of 22 adjacent prestressed concrete box beams. 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. Each beam was prestressed using 12.7 mm (0.5 in) diameter, Grade 270 (1863 MPa), seven-wire low relaxation strands. The test program focuses on three beams. Prior to casting, long-term monitoring instrumentation was installed in each beam. TDR monitoring wires have been installed alongside a total of five strands in these three beams. The wire is fully insulated, silver-coated copper wire, which is commercially available. A section of coaxial cable was connected to the strand/wire to provide electrical access.

Corrosion monitoring with TDR began at the time of fabrication, and is continuing now that the bridge is in service. The TDR signal is noisy due to the presence of other electrically connected conductors. Therefore, differential TDR is used in the monitoring. Figure 7 shows TDR readings taken on October 13, 1999 and March 29, 2000, which are 9 days and 177 days after fabrication of the beam, respectively. The end of the sample can be easily identified indicating that energy loss for the embedded transmission line is not a major problem. The electrical length of the sample is significantly longer than the one without concrete (prior to the concrete pour). Also shown in Figure 7 is the differential comparison of the two waveforms. It shows the total changes that occurred in the 168-day time period. TDR returns from this strand are repeatable with minor changes likely due to the small changes in the concrete's water content. Furthermore, the beams have 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.

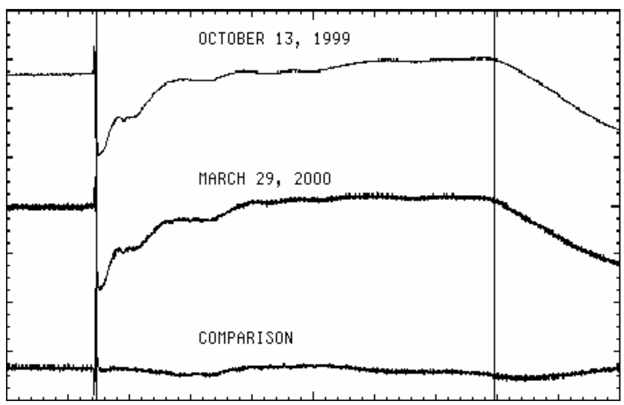


Figure 7. TDR return from strand #2 of Beam B7(4) in Bridge 8F.

SUMMARY

A novel nondestructive evaluation technique for detecting damage in embedded or encased steel reinforcement or bridge cables using time domain reflectometry has been developed and demonstrated. Asymmetric transmission line models apply to steel elements with sensor wires and give an accurate prediction of the system characteristics. TDR can reveal the existence, location, and severity of corrosion on steel elements. Its effectiveness has been demonstrated through both small-scale laboratory tests and field implementation. Differential TDR method is being used as a permanent corrosion monitoring method for steel prestressing strands in an HPC bridge. The nature and repeatability of initial measurements have demonstrated that the method is viable for actual field use. The TDR nondestructive evaluation technique need not be limited to the application of new bridges. It can also be applied to other steel reinforced structures.

ACKNOWLEDGMENTS

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