MTDR Monitoring Systems for the Integrity of Infrastructures

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ABSTRACT: Most infrastructures are formed by large amount of parts, like members of truss, decks of bridge, and so on. Relative movement including shearing and extension between members causes load redistribution or even failure. Monitoring the integrity of the structural system can assure its performance and safety. MTDR (Metallic Time Domain Reflectometry) is proposed here to be an intelligent monitoring system using one coaxial cable embedded into members as the sensing and conducting media all the way through the monitored structure. Relative movements between each member at the connecting points are monitored simultaneously by sending a fast rise impulse into the cable. This paper presents laboratory measurements necessary to quantitatively interpret the reflected waveform. The type and magnitude of reflected waveform caused by shearing and extension between members were investigated. The interpretive techniques were defined and verified experimentally. Quantification between reflected waveform change and amount of relative movements are achieved and provided.

INTRODUCTION

THE Time Domain Reflectometry (TDR) was developed initially by electrical engineers as a method to locate discontinuities in coaxial transmission cables (Moffit, 1964). The technique has been extended to measurement of the properties of materials in which conductors are embedded, such as soil water content (Topp, Davis, and Annan, 1980) and evaluation of material dielectric behavior (Cole, 1975). In rock mechanics, the technique has been employed to identify zones of rock mass deformation (Dowding, Su, and O'Connor, 1989), and blasting performance. Smith (1994) described how fiber optic cables can be applied to form OTDR measurement of structural deformation. Since then, TDR system is divided into MTDR which uses metallic coaxial cable for measuring and transmitting system and OTDR which uses optical fiber.

This technique can be applied to monitor fracturing within concrete structures (Su, 1990). When a coaxial cable is embedded in a concrete structure, it works like a continuous sensor, which can detect fracturing and relative movement at any location along its length. An electromagnetic pulse is launched down the cable and reflection from points of cable deformation can be located precisely. TDR fracture monitoring provides a viable tool when fracture locations are not known in advance. This is the major advantage for TDR compared with other monitoring systems. Telemetric monitoring based on TDR theories has been proven to be applicable (Dowding and Huang, 1994). Intelligent systems for monitoring the integrity of infrastructures are made possible by using the TDR system and techniques developed for analysis. Multiple reflection can cause difficulty in analyzing the reflected waveform. Su and Chen (1998) proposed the area integration method in calculating the effect of movement on waveform. Shearing and extension of the system cause reflected waveform charged. The type and magnitude of the reflected waveform should be investigated to build up its relation to magnitude of movement.

Monitoring system for the integrity of infrastructures was proposed by monitoring on the connection between elements. As shown on Figure 1, coaxial cable is fixed on two sides of a joint or a bearing point. One coaxial cable can have many points monitored simultaneously using TDR technique (Dowding, Su, and O'Connor, 1988). Type and magnitude of reflected waveform caused by different type of movement should be investigated to build up its quantitative relations to provide the basis of interpreting monitored data.

TDR BASIC

A coaxial cable is composed of an outer and an inner conductor normally with plastic dielectric material between them. In the longitudinal view, the coaxial cable may be presented as an ideal, two-wire transmission line having forward and return conductors to represent the outer and inner conductor respectively. Propagation of a pulse along a coaxial cable, i.e., the current and voltage propagating along a two-wire transmission line, is controlled by four basic properties of coaxial cables namely, inductance, resistance, capacitance and dielectric conductivity. Among them, inductance and capacitance are used here to explain the phenomena of this technique (Dowding, Su, and O'Connor, 1988).

Time domain analysis of wave motion is accomplished by looking at the motion of transverse electromagnetic waves.

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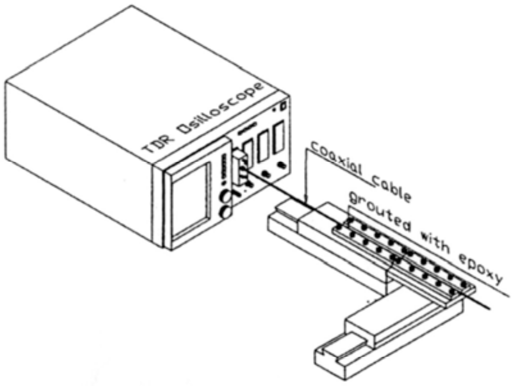

Figure 1. *Diagram of test set-up.*

This is the simplest mode of electromagnetic wave field and is restricted to the normal of the wave propagation direction. By assuming the coaxial cable to be a lossless line, resistance and dielectric conductivity are neglected; the governing equation of wave transmission in the system can be represented by Equation (1):

$$\partial^2 v / \partial x^2 = L \times C \partial^2 V / \partial t^2 \qquad (1)$$

The above equation can be recognized as the basic wave equation for voltage pulse V as a function of distance x and time t. By assuming the wave equation governs the behavior of the system, the reflected electrical signal can be analyzed in the time domain in a fashion similar to that of reflected seismic waves.

TYPE OF VOLTAGE REFLECTIONS

Coaxial cable deformities produce discontinuities that can be divided into two categories: a change in characteristic impedance Z_0 (type I), or a change in reactive lumped circuit elements (type II) (Dowding, Su, and O'Connor, 1988). Either type produces a reflected voltage pulse. Travel time between initiation and reflection of the pulse is converted to distance by specifying a propagation velocity, while the slope and amplitude of the reflection can be related to specific changes in cable properties. Since individual discontinuities are separated in space, they are also separated in time and thus can be analyzed separately. This relation between location and travel time forms the basis of time domain reflectometry.

Change in Characteristic Impedance

When a metallic cable is deformed in tension, its diameter decreases as necking occurs. A decreased cross-sectional area creates a new characteristic impedance, Z_1, different than the original, Z_0. At the interface, the reflection coefficient can be defined in terms of characteristic impedance (Dowding, Su, and O'Connor, 1988):

$$\rho = (Z_1 - Z_0)/(Z_1 + Z_0) \qquad (2)$$

expressed in terms of the original characteristic of the cable.

Change in Reactive Lump Circuit Elements

When a cable is deformed by shearing, the deformation is localized and change in impedance can be modeled by adding an equivalent capacitance to the lumped circuit system. Then, the reflection, ρ, cannot be expressed simply in terms of impedance, but must be idealized by a localized change in capacitance (Dowding and Huang, 1994).

For the ideal shunted capacitance case, the reflection coefficient, ρ, can be approximated by (Dowding, Su, and O'Connor, 1988)

$$\rho = \Delta C \cdot Z_0 / 2 \cdot t_r \qquad (3)$$

where

ΔC = magnitude of the equivalent shunted capacitance
Z_0 = the cable characteristic impedance
t_r = the rise time

MULTIPLE REFLECTION

In the proposed set-up for infrastructure integrity monitoring, deformation of joints at different locations is monitored simultaneously along one cable. That means more than one signal can be picked up at the same time. Capability to watch and to distinguish between this change is a must herein. Resolution of a MTDR system in signal change is a few centimeters depending on system's rise time (Pierce, Bilaine, Huang, and Dowding, 1994). Rise time of the pulse may change when it passes cable discontinuity. The phenomenon is examined by Su and Chen (1998), who provided a viable technique to analyze multiple reflections.

SHEARING AND EXTENSION OF MONITORING SYSTEMS

The type and magnitude of reflected waveform caused by shearing and extension was investigated in the laboratory for a semi-rigid coaxial cable grouted into blocks using epoxy. Most coaxial cables can be employed in building TDR monitoring systems. The cable chosen in this test has a tin-plated copper outer conductor 3.58 mm in diameter which provides good bonding when grouted with epoxy.

Tests are performed on a specially fine fabricated machine having multiple moving parts (see Figure 2). Six shearing blocks and four extension blocks are built on the machine and each can move by an independent control unit without interfering with others. Two samples can be prepared at the same

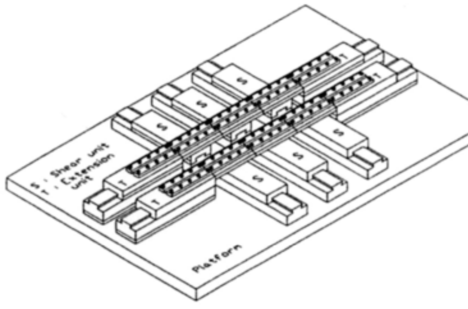

Figure 2. *Cable-grout test machine.*

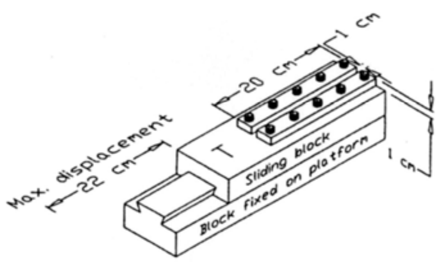

Figure 3. *Extension unit.*

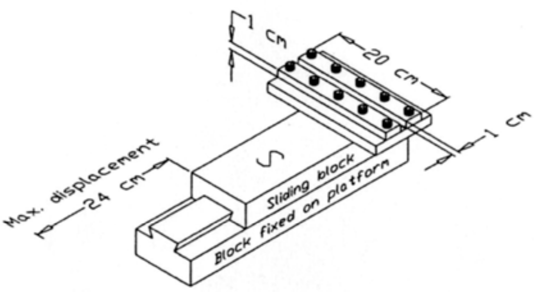

Figure 4. *Shearing unit.*

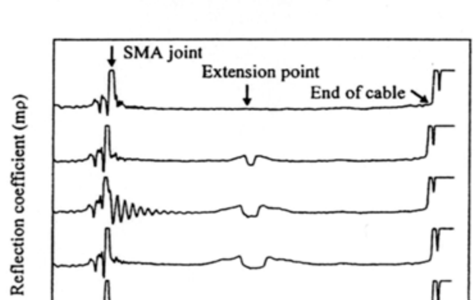

Figure 5. *Typical waveforms of extension test with different deformation.*

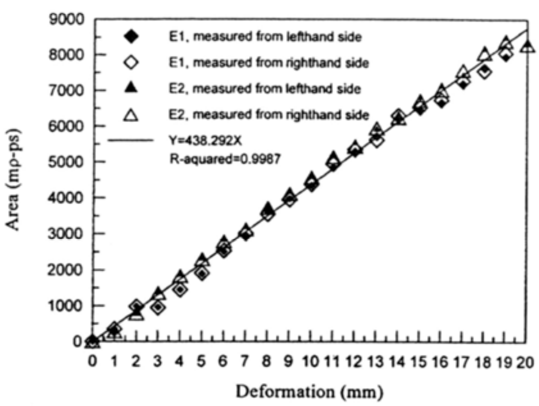

Figure 6. *Relationship between extension deformation and area.*

time. Four interfaces for each sample set-up provide the chance to test the system multiply. Different amounts of deformation at different location can be applied to verify effects of multiple reflection. Dimensions of the extension and shearing unit are given in Figures 3 and 4. Each unit has a base block fixed on the platform and a sliding block which can be moved by a chain system not shown in the figure. On the top of the sliding block, plates fixed with nuts are used to form a groove for cable embedment. Cable grouted with epoxy is connected to TDR Oscilloscope directly. Then, the system is ready to be tested for different amounts of shearing and extension movement.

EXTENSION REFLECTIONS

Typical extension test results are presented in Figure 5 where arrows correspond with location of extension point on the waveform. As can be seen from the figure, extension causes a necking down of the outer conductor over a certain length. The length of the waveform change increases as the cable is extended until either the outer conductor fails or the bond between epoxy and cable fails. In here, voltage drop on certain parts of the waveform is more clear than previous research (i.e., Dowding et al., 1989). The reason should come from different geometry of coaxial cable used.

Test results are listed in Tables 1(a) and 1(b). Integrated area of reflected voltage and maximum reflection coefficient are given for each measurement. Difference between parameters taken from different ends is compared too. The result is the same as previous research. At the end, relation between magnitude of extension and integrated area of the reflected waveform are given as a linear best fit for all four sets of data, as shown in Figure 6.

SHEAR REFLECTIONS

The change in reflected waveform during shear is illustrated in Figure 7, when it can be seen that a negative reflec-

Table 1(a). Extension test results of test no. E1.

		Area (mρ-ps)			$E_{r,\,max.}$ (mρ)		
Deformation Type	Deformation (mm)	Connection at Left	Connection at Right	Difference (%)	Connection at Left	Connection at Right	Difference (%)
Extension	0	0	0	0.00	0.00	0.00	0.00
	1	357	354	0.88	6.28	5.86	7.01
	2	993	983	0.98	9.54	9.48	0.64
	3	961	951	1.00	9.33	9.87	5.66
	4	1455	1457	0.16	10.57	10.88	2.95
	5	1902	1917	0.81	11.19	12.61	11.97
	6	2520	2536	0.63	12.17	12.89	5.72
	7	2968	3015	1.59	12.44	12.51	0.61
	8	3623	3553	1.96	13.21	13.03	1.36
	9	3984	3959	0.62	13.13	13.31	1.40
	10	4353	4383	0.68	13.79	13.40	2.86
	11	4868	4952	1.72	13.87	13.95	0.56
	12	5314	5355	0.77	13.61	14.15	3.92
	13	5696	5622	1.29	13.85	13.94	0.61
	14	6248	6309	0.97	14.07	14.64	3.96
	15	6478	6538	0.91	14.06	14.05	0.10
	16	6695	6746	0.76	14.31	14.73	2.95
	17	7225	7277	0.71	14.69	14.90	1.43
	18	7627	7569	0.75	14.83	15.08	1.66
	19	7978	8063	1.06	14.79	15.10	2.13
	20	8324	8309	0.17	14.78	15.08	1.98

Table 1(b). Extension test results of test no. E2.

		Area (mρ-ps)			$E_{r,\,max.}$ (mρ)		
Deformation Type	Deformation (mm)	Connection at Left	Connection at Right	Difference (%)	Connection at Left	Connection at Right	Difference (%)
Extension	0	0	0	0.00	0.00	0.00	0.00
	1	281	283	0.57	5.88	5.31	10.04
	2	784	789	0.64	9.24	9.38	1.53
	3	1384	1365	1.33	11.84	11.19	5.65
	4	1871	1840	1.68	12.83	11.65	9.58
	5	2317	2305	0.49	13.01	15.99	20.56
	6	2848	2797	1.79	13.16	12.72	3.38
	7	3185	3132	1.69	13.51	13.09	3.17
	8	3727	3732	0.14	14.05	13.63	3.07
	9	4180	4120	1.44	13.83	13.74	0.64
	10	4635	4577	1.26	13.92	13.62	2.19
	11	5203	5147	1.09	14.22	14.15	0.49
	12	5535	5440	1.73	14.67	13.89	5.50
	13	5917	5958	0.69	14.76	14.26	3.42
	14	6283	6252	0.50	15.19	14.48	4.83
	15	6830	6734	1.41	15.16	14.66	3.39
	16	7145	7029	1.64	15.11	14.47	4.35
	17	7443	7591	1.98	14.67	15.01	2.27
	18	8192	8071	1.50	15.49	15.23	1.65
	19	8507	8402	1.24	15.15	15.04	0.74
	20	8824	8747	0.88	15.33	15.12	1.37

Table 2(a). Shear test results of test no. S1.

Deformation Type	Deformation (mm)	Area (mρ-ps) Connection at Left	Area (mρ-ps) Connection at Right	Area (mρ-ps) Difference (%)	$E_{r,max.}$ (mρ) Connection at Left	$E_{r,max.}$ (mρ) Connection at Right	$E_{r,max.}$ (mρ) Difference (%)
Shear	0	0	0	0.00	0.00	0.00	0.00
	0.6	140	139	0.65	3.42	3.00	13.20
	1	311	308	0.74	7.78	7.43	4.60
	1.5	668	666	0.34	16.02	15.49	3.40
	1	1286	1267	1.48	29.61	29.60	0.03
	2.5	1806	1793	0.76	40.21	40.21	0.01

Table 2(b). Shear test results of test no. S2.

Deformation Type	Deformation (mm)	Area (mρ-ps) Connection at Left	Area (mρ-ps) Connection at Right	Area (mρ-ps) Difference (%)	$E_{r,max.}$ (mρ) Connection at Left	$E_{r,max.}$ (mρ) Connection at Right	$E_{r,max.}$ (mρ) Difference (%)
Shear	0	0	0	0.00	0.00	0.00	0.00
	1	256	257	0.49	6.44	6.30	2.24
	1.5	601	599	0.30	14.54	15.00	3.11
	2	1121	1097	2.12	28.02	26.66	4.98
	2.5	1746	1666	4.68	43.12	41.05	4.91

tion coefficient spike is founded at the equivalent interface point along the waveform. Magnitude of it increased as the shearing increased. Tested data are listed in Table 2(a) and Table 2(b). Eventual failure of the outer conductor formed an open circuit and the waveform end at that point.

A second order best fit polynomial of the integrated area vs. shearing relationship is given in Figure 8. There are two samples tested as labeled by *S*1 and *S*2 individually. And, as suggested by Su and Chen (1998), waveforms are taken from two ends separately. Areas calculated from integration of reflection coefficient over time are compared with $E_{r,\max}$ (maximum of reflected voltage). Differences between parameters taken from two sides are calculated to make the comparison. The result is consistent with previous research.

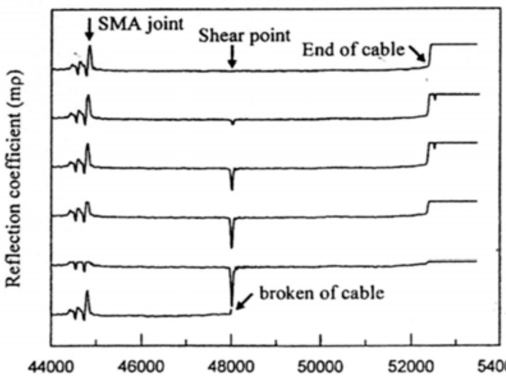

Figure 7. Typical waveforms of shear test with different deformation.

CONCLUSION

MTDR technique can be applied to monitor the relative movement between elements of an infrastructure so as to guarantee its integrity or to be a warning system before too large a local failure. The coaxial cable is fixed on both sides of a joint or grouted into elements depending on the type of the structure and field condition. The cable is then working like a multiple points relative movement sensor and waveform transmitting medium. This technique is proved to be

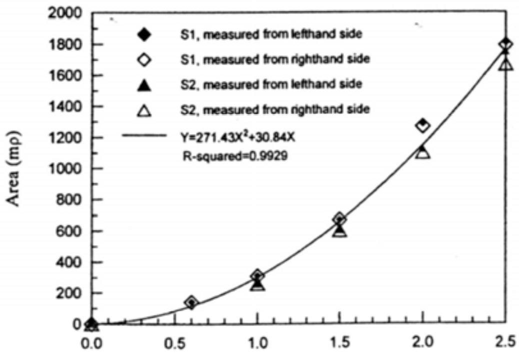

Figure 8. Relationship between shear deformation and area.

able to see multiple deformation simultaneously using one cable and is easy to install as an intelligent system for infrastructure monitoring. The type and magnitude of reflected TDR waveform caused by shearing and extension is distinguishable and can be quantified to magnitude of deformation. And, integrated area of the reflected waveform can provide the best relationship to magnitude of deformation. This provides an applicable technique in using TDR as the monitoring system for infrastructures.

NOMENCLATURE

C = capacitance
E_i = magnitude of voltage of incident wave
$E_{r,max}$ = maximum voltage of reflected wave
L = inductance
m = the maximum slope of the voltage wave in time
t = time
t_1 = time of reflected wave start to rise
t_2 = time of reflected voltage return to normal
t_r = rise time
V = voltage pulse as a function of distance and time
X = distance
Z = impedance
Z_0 = cable characteristic impedance
Z_1 = impedance of a new section
ρ = reflection coefficient
ΔC = magnitude of the equivalent shunted capacitance

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