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ELECTRIC TIME DOMAIN REFLECTOMETRY SENSORS FOR NON-INVASIVE STRUCTURAL HEALTH MONITORING OF GLASS FIBER COMPOSITES

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Abstract—Time domain reflectometry (TDR) offers the advantage of distributed sensing using a single transmission line sensor. In the present study, a parallel plate type non-invasive TDR sensor for structural health monitoring (SHM) of composites has been designed, modeled and experimentally tested. Five layer unidirectional glass fiber/epoxy composite specimens are fabricated. Specimens included a damage initiator in form of a cut in the central ply. The TDR sensor detects sub-surface damage in the composite non-invasively as the effective dielectric constant of the composite decreases due to the presence of delamination cracks. Previous work done on dielectrostriction is used to model the TDR response to strain changes. Qualitative agreement between theory and experimental results for strain sensing are found.

1. INTRODUCTION

Composite materials offer many advantages over metallic materials such as increased stiffness, reduced weight, increased strength and the ability to tailor material properties. Their integration in structures is hindered by reliable and long term failure data [1], especially in high-performance structures found in aerospace. A significant advantage of composite materials is the ability to control material properties by changing the ply layup and processing route. However, this greater control on the composite properties implies that any variations in

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the manufacturing process will be reflected in the variations in the properties of the composite materials. While the failure criteria are very well defined for traditional materials such as metals, the failure criteria are much more complicated for composite materials [1]. Hence real time structural health monitoring (SHM) is crucial for composite material structures In this aspect, there has been a recent interest in SHM of composites using fiber optics [2, 3], acoustic emission [4, 5], ultrasonic [6, 7], x-ray radiography [6] and eddy current [8, 9] methods. Fiber optic sensors suffer from the weakness of being highly invasive difficult to integrate during composites manufacturing process, and require expensive and complicated instrumentation. Acoustic emission and ultrasonic methods are well suited for laboratory environments but are prone to high interference in practical implementations. X-ray radiography is suitable only for laboratory-scale damage detection due to large equipment required to perform radiography. The goal of this paper is to explore an automated low cost and reliable technique to monitor strain and damage of composite structures using electric time domain reflectometry (TDR) as a potential SHM technique.

TDR consists of generating a high frequency electromagnetic pulse through a pair of conductors (called transmission lines) and detecting the reflection. All the discontinuities along the transmission line lead to reflected waveforms from those discontinuities. Using the location of the reflected waveforms in time domain, the spatial location of the discontinuities can be estimated. The theoretical basis of this technique is the transmission line theory developed in 1880s by Heavyside. The technique has been widely used since to detect faults in printed circuit boards and cables [10]. TDR technique has been also used for geological measurements to monitor soil moisture content and rock faults [11] studying faults in concrete structures [12, 13], and detection of leakage in pipelines [14]. In composite applications, TDR has been successfully implemented for flow and cure monitoring in liquid composite molding processing [15, 16]. Double cantilevered beam testing of composite specimens has been successfully reported in literature [17]. With recent advances in microwave engineering and with the advent of picoseconds rise time and gigahertz frequency pulses, TDR has been used to probe much smaller structures. An example is the use of localized carbon nanotube networks for micro-crack detection using TDR [18, 19]. Whereas micro-cracking damage is gradual, the present study deals with delamination damage in composites which are sudden and are mostly inside the composite structure and hence it's not visible from outside. Yet delamination can cause catastrophic failure of the composite structure. The present research explores the use of TDR sensors to detect sub-surface delamination damage.

An advantage of the TDR technique is the ability for distributed sensing, i.e., the ability to monitor multiple sensing points using a single transmission line sensor. Hence it offers potential cost savings over traditional point sensing techniques which require a sensor for each spatial point of interest. TDR is especially useful for composite structures as fiber composites are dielectric in nature (due to polymer matrix) and TDR is based on measuring the dielectric response of the system. However three major factors have hindered the growth and practical implementation of TDR for SHM of composite structures: 1) Low sensitivity and high noise, 2) The need to embed sensors inside the structure and 3) Lack of theoretical modeling of TDR sensor response. In this research, we have addressed these key issues. With respect to the first two challenges, we have used parallel plate sensors as opposed to presently used parallel wire or coaxial cable sensors. It is a common perception in the sensors design community that embedded sensors result in better sensitivity, as they are closer to the damage site. But embedded sensors result in local defects which can cause premature failure initiation [20, 21]. In the present work, electromagnetic waves are used to penetrate the composite structure and the response of these penetrated waves is monitored externally. This allows through thickness sensing without embedded sensors and the accompanying defects. The third problem is solved by assuming a linear variation of dielectric with strain (dielectrostriction). The phenomenon of dielectrostriction is well established by Lee *et al.* [22, 23] for polymers but there are no such studies for fiber composites. As the phenomenon of dielectrostriction has been relatively recently reported, previous studies on TDR based SHM have not taken dielectrostriction into account while designing TDR based sensor. The TDR sensors design community will find the present paper very useful as a guideline to design TDR sensors, which can either be integrated with the composite structure or NDT-style portable TDR sensors. This paper identifies all the parameters which are necessary to design and optimize a TDR based SHM/NDT system.

It has been demonstrated that a single TDR based sensor can be used to monitor a linear region for delamination cracks, which result in a large perturbation of the TDR response. For the composite specimen fabricated in this study, the delamination crack is inside the specimen and cannot be observed from the composite surface. TDR sensors can detect such delamination due to the decrease in effective dielectric constant of the composite material.

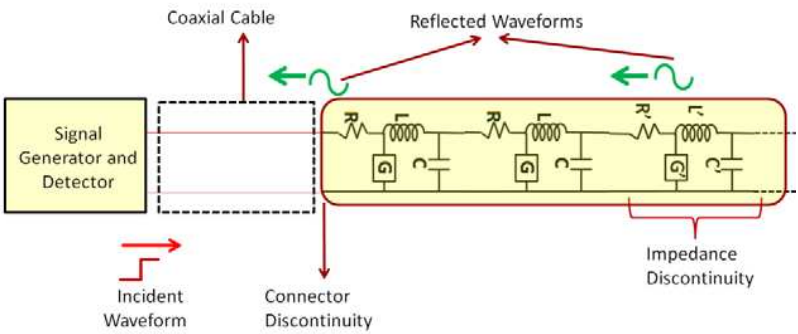


Figure 1. Basics of TDR measurement.

2. ELECTRIC TIME DOMAIN REFLECTOMETRY

Figure 1 shows the equivalent electric circuit diagram of a typical TDR setup. Because the time domain response is a function of the sensor configuration and surrounding dielectric properties, the test allows for reconstruction of the material electrical properties along the entire length of the transmission line. The electrical properties of the specimen and transmission line are defined by the characteristic impedance, Z.

Electrical properties of the specimen and transmission line system are defined by "characteristic impedance" (Z) which is a function of distribute impedance (L), distributed capacitance (C), distributed resistance (R) and distributed conductance (G). Characteristic impedance and propagation speed, v of a lossless transmission line ($R = 0$, $G = 0$) are given by:

$$Z = \sqrt{\frac{L}{C}} \tag{1}$$

$$v = \frac{1}{\sqrt{LC}} \tag{2}$$

Depending on the impedance distribution along the transmission line, the TDR module generates a voltage vs TDR time plot. A typical TDR plot is illustrated in Figure 2. If there is no discontinuity along the transmission line, the voltage output will be constant throughout the TDR time scale. But if there is a discontinuity along the transmission line, the voltage output at that point will be different from the incident TDR voltage (E_i). Voltage at mth location, $E_{L,m}$ and incident voltage, E_i are related by Equation (3). In Equation (3), Z_{module} is the module impedance (usually $50\,\Omega$).

$$E_{L,m} = E_i \left(\frac{2Z_{L,m}}{Z_{module} + Z_{L,m}} \right) \tag{3}$$

At the end of a TDR plot, there is an open circuit reflection for those transmissions which terminate in infinite impedance (such as one used in the present experiment). The TDR timescale can be converted to spatial distance using the velocity of electromagnetic waves propagating along the transmission line using Equation (4). For example, Equation (4) can be used to find the actual spatial location of the fault in the transmission line from the open end of the transmission line

$$\Delta x = \frac{\Delta t}{2\sqrt{LC}} \tag{4}$$

Whenever there is an impedance discontinuity along the transmission line due to some load impedance $Z_{L,m}$, the TDR output voltage at that point is different than incident voltage. In Figure 2, it's assumed that there is only one impedance discontinuity along the transmission line. But in actual measurements, there are multiple impedance discontinuities and hence Equation (3) needs to be replaced by a recursive expression which takes into account all the reflections and transmissions. In the present paper, even though there are multiple reflections in the specimen, an average value of TDR voltage will be calculated in the specimen and an average impedance (defined as effective impedance) will be calculated based on Equation (5) as:

$$Z_{Effective} = \frac{\sum_m Z_{L,m}}{m} \tag{5}$$

3. TDR BASED SENSORS FOR STRAIN AND DAMAGE SENSING

TDR signal response is dependent on both the sensor geometry and the specimen properties. TDR sensor geometry changes the distributed capacitance and inductance and hence it is one of the key parameter for increasing the sensitivity of TDR based SHM system. Chen *et al.* [13] reported an improvement of 15–80 times by changing the geometrical design of the transmission line. A good geometrical design must ensure that there are uniform electromagnetic fields inside the system under observation. Obaid *et al.* [17] used two parallel wires embedded inside the specimen for double cantilevered beam (DCB) measurements ((Figure 3(a)). This is a good configuration for DCB testing, where the location on cracks is known before hand

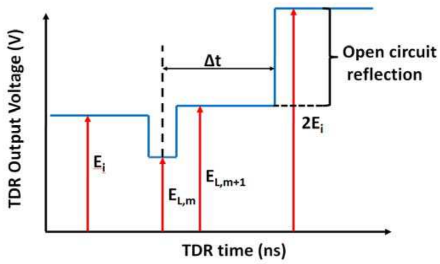


Figure 2. TDR waveform for a uniform transmission line with an impedance discontinuity at mth location and an open circuit at the end of the transmission line.

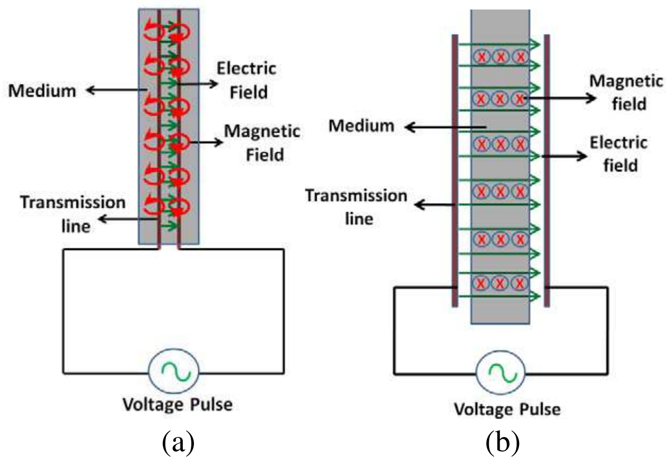


Figure 3. Instantaneous electric and magnetic fields in transmission lines due to a voltage pulse: (a) Embedded transmission lines, (b) parallel plate transmission line.

and is in between the transmission lines. In the present research, an initial attempt was made to use embedded wires for strain and damage sensing in fiber composites. However, due to low signal to noise ratio, even *in situ* strain measurement was not possible. The reason for reduced efficiency of the parallel wires based TDR sensing approach is that the electromagnetic fields are present only in the region between embedded transmission lines. Whereas, the parallel plate sensor configuration, shown in Figure 3(b), has electromagnetic fields throughout the specimen.

Impedance of the parallel plate transmission line system can be expressed in terms of material dielectric and magnetic properties, specimen geometry and transmission line width, w [24] as:

$$Z = \sqrt{\frac{\mu}{\varepsilon C}} = \frac{\delta}{w}\sqrt{\frac{\mu}{\varepsilon}} \tag{6}$$

For a transmission line consisting of both an air-gap and a dielectric specimen (Figure 4) and assuming that the specimen is non-magnetic, the impedance is given Equation (7).

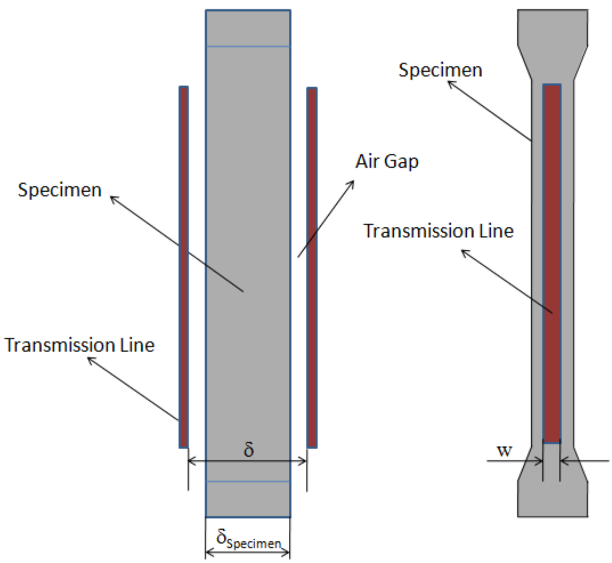


Figure 4. Dielectric specimen between parallel plate transmission lines.

$$Z = \frac{\delta}{w}\sqrt{\frac{\mu_0}{\varepsilon_{eff}}} \tag{7}$$

where ε_{eff} is the effective dielectric constant given by Equation (8) [24] as:

$$\varepsilon_{eff} = \varepsilon_0 \frac{C}{C_0} \tag{8}$$

where C is the capacitance of the parallel plate transmission line with the dielectric inserted in and C_0 the capacitance with air/vacuum in between the parallel plates.

$$\varepsilon_{eff} = \varepsilon_0 \frac{\delta}{\delta - \delta_{Spec}\left(1 - \frac{1}{\varepsilon_r}\right)} \tag{9}$$

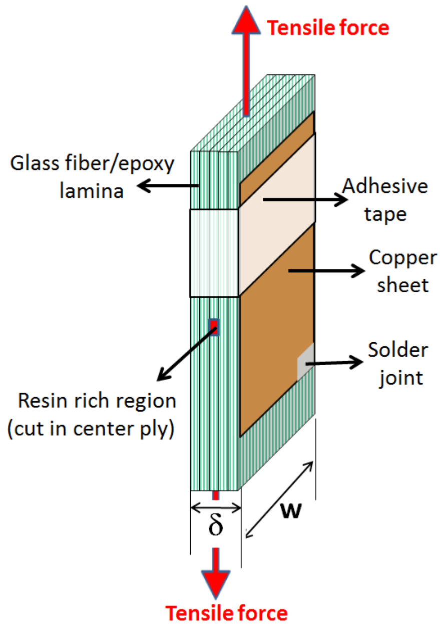


Figure 5. Schematic of TDR sensor implementation for composite specimen with pre-introduced damage.

In the present setup, an adhesive tape keeps the transmission lines in place (Figure 5). As the specimen elongates, the air gap between the transmission lines increases due to Poisson's contraction of the specimen. With damage, as there are cracks inside the specimen, that air gap increases as well, resulting in a decrease in the effective dielectric constant and hence an increase in specimen impedance.

It has been proved in previous research by Lee *et al.* that the dielectric constant of any solid material depends on the applied strain [22, 23]. This phenomenon is known as dielectrostriction. Dielectrostriction is a complicated, anisotropic phenomenon but in the present case of uniaxial tensile loading, the following linear relationship can be assumed as:

$$\varepsilon_r = \varepsilon_{r,0}(1 + \alpha u_{zz}) \tag{10}$$

where u_{zz} is the strain in the axial direction and $\varepsilon_{r,0}$ is the dielectric constant of the unstrained specimen.

Figure 6 shows TDR waveforms (unstrained, strained, damaged and completely failed) of the composite specimen between parallel plate transmission lines. Each of the TDR waveform consists of three distinct regions consisting of the coaxial cable connecting the module to the

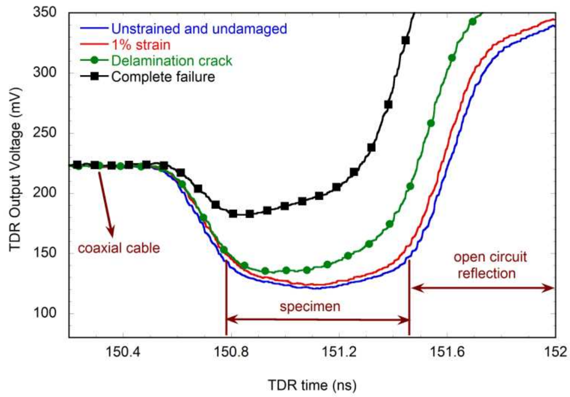


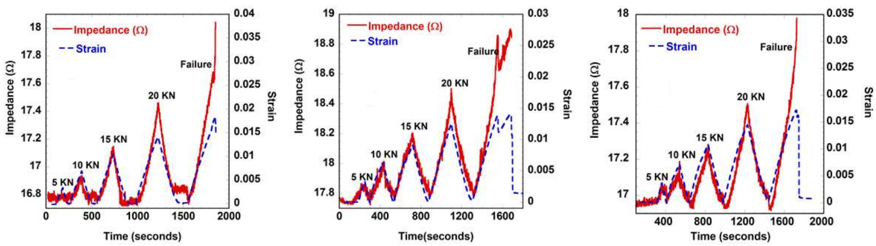
Figure 6. TDR waveforms of the composite specimen.

transmission lines, the specimen between the transmission lines, and an open circuit reflection, which is due to the open ends of transmission lines. It can be seen that as the specimen undergoes strain and damage, the TDR waveform changes. This change in TDR waveform can be used to access the strain and damage state of the specimen. As the specimen undergoes tensile strain, the TDR voltage increases as predicted by Equation (9). While there is only a small increase in the TDR waveform with strain, there is considerable difference between TDR waveforms of the specimen with and without damage. The TDR output voltages depend on the average impedance of the specimen given by Equation (7). The average impedance is dependent on the effective dielectric constant given by Equation (8). For the parallel plate setup, effective dielectric constant is given by Equation (9). In addition to the geometrical properties of the specimen, there is also a strain dependence of the dielectric constant [22, 23].

4. RESULTS AND DISCUSSION

ASTM D3039 tensile specimens were fabricated from E-glass fibers (COM-VEW130-50, Jamestown Distributers) with stacking sequence of $[0_5]$. The center ply was cut in the middle to initiate delamination in the composite specimen. The ply lay-up was sealed in a vacuum bag with a resin distribution layer to enhance matrix infiltration and subsequently infused with an epoxy SC-15 resin The laminates were cured at room temperature for 48 hours followed by post cure at 120°C for 2 hours. Progressively stepwise cyclic loading in steps of 5000 N has been applied to the specimen using INSTRON 4484 universal testing machine. The loading was applied at the rate of 1.27 mm/min. TDR module from Hyperlabs Inc. (HL8200-USB) was used for TDR measurements. TDR waveforms were recorded at every 1 second interval. The copper foils used as transmission line were de-greased using isopropyl alcohol and stretched over the length of the specimen on both sides to form a parallel plate transmission line. The parallel transmission line was soldered to a SMA connector. The specimen strain was measured by bonding a surface-mounted resistive strain gage (Micro-Measurements, Inc.) in a region outside the copper strips.

Figure 7 shows the impedance response of the composite specimens under progressively increasing cyclic loading of 5000 N for three different specimens. An average value of TDR output voltages from 150.5 to 151.5 ns has been used to compute the average specimen impedance. A good correlation between strain and impedance can be observed for the specimen. A good specimen to specimen repeatability is observed. The experimentally measured impedances have been compared against theoretical values predicted by Equation (6) and Equation (10). The comparison between theoretical and experimental



(a) (b) (c)

Figure 7. Impedance response of three different composite specimens.

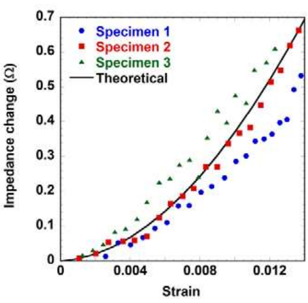
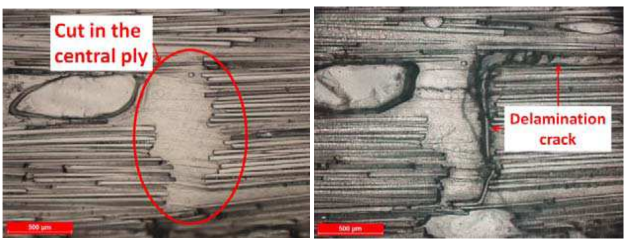


Figure 8. Comparison between theoretical and experimental results.

results is shown in Figure 8. Since no previous studies have been conducted about the strain dependence of the dielectric constant of composite materials, several values of α were used so as to extract strain dependent dielectric constant as required by for Equation (10). A value of $\alpha = -0.3$ was found to give a satisfactory match between theory and experimental results as shown in Figure 8. Poisson's ratio of 0.22 was assumed (a typical value for VARTM manufactured unidirectional glass fiber/epoxy composites). A good qualitative agreement between theoretical results and experimental predictions was observed.

In our previous research [19], it has been shown that the modification of composites using CNT networks results in enhanced TDR response to both strain and damage. This is likely due to high dielectric constant vs strain variation in CNT networks arising from the change in CNT-CNT tunneling distances with strain and damage. However, the study was primarily experimental in nature and did not compare experimental data with theoretical predictions. In the present study, a comparison of experimental results and theoretical predictions has been done for glass fiber composites. In future, research efforts will be made towards modeling not only baseline composites but also CNT modified composites, taking the variation of dielectric constant of the CNT network into account.

Figure 9 shows the micrographs of the undamaged and damaged composite specimen. Micrographs shown in Figures 9(a) and 9(b) were obtained using edge replication technique at unloaded stage and 25 kN load respectively. Micrographs show that the damage is completely inside the specimen and is not visible from outside the specimen. But the impedance of the specimen increases suddenly due to the decrease in the effective dielectric constant (Equation (8)). Hence the TDR technique can be used for non-invasive monitoring of cracks inside composite structures and warn about the catastrophic failure.



(a) (b)

Figure 9. Photomicrographs of the edge replica of the composite specimen: (a) undamaged specimen, (b) damaged specimen.

5. CONCLUSIONS

Impedance measurements using time domain reflectometry can be used for non-invasive *in situ* strain and damage sensing of composites. Impedance measurements using parallel plate transmission line technique enable the detection on sub surface damage. Strain-impedance behavior of composites can be modeled assuming a linear dependence of the dielectric constant on strain. In addition to the sensor geometry, material properties, especially the dielectrostriction parameter plays a crucial role in determining the sensitivity of TDR sensors and all these parameters must be considered when designing external TDR sensors or smart structures with embedded/surface mounted TDR sensors. Impedance change measurements have been found to be useful for damage sensing in ply discontinuity specimen, as the impedance jumps sharply near specimen failure (resulting from subsurface delamination crack). Delamination cracks are not visible on the surface however they can cause catastrophic failure of the structure. External TDR sensors can be used to non-invasively detect such delamination cracks inside the structure.

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