An Automated Technique for Measuring Crack Propagation during Mode I DCB Testing

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ABSTRACT

The paper describes a new technique for automated measurement of crack initiation, growth and propagation in composite materials during Mode I DCB testing. The proposed method detects change in geometry and electromagnetic properties (dielectric or magnetic) along a transmission line that can be embedded in or bonded to a material or structure. Crack initiation and propagation cause gross changes in properties and are easily detected. Traditional methods have relied on time and labor consuming optical techniques or electrical techniques resulting in limited resolution and accuracy of test data. The proposed technique is fully automated and has much better resolution and accuracy than currently available techniques. It can also be used to perform Mode I fracture toughness measurements in composite materials under extreme environment conditions (hot-wet, elevated temperature etc).

INTRODUCTION

Fracture toughness is an important parameter in composite materials, as it relates to the ability of the material to resist crack propagation. Fracture in composites typically occurs due to interlaminar stress concentrations, whether it is due to a free edge, ply drops, joints or notches. The most common method for measuring fracture toughness of composite materials is the Mode I Double Cantilever Beam (DCB) method, as described in ASTM 5528 [1]. Mode I fracture relates to out of plane forces causing the crack to propagate in the plane of the material.

In the DCB test method, the ends of the specimen are pulled apart forcing a crack to propagate down the length of the beam. The progress of the crack is monitored as a function of the load, and used to calculate the fracture toughness of the material. There are several methods currently in use to monitor the progress of the crack during the test. The most common method is a visual technique using a monoscope or a traveling microscope. This method requires marking of the side of the test specimen and monitoring of the crack progression by arrival at each mark. It is a time-consuming method that has limited resolution and somewhat subjective in nature. Several techniques have been developed to automate the process and are primarily optical or electrical-based methods.

Uhlig et al. [2, 3] developed an automated optical crack tracing system that uses a CCD camera to monitor the crack front during the test, with real-time image processing to obtain crack propagation data. A fully automated system is available [3] that requires no additional sample preparation time, has a high degree of accuracy and can complete the test rapidly. However, this method requires direct view of the tested specimen, which may not be possible for extreme environment testing.

Crack gages are available from several sources, and though they have different configurations, they essentially rely on change in electrical properties of a surface bonded system, as the crack propagates through it. One version uses a foil configuration [4], which cracks during the test, and a second version [5] uses an array of conductive wires that break in sequence as the crack front moves through the gage. Crack gages are mounted on the side face of the DCB test specimen and can get expensive for longer beam type coupons. The foil-based gage requires substantial thickness for mounting (> 0.5”), while the conductive wire array gage is limited in resolution and cost. Both gage methods require substantial specimen preparation, prior to testing.

None of these methods combine low cost, non-intrusive or in-situ, usability under extreme conditions and simplified specimen preparation, at the same time. In this paper, we demonstrate a Time-Domain Reflectometry (TDR) based technique as a novel automated sensing technique for crack propagation measurement that meets all these requirements. The sensors can be integrated into the composite specimen during manufacture and only need to be connected to the TDR system to begin testing. In addition any conductive material (metal wires, carbon fibers, metal-clad fibers etc) can function as the sensor material, with little performance degradation. The system can be fully automated and perform in extreme environments.

BACKGROUND

Time-Domain Reflectometry (TDR) is method of sending a fast pulse down a controlled-impedance transmission line, and detecting reflections returning from impedance and geometric discontinuities along the line (Figure 1). Time scales are fast, so reflections occurring at different positions in the line are separated by time-of-flight, forming a "closed-circuit radar". Frequencies are in the communications range, so the measurement is commonly used in locating faults in networking and cable TV systems. TDR has gained popularity in recent years in infrastructure applications [6]. The transmission line is embedded in a bridge or highway structure, such that a flaw in the surrounding structure causes a mechanical distortion in the line, which produces an impedance discontinuity, which is located by time-of-flight. Similar methods are used in groundwater level detection, where the line is embedded in a soil layer such that a water level causes an impedance change, which is again located by propagation delay.

TDR has not yet been applied to smaller applications such as composite parts since the propagating pulse is not sufficiently localized. Typical infrastructure applications use pulse widths around 500 ps with input bandwidths near 2 GHz, producing pulse spreading in the line around 100 mm. This resolution is sufficient for infrastructure applications, but for composite parts is an order of magnitude too high. Composites parts require pulse localization below 10 mm, and such instrumentation with pulse widths around 35 ps and input bandwidths near 20 GHz is only now becoming available. The basic TDR layout is shown below. On the left is the TDR oscilloscope, which both supplies the input voltage step and captures the returning reflection. The scope has a 10ps/cm maximum sweep speed and a 20 GHz input bandwidth, with a 35 ps risetime step applied internally to the input. Extending from the input is the thin planar transmission line, embedded within the composite part, which is used as a sensor.

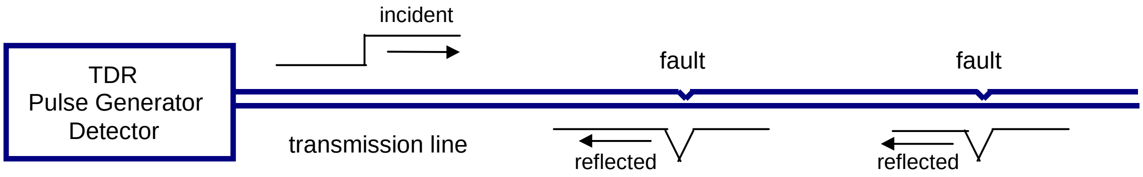

Figure 1 Schematic of Typical Time-Domain Reflectometry (TDR) System

Current Application of TDR to Composites

Recently, TDR sensors have been developed and evaluated for resin flow monitoring, cure during composite manufacturing as well as structural health monitoring [7]. Any dielectric and/or geometrical discontinuity between the transmission line and the ground plane changes the characteristic impedance, and introduces a voltage reflection at a particular time and magnitude. The system has been proven out to accurately measure distributed parameters such as the resin flow position, degree of cure, defect detection and strain measurement. The transmission line can be embedded into the part and on the surface or integrated into the tooling making it reusable as well as sensing through gel coats commonly applied on the mold surface. TDR sensors are unique due to the fact that they are lineal sensors and can be used to interrogate changes along the entire length of the sensor, rather than at a point (for example: fiber optic sensors). This reduces the number of sensor lines and associated acquisition hardware.

TDR for Crack Propagation Measurement

TDR sensors can be very good crack propagation detection sensors, as the propagation of the crack alters both the electromagnetic properties, as well as the dimensions of the structure. If the sensor is configured such that the crack propagation is between the signal and the ground planes, the TDR sensor can not only detect the crack front, but also the relative movement of the planes of the crack. The transmission line is typically an electrically conductive material and a variety of material choices are available, such as metal wires or graphite fibers. To minimize material impact when embedded into a composite material, metal coated structural fibers can also be used, such as metal coated carbon or Kevlar fibers.

A DCB test involves a moving crack front between two planes and the inclusion of the transmission line in one plane and the ground in the other plane will enable accurate detection of both location and velocity of the crack front (Figure below). In this method the time shift (Δt_C) of the electromagnetic signal due to the crack propagation is monitored. At a given crack location, Δt_C can be measured based on a reference signal (when the applied load is zero), which indicates the position of the starter crack or initial delamination. The crack length L_C will be simply taken as $V^*(\Delta t_C /2)$, where V is the speed of the signal in the sensor material.

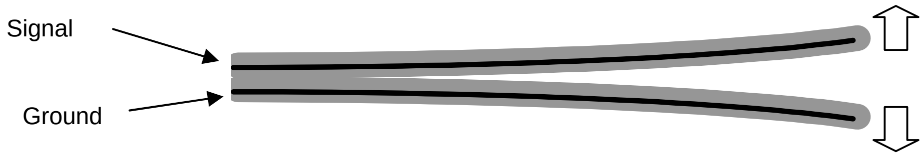

Figure 2 TDR Sensor Configuration for Mode I DCB Test

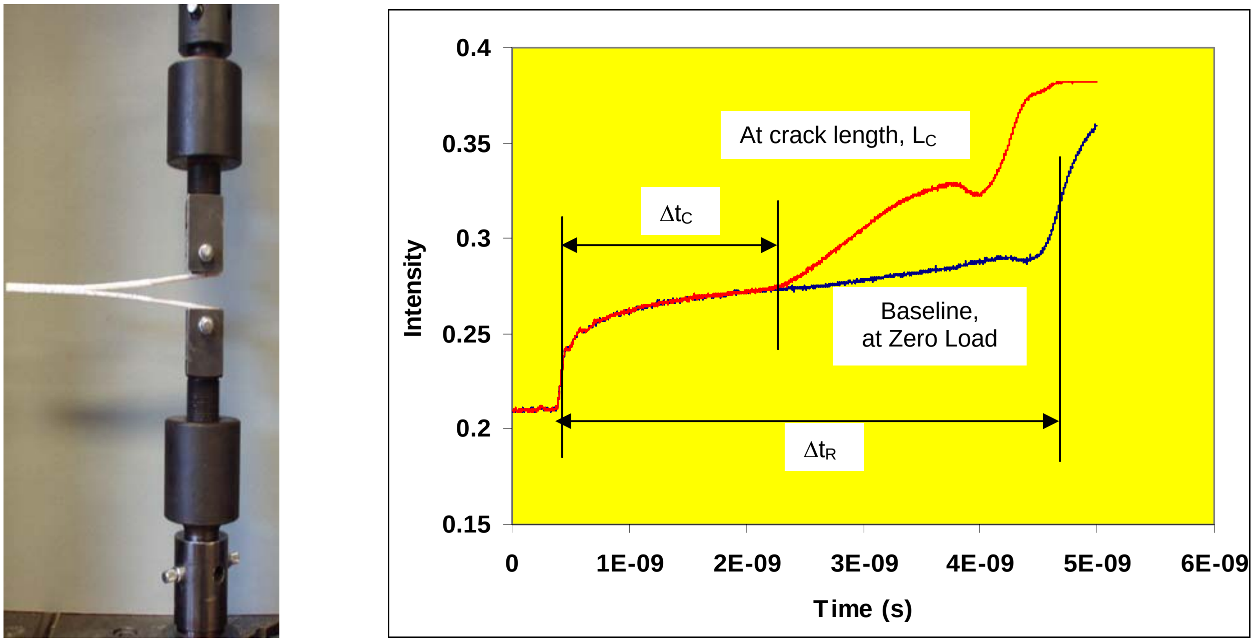

Figure 3 TDR Sensor Response during Mode I DCB Test

Traditional methods of tracking crack propagation involve visual tracking with a monoscope, video camera based systems, and the application of electrical conductivity-based crack gauges. Typical crack gauges long enough for DCB samples can cost up to $180 each [8], making their cost prohibitive for a large series of tests. The TDR method has the potential to be a fully automated indicator of crack growth, much lower in sensor cost than crack gauges with significantly higher resolution.

EXPERIMENTAL

In this effort, double cantilever beam (DCB) specimens were fabricated to evaluate the ability of TDR sensors for automating crack growth measurement during the test. DCB specimens were fabricated for two tests: the first set consisted of three (3) adhesively bonded DCB coupons for direct comparison of visual or optical technique with TDR sensor and the second was a “blind” test in a glass/epoxy DCB configuration to measure the epoxy fracture toughness. Two sensor types were evaluated, with the first set using carbon fiber thermoplastic prepreg tape (IM7/PEI) and the second using ARACON (conductive Kevlar) fiber tow, to demonstrate the flexibility in sensor material. Table 1 lists the specifications for all the DCB specimens tested.

Table 1 Specifications of the DCB Test Specimens

DCB Test Type	Adherend or Substrate	TDR Sensor Material	Crack Sensor	Number of Tests
Adhesive DCB Hysol 9539.3 NA Adhesive	S2/8553 Unidirectional, 30 ply Autoclave, 350 F, 3 hr Cure	IM7/PEI 3mm unidirectional prepreg tape	Visual (monoscope) & TDR	3
Resin DCB SC 79 Resin	8 layers S2 glass fabric, 24 oz/yd^2, SC 79 epoxy resin VARTM process, 250 F post cure 4hr	ARACON fiber tow	TDR	1

Materials

DCB specimens were prepared in accordance with ASTM D5528-94a. The initial delamination was made by insertion of a 50 micron thick Kapton film between the two adherends in the adhesive case and at the mid-plane of the laminate for the resin case. Specimens were manufactured as listed in Table 1. Aluminum cubes (25mm by 25mm) were then bonded to each side of the specimen where the initial delamination was made. An overnight room-temperature cure adhesive was used for this operation. The edge of the specimens were then painted white with enamel and marked at 5mm intervals for visual monitoring of the crack length during the test, except for the Resin DCB test which only had the TDR sensor.

TDR Sensor Description

A TDR sensor for crack propagation detection consists of a signal line and ground plane straddling the crack plane (Figure 2). Two sensor types were evaluated: a 3 mm wide carbon fiber thermoplastic prepreg tape (IM7/PEI) and conductive Kevlar (ARACON) tow. In the Adhesive DCB test, the carbon tape was placed axially down the center of each coupon location in the laminate, between the 15th and 16th plys (center of the coupon). In the Resin DCB test, the ARACON tow was placed one (1) layer below the top surface for the signal line and one (1) layer from the bottom surface for the ground plane, in the 8-layer fabric laminate. The TDR pulse was injected into the composite specimen via a flexible 1mm diameter copper clad transmission line. The termination of the conductive fiber lines were crimped with a small copper ring and a SMA type connector was attached by solder.

Test Method and Data Acquisition

The specimens were mounted in a fixture to load the end blocks (Instron 4484 static load frame) and the end of the specimens was supported in order to keep the beam orthogonal to the direction of the applied load. The load and ram displacement were recorded. The crosshead speed was 0.01mm/min for the loading cycle. Crack propagation as a function of distance was monitored using the conductive fiber transmission line and compared to results of visual observation using a traveling microscope.

Crack propagation was observed by microscope at 12 marks each 5 mm apart on the bondline. The time at which the crack passed each mark was noted and recorded with the TDR record number at that time. Crosshead speeds of 0.01mm/min and 0.05mm/min were used during the loading and the unloading cycles, respectively. The load and displacement data were noted for crack growth measured every 1 mm from the tip of the insert, for the first 40mm, then every 5mm for a total length of about 60mm. The crack length was measured along the edge of the specimen with a traveling microscope. The specimens were not pre-cracked, and the initiation and propagation values were determined in one loading-unloading cycle.

The equipment used for recording data from the TDR sensor was an Agilent Technologies HP54750 digitizing oscilloscope with a 54754A differential TDR plug-in. This equipment has a 10ps/cm maximum sweep speed and a 18 GHz input bandwidth, with a 35 ps risetime step applied internally across the input. Each TDR scan had 4096 points per scan, which essentially means that the sensor length can be resolved into 4096 points. This represents the highest resolution of the oscilloscope. Scan rate was performed at 1 Hz or one scan per second and is a function of the hardware capability. Higher scan rates can be achieved using a pc-card based system or improved data handling in the scope. In order to reduce noise and improve signal characteristics, averaging was performed on each set of 16 scans, to provide a single data point. This averaging technique resulted in approximately 200-270 data points (crack locations) per DCB test. Reduced averaging can increase the number of data points significantly, to well over 1000 data points per test which is much higher than is possible with any current sensor.

RESULTS AND DISCUSSION

Crack propagation Measurements for adhesive DCB

A typical measured signal sequence from the TDR sensor during the DCB test is shown in **Error! Reference source not found.**. The initial baseline before loading is the reference, and shows the usual signal injection on the left and open-circuit reflection on the right. As loading begins the signal rises from this initial baseline on the right, as the signal-ground spacing and impedance increases toward the loaded end of the coupon. The position along the time axis at which this initial rise occurs is a function of crack propagation, and moves to the left along the time axis as the crack propagates to the left. The propagation can be quantified by setting a threshold for the vertical signal increase and picking off the delay at which this threshold is exceeded. A threshold of 5% deviation was selected to minimize noise and the appropriate delay times determined.

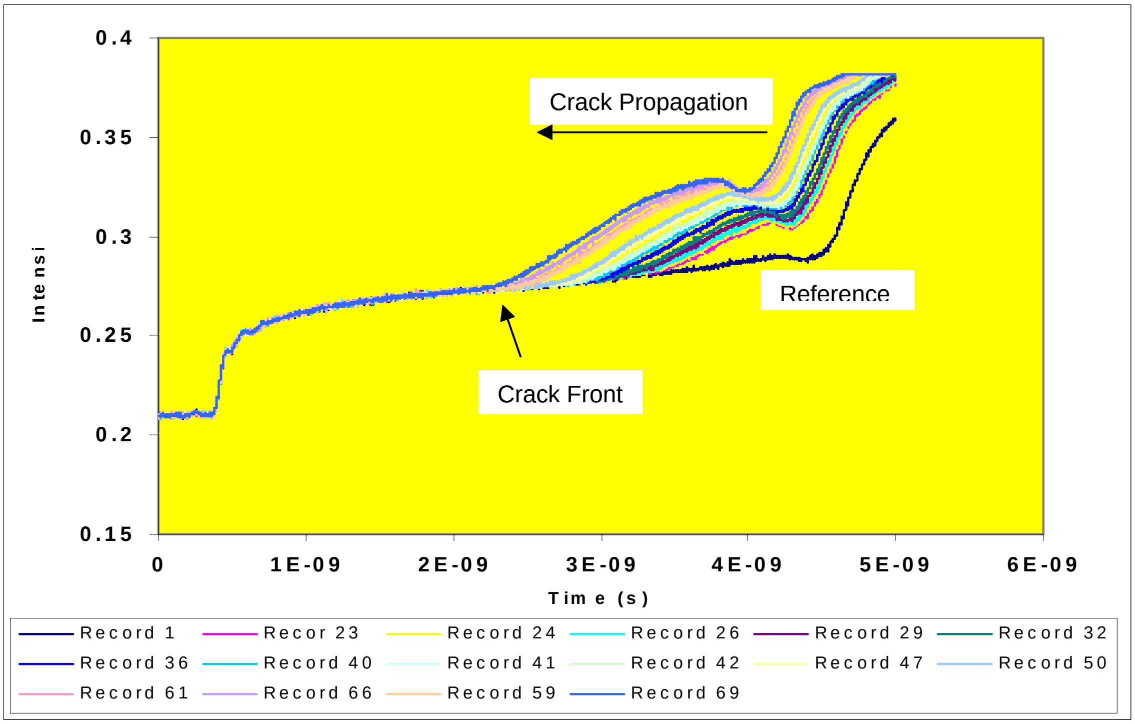

Figure 4 Typical TDR Measurement Sequence showing Crack Front Movement

A comparison of the visual crack location and the location as measured by the TDR sensor is shown in Table 2. For all three specimens, the correlation between the TDR measurement of crack location and the visual measurement is excellent with some variations in isolated instances, which may in fact be due to error during visual measurements. Given the excellent correlation between visual and TDR crack propagation measurements, similar correlation is expected in the fracture toughness calculation.

Table 2 - Crack Propagation Measurement during DCB Test I

Specimen 1		**Specimen 2**		**Specimen 3**	
TDR (mm)	Visual (mm)	TDR (mm)	Visual (mm)	TDR (mm)	Visual (mm)
0.00	0	0	0	0	0
0.38	1	0.8	1	0.8	1
1.82	2	2.9	3	2.23	2
4.70	4	4.4	4	3.66	4
5.42	5	7.9	8	6.52	7
7.58	7	9.4	9	14.38	15
14.78	15	10.1	10	20.10	20
19.82	20	15.1	15	24.39	25
25.58	25	19.4	20	30.11	30
29.90	30	24.4	25	32.97	35
34.22	35	28.0	30	40.12	45
41.42	40	33.0	35	48.70	50
56.54	55	39.41	40	52.28	55
59.42	60	44.41	45	60.14	60
65.18	65	47.99	50	65.15	65
68.06	70	53.71	55	70.15	70

The mode I critical fracture energy, G_{IC}, was calculated from:

$$G_{IC} = \frac{3P\delta}{2B(a+\chi_I)}\frac{F}{N} \qquad (1)$$

where the expressions for χ_I, F and N may be found in [9].

As expected, the calculated G_{IC} curve for both measurement techniques is identical (Figure 5) for Specimen 1, given the similarity in crack locations for both methods. Specimens 2 and 3 also show similar results. During the three tests, TDR sensor data was only recorded for the same time steps as visual recording for comparison purposes. However, as described previously, the TDR sensor is capable of significantly higher resolution in terms of crack front movement.

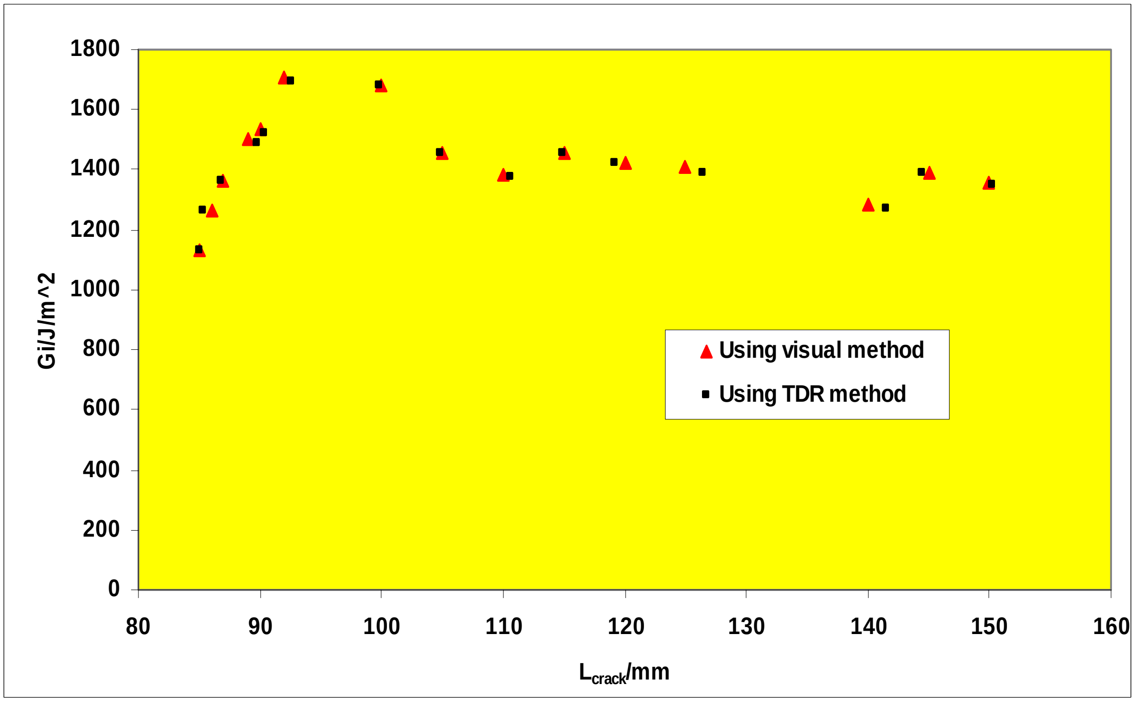

Figure 5 Calculated Fracture Resistance Curves comparing TDR and Visual Methods

Crack Propagation Measurement for "Blind" Test

In this test, crack growth in the DCB specimen was measured using the TDR sensor, at high resolution. The sensor geometry and location was similar to the previous case, with the signal and ground lines straddling the crack plane. Measured crack front movement is shown in Figure 6. As described previously, the TDR sensor is capable of high resolution measurement of crack front movement in the specimen compared to the visual method. In the visual method, a total of fifteen (15) crack locations are monitored, where as in the TDR method 260 crack locations are automatically measured. This can be further increased by reducing the averaging during TDR data acquisition, however a corresponding increase in noise can be expected.

It is also interesting to note that the TDR method has enough resolution to track the stick-slip behavior that is characteristic of fabric-reinforced composites. Further refinements in both the data acquisition strategy, averaging and sensor optimization can lead to more accurate measurements for tracking stick-slip behavior. Figure 7 shows the calculated fracture resistance curve for the specimen, which also has higher resolution (23 data points) compared to the visual method (15 data points). For this test, specimen preparation was relatively simple, with the sensors embedded in the composite during fabrication. Preparation for DCB test involves connecting the signal and ground lines to the TDR system. Care is required during this process, due to the high-frequency electronics involved and possible electrostatic discharge (ESD) problems that can damage the electronics.

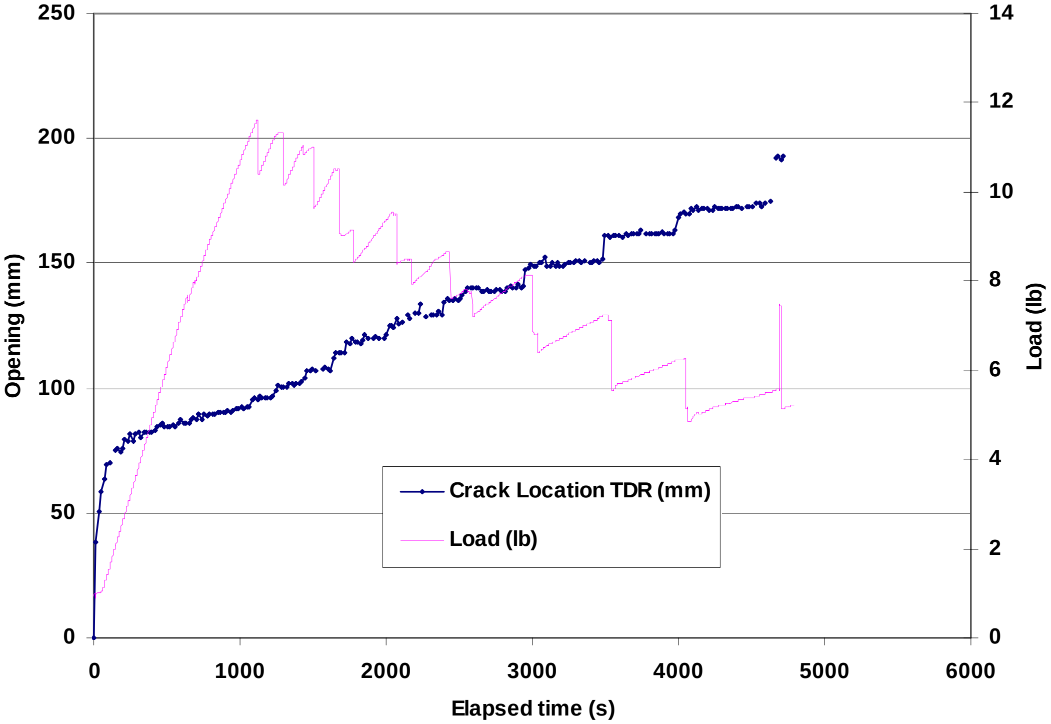

Figure 6 High-Resolution TDR Measurement of Crack Location during Mode I DCB

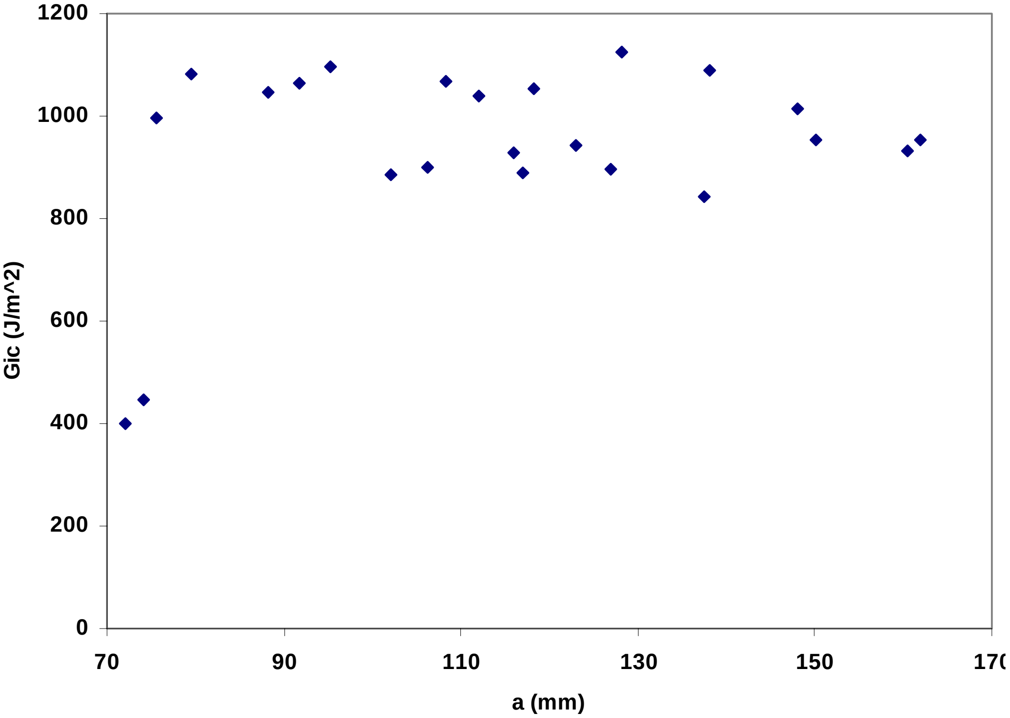

Figure 7 Calculated Fracture Resistance Curve with Higher Resolution compared to Visual

In summary, the TDR method has the ability to measure crack propagation rate and location using a single non-intrusive (conductive fiber) low-cost sensor at high resolution and accuracy. The entire measurement process can be fully automated to show load-crack growth during the DCB test. TDR sensors can also monitor stick-slip behavior that is characteristic of composite materials. One can also envision multiple TDR sensors in a single DCB test to monitor the shape of the crack front, as the assumption during testing is that of a uniform crack front movement. The proposed method can be applied to all non-conducting materials – plastics, ceramics and composites. In the case of electrically conductive systems, especially with carbon fiber reinforcement, the proposed method needs to be modified to account for material conductivity and is a topic of current research. The automation and ease of sensor installation and setup allow the proposed technique to be used in extreme environments – temperature, humidity, corrosive etc. Demonstrations of the TDR method for hot-wet fracture toughness measurement and elevated temperatures for resins such as BMI's and polyimides are in progress.

CONCLUSIONS

A Time-Domain Reflectometry based low-cost, in-situ and non-intrusive solution has been demonstrated for crack detection and propagation measurements during Mode I DCB testing of composite structures. The TDR technique detects change in geometry or electromagnetic properties along a transmission line that can be embedded in or bonded to a material or structure. Crack initiation and propagation cause gross changes in these properties and hence are easily detected, with high resolution. The proposed method has the potential to detect the development and propagation of cracks during the test, regardless of temperature, humidity and other external conditions. It is a fully automated crack sensor with no visual observation required as in current techniques.

The proposed methodology could also be adapted for Mode II, Mode III and mixed Mode fracture tests, as well as real time crack detection and monitoring in materials and structures. The TDR technique also has significant capabilities in the structural health monitoring field. Since this method does not require visual access, hard to reach zones in composite structures can be monitored easily with this technique. The sensor has been successfully used to monitor the manufacture and cure of composite structures and can later be used for health monitoring, providing a cradle-to-grave capability unlike any other system.

ACKNOWLEDGEMENTS

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REFERENCES

1. ASTM D5528 Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Composites.

2. Uhlig, C.; Kahle, O.; Wieneke, B.; Bauer, M , Optical Crack Tracing – A New Method for the Automatic Determination of Fracture Toughness for Crack Initiation and Propagation, International Conference and Poster Exhibition MicroMat 2000, Berlin, April 2000, p.618-629.

3. http://www.lavision.de/products/systems/opticalcracktracer/index.htm

4. http://www.rumul.ch/240_e_fractomat.htm

5. http://www.vishay.com/brands/measurements_group/guide/500/lists/cpg_list.htm

6. "Time Domain Reflectometry Clearinghouse": http://iti.acns.nwu.edu/clear/tdr

7. Crane, R.M., Gillespie Jr. J. W., Heider, D., Yarlagadda, S., Advani, S. G., "Intelligent Processing and Inspection of Composite Materials for Naval Structures," AMPTIAC Quarterly, Vol. 7, No. 3, 2003.

8. Bardis, J. D., and Kedward, K. T., "Effects of Surface Preparation on Long Term Durability of Composite Adhesive Bonds," FAA Technical Report DOT/FAR/AR-01/8, April 2001. http://www.infernolab.com/txt/faa_tech_report_2000.pdf

9. Williams, J.G. (1989). Fracture Mechanics of Anisotropic Materials, In: K Friedrich (ed.), In: Application of Fracture Mechanics to Composite Materials, pp. 3–38. Elsevier, The Netherlands