A TIME DOMAIN REFLECTOMETRY (TDR) BASED METHOD FOR MEASURING MODE I FRACTURE TOUGHNESS OF POLYMER COMPOSITES

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Introduction

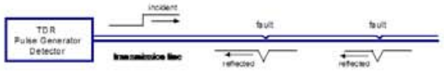
- Interlaminar fracture toughness (G_{IC}) of polymer composites can be measured using the double cantilever beam (DCB) method in accordance with ASTM standard "D5528-94a".
- In this test, the crack length propagation and the time at which the crack propagation occurs are recorded using optical techniques, usually with a traveling microscope.
- The accuracy of optical techniques is limited by the expertise of the technician. The current test method requires the investment of significant time by the technician
- There is a need for an automated system that can monitor crack propagation during the DCB test and generate load-crack propagation plots.

Objective

Develop a time domain reflectometry (TDR) based automated test method for measuring Mode I fracture toughness (G_{IC}) of polymer composites.

Time-Domain Reflectometry

Time-Domain Reflectometry (TDR) is a method of sending a fast pulse down a controlled-impedance transmission line, and detecting reflections returning from impedance discontinuities along the line.



- Time scales are fast, so reflections occurring at different positions in the line are separated by time-of-flight, forming a "closed-circuit radar".
- The transmission line is typically an electrically conductive material such as copper wire or graphite fibers.
- Crack propagation during a DCB test can be measured using this technique. In this method the time shift (Δt) of the electromagnetic signal (EM) due to the crack propagation is monitored. Δt can be measured based on a reference signal (when the applied load is zero). The crack length L_{Crac} will be simply taken as $V^*(\Delta t/2)$, where V is the speed of the signal in the sensor material (Figure 1).

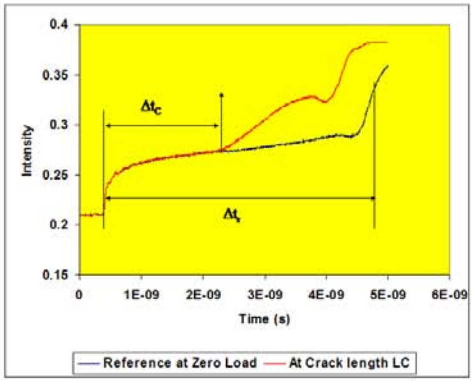


Figure 1: TDR signals at zero applied load to the specimen and at a specific crack length LC

DCB Demonstration

- The TDR-based automated system was used to measure Mode I fracture toughness of Hysol 9359 adhesive.
- Substrate coupons were fabricated using S2/8553 glass epoxy prepreg with IM7/PEI carbon fiber prepreg strips serving as the sensing lines for TDR.
- Specimen preparation followed ASTM standard D5528-94a
- All the DCB-measurements were performed on a universal Instron machine using a cross-head speed of 0.05 in/min (Figure 2).
- The crack propagation was measured using both optical microscope and TDR technique for comparison.

DCB Experimental Set-Up

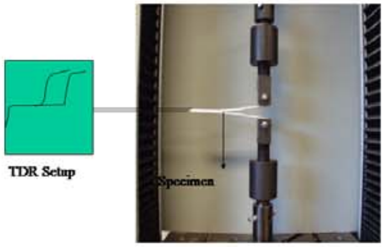


Figure 2: DCB test setup

Results

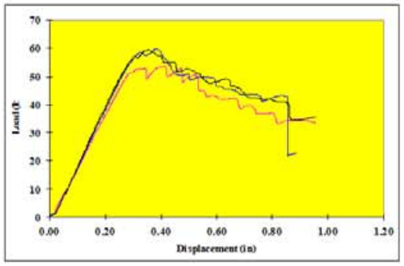


Figure 3: Load-displacement curves for the DCB specimens

TDR-Records for Specimen#1

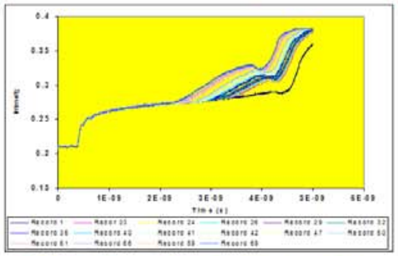


Figure 4: TDR signals for DCB specimen #1. This figure shows a signal shift on the time scale from the reference signal (Record 1) due to the crack propagation. Record 23 corresponds to the initial crack length in the specimen. The speed of signal $V=1.44\times10^8$ m/s.

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TDR-Records for Specimen#2

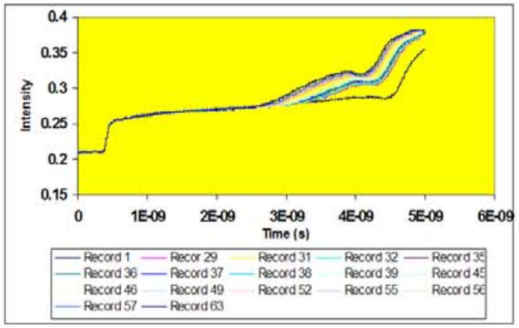

Figure 5: TDR signals for DCB specimen #2. This figure shows a signal shift on the time scale from the reference signal (Record 1) due to the crack propagation. Record 29 corresponds to the initial crack length in the specimen. The speed of the signal V=1.43×10⁸ m/s.

TDR-Records for Specimen#3

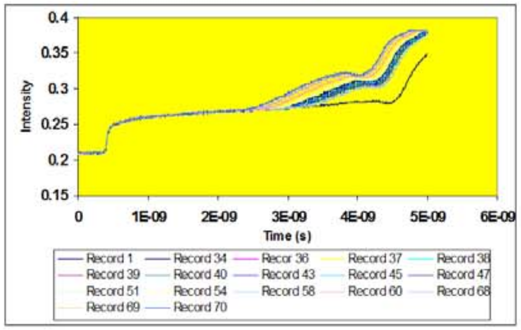

Figure 6: TDR signals for DCB specimen #3. This figure shows a signal shift on the time scale- from the reference signal (Record 1) due to the crack propagation. Record 34 corresponds to the initial crack length in the specimen. The speed of the signal V=1.43×10⁸ m/s.

Data Reduction Methodology

For each sample the crack length was measured as follows:

The speed of the signal (V) was calculated as:

Total Sensor length (Carbon Strip) (L) = $V^*\Delta t_r/2$ (1)

The length of the specimen was equal to length of the sensor.

At any new crack propagation L_C the length of of the specimen can be given as:

$$L_C = V^*\Delta t_C/2 \qquad (2)$$

Hence, the crack propagation length L_{crack}

$$L_{crack} = L - L_C \qquad (3)$$

The interlaminar fracture toughness (G_I) values were calculated using compliance calibration method (CC Method) which is given as:

$$G_I = n^* \delta\, ^*P/2^*b^*\, L_{crac} \qquad (4)$$

where P is the applied load, δ is load point displacement, L_{crac} is the crack length and b is the width of the specimen. n is the slope of the plot: log C-log(L_{crac}) , where C is the compliance and equals to δ/P.

Crack Length Comparison

Specimen#1

TDR (mm)	Optical (mm)
0.00	0
0.38	1
1.82	2
4.70	4
5.42	5
7.58	7
14.78	15
19.82	20
25.58	25
29.90	30
34.22	35
41.42	40
56.54	55
59.42	60
65.18	65
68.06	70

Specimen#2

TDR (mm)	Optical (mm)
0	0
0.8	1
2.9	3
4.4	4
7.9	8
9.4	9
10.1	10
15.1	15
19.4	20
24.4	25
28.0	30
33.0	35
39.406	40
44.411	45
47.906	50
53.706	55

Specimen#3

TDR (mm)	Optical (mm)
0	0
0.796	1
2.226	2
3.656	4
6.516	7
14.381	15
20.101	20
24.391	25
30.111	30
32.971	35
40.121	45
48.701	50
52.276	55
60.141	60
65.146	65
70.161	70

Data Reduction

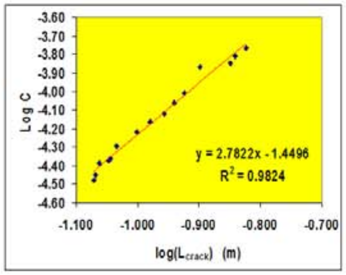

Figure 7: The slope values were used in Equation (4) for calculating interlaminar fracture toughness (GI) (Figure 6).

Fracture Toughness

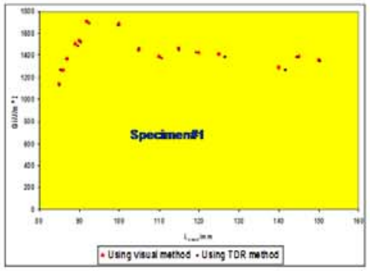

Figure 8: Calculated resistance fracture curves measured for DCB specimens using the crack length values obtained by TDR and visual techniques.

Conclusion

- **The TDR technique has been successfully used to automate crack propagation measurement in Mode I DCB testing of polymer adhesives.**
- **The carbon fibers as strips can be used as TDR sensor for measuring the fracture properties of the composite.**
- **The technique provides an easy approach to automating fracture toughness measurements of polymers.**
- **The technique can also be applied to DCB testing of polymer composites based on non-conductive fibers (glass and Kevlar).**

Acknowledgements

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