2D DISTRIBUTED SENSING VIA TIME DOMAIN REFLECTOMETRY (TDR)

A. Dominauskas, D. Heider, and J. W. Gillespie, Jr.

University of Delaware • Center for Composite Materials

RELEVANCE

Sensors are needed for processing QA/QC and for health monitoring:

- Flow front detection,
- Cure behavior,
- Defect detection,
- Process strain,
- Service related strain.

In the last decade, various research programs have been conducted to develop flow, cure and strain monitoring sensor systems.

ADVANTAGES OF TDR SENSORS

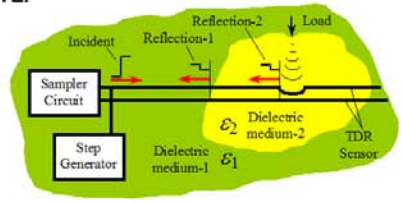
TDR sensors have the following *advantages* over other sensor types (DC resistance, AC Dielectric, optic fiber, ultrasonic, etc.) :

- Low cost,
- Tool-mounted and embedded configurations,
- High accuracy (3mm),
- **Multifunctional sensing,**
  - Resin flow behavior,
  - Cure,
  - In-service strain response,
- Distributed 2D sensing.

TDR sensors completely fulfill the requirements for next-generation sensors!

TDR METHOD FOR SENSING TL DISCONTINUITIES

Time domain reflectometry (TDR) is a method of sending high-rise (35ps) voltage step-pulse into a transmission line (TL), and detecting reflections returning from impedance discontinuities within the TL.



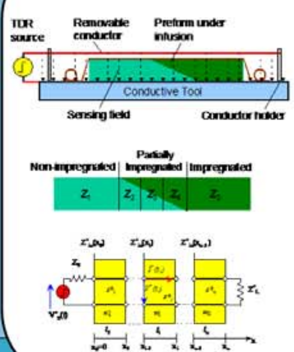
- Any dielectric and/or geometrical discontinuities in the TL changes the characteristic impedance, and introduces a voltage reflection at a particular time and magnitude.

HARDWARE AND SOFTWARE

- HP54750A (18GHz bandwidth) oscilloscope
- GPIB interface.
- DAQ software written in LabVIEW.
- Developed Multi-section TL-sensor modeling software.

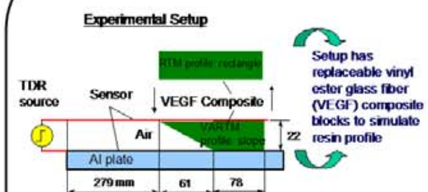
Various TDR sensors

VISION: NON-CONTACT 2D SENSING



- VARTM set-up constructed within TL can be sensed by its EM field: 2D flow, curing and process strain.
- 2D Flow reconstruction uses combined (effective) dielectric behavior of several materials.
- It affects the TDR response and can be modeled as a non-uniform TL with multiple uniform sections.

EXPERIMENTAL SET-UP



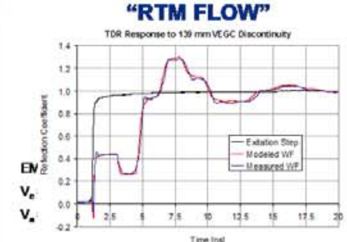
Setup has replaceable vinyl ester glass fiber (VEGF) composite blocks to simulate resin profile

Goals:

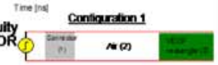
- Prove 2D measurement concept;
- Establish measurement algorithms;
- Model comparison.

- Multi-section TL program have been developed based on scatter function and Debeye relaxation models.

MODEL VALIDATION "RTM FLOW"

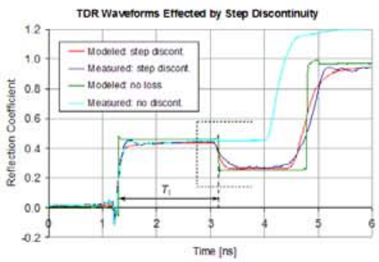


- 139 mm VEGF discontinuity shows clear change in TDR waveforms (WF).



- Model fits the measured WF well showing attenuating successive reflections.
- Minor mismatches are related with connector effects on WF scattering.

TDR WAVEFORM DISTORTIONS



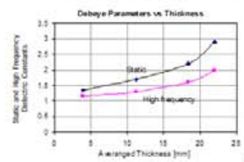
WF "softening" is a function of:

- excitation step rise time (47ps);
- dielectric loss; and
- relaxation frequency.

- Measured TDR WF have finite rise and fall times;
- Fall times and rise times introduces errors in calculation of locations.
- Only the physical model of TL can generate zero loss and zero rise time WF's.
- Superposition of such WF's to the measured WF's determines exact discontinuity location.

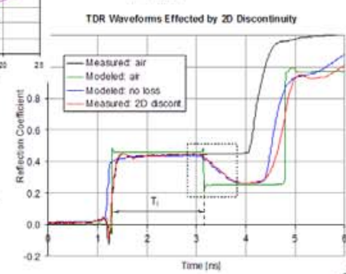
TDR RESPONSE TO THE "VARTM PROFILE"

Configuration 3

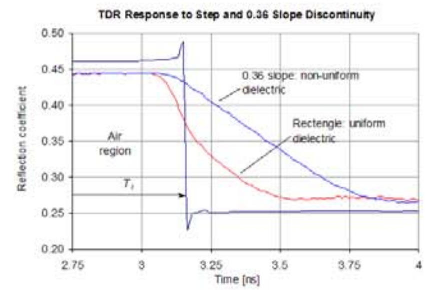


- The model with 6 TL sections was in good agreement with the experimental validations of the VEGF block which has 20° slope (0.36).
- Based on measurements only is difficulty to exact calculate slope location because of high fall time.

- Dielectric parameters ε_1, ε_2, ε_3 have been back calculated from the measured TDR-WF using a model.



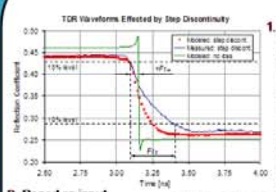
DISCONTINUITY COMPARISON



- Different discontinuities result in changing rise time .
- Response to 0.36 slope is almost linear.
- It emulates real slope.
- Model based zero loss WF can be used to accurately determine the beginning of the discontinuity:

$$L_s = 300 \times T_1/2$$

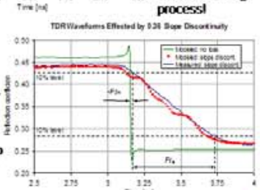
2D CALCULATION ALGORITHM



1. Empirical or model based values of Ft_m and ε_s as a function of Ft_s, material, geometry and others must be determined. Empirical method can be a very complicated and time-consuming process!
2. Based on input parameters of actual WF, algorithm determines whether is step or slope like 2D discontinuity.

If $Ft_s \approx Ft_s \Rightarrow$ step

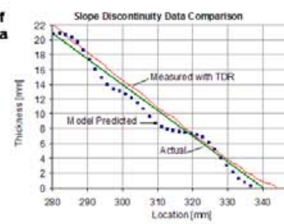
If $Ft_s > Ft_s \Rightarrow$ slope



ALGORITHM AND VALIDATION

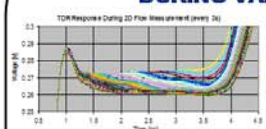
3. Based on value of Ft_m 10% level data points will be shifted towards zero loss WF.
4. 10% level data points will be multiplied by averaged "slope" speed V_s = 231.3mm/ns and divided by two:

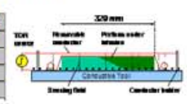
$$V_s = V_o \times \sqrt{\frac{1}{(\varepsilon_1 + \varepsilon_2 + \varepsilon_3)/3}}$$



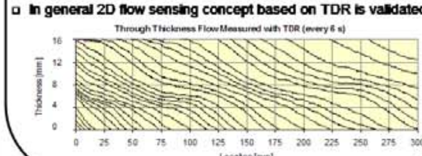
- Agreement of all three types of data proves 2D TDR measurement concept.
- Measured and model predicted slope fit actual slope very well showing accuracy of 3 mm.

2D FLOW MEASUREMENT DURING VARTM





- Good sensor response - 14 mV;
- Sensor conductor was 3 mm above the preform;
- Results are similar to the validation results;
- In general 2D flow sensing concept based on TDR is validated.



CONCLUSIONS AND FUTURE WORK

TDR measures linear and through-thickness dielectric distribution:

- Modeled and measured waveforms emulate the shape of 2D discontinuity;
- Measurement accuracy of ± 3 mm can be achieved;
- Simple TDR algorithms can be applied for on-line intelligent composite processing.

Integrated tool embedded TDR sensor in VEGF mold

Future Work:

- Further development of 2D sensing capability;
- Development of TDR sensors for conductive fiber composites;
- Investigate cure sensing of different resin systems.

ACKNOWLEDGEMENTS

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