Nanotube-Reinforced Adhesives for *In situ* Damage Sensing Applications

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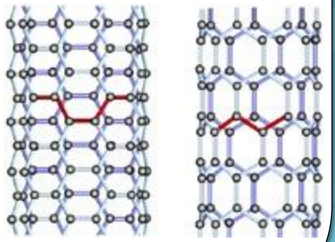
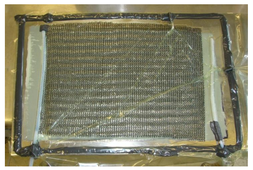
MOTIVATION

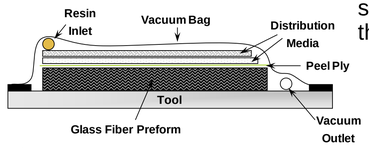
- It has been demonstrated that Carbon Nanotubes (CNT) can be utilized as sensors for detecting the onset and accumulation of micro-scale damage in composite materials *in situ*.
- The introduction of CNT into adhesives allows for the formation of a conductive network within the adhesive which can be used to monitor the health of the joint.
- Research is aimed at extending the *in situ* sensing approach to hybrid composite joints to enable real-time damage sensing and health monitoring.
- Future naval and aviation structures will require reliable hybrid mechanical joints between composite materials and metal surfaces.
- Fiber reinforced composites are being widely used within the naval and aviation industries due to their light weight, high-corrosion resistance, and high strength to weight ratio.



Carbon Nanotube Atomic Structures

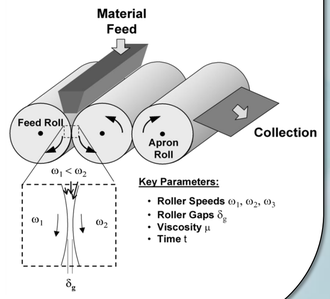
MATERIALS



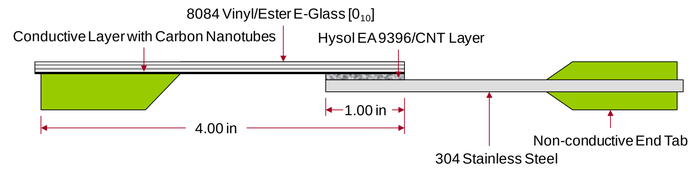


- In single lap joints, substrate refers to the material on which adhesive is applied.
- Composite substrates are manufactured using Vacuum Assisted Resin Transfer Molding (VARTM).
- Selective modification of the composite substrate enables damage sensing over the entire joint area.
- Steel substrates are prepared through abrasive and chemical methods to increase surface adhesion.
- Hysol is a commercially-available high performance adhesive widely used in the aviation industry.
- A high precision calendering mill was utilized to disperse multi-walled CNT into the viscous Hysol by shear mixing.

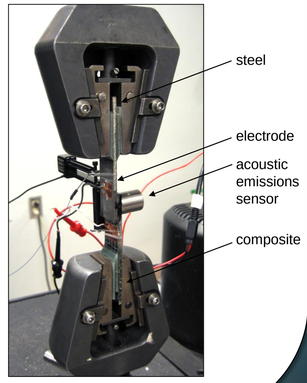
HIGH-PRECISION 3 ROLL CALENDERING



EXPERIMENTAL

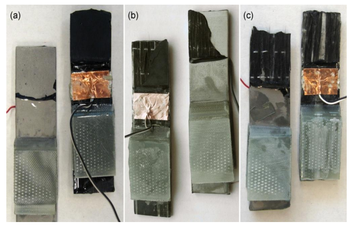


- Single Lap Shear specimens were fabricated to test the shear strength of the Hysol.
- Specimen performance is evaluated under quasi-static tension, cyclic, and fatigue loading conditions.
- Electrical, mechanical and acoustic emission data are acquired in real-time using a custom sensing and data acquisition system.
- Micro edge replication studies are conducted at various loads during cyclic experiments.

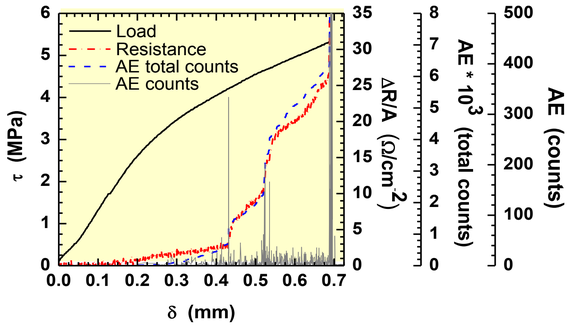


FAILURE MODES

- By selectively modifying the composite and metal substrates through chemical and abrasive methods, different types of failures in the specimens are possible.
  - (a) Adhesive Failure
  - (b) Combined Failure
  - (c) Composite Failure

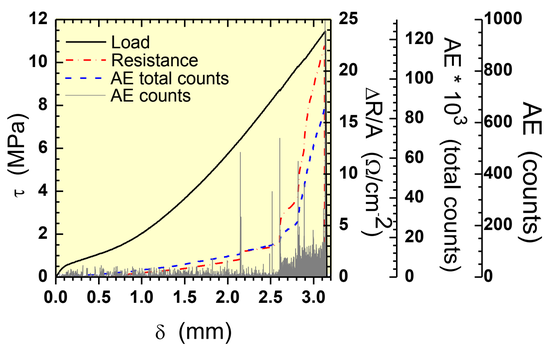


ADHESIVE FAILURE



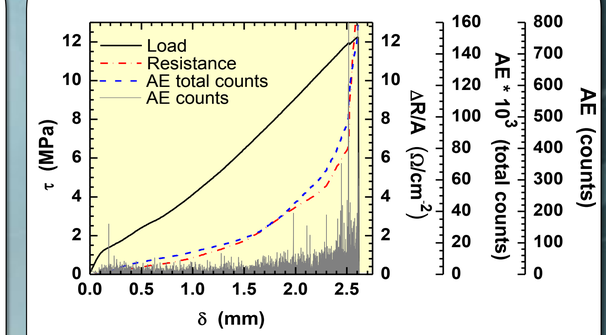
- During tensile loading, the damage in the Hysol joint is reflected in the increasing change in resistance and total Acoustic Emissions (AE) as the CNT network in the adhesive is destroyed. The jumps in damage represent debonding between the epoxy & steel.

COMPOSITE FAILURE



- Composites are processed with a high void content are used to promote composite failures. The damage sustained at higher extensions corresponds to fiber breakage and ply delamination.

COMBINED FAILURE



- Progressive damage accumulation at lower extensions suggests damage to the adhesive, while the rapid increase in damage represents damage at the composite interface.

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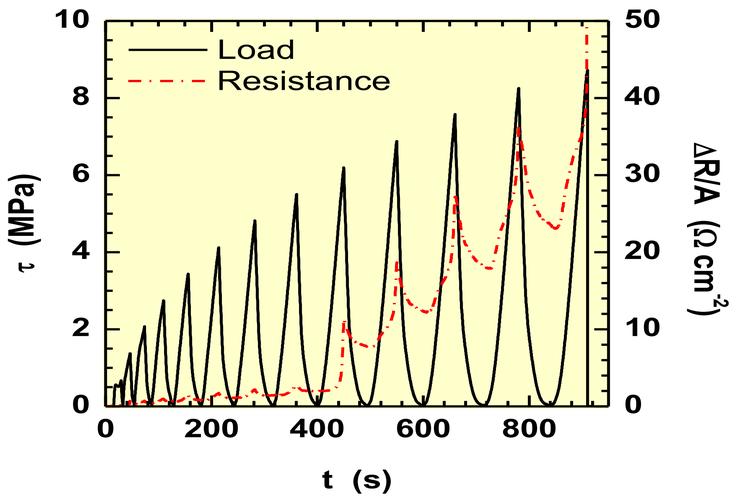
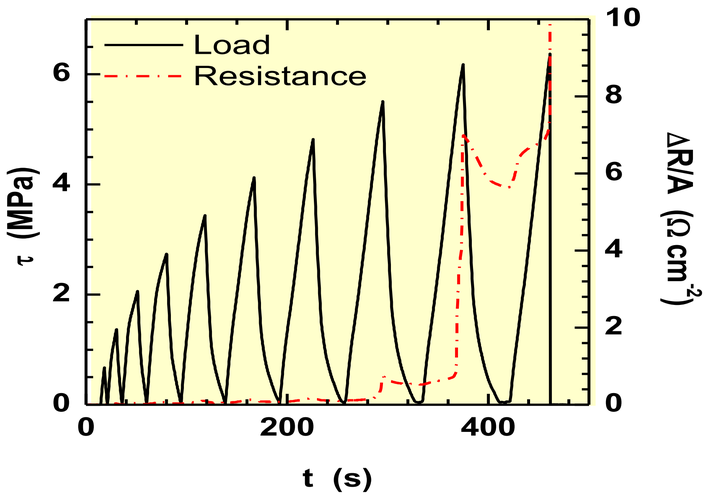
ADHESIVE FAILURE - CYCLIC



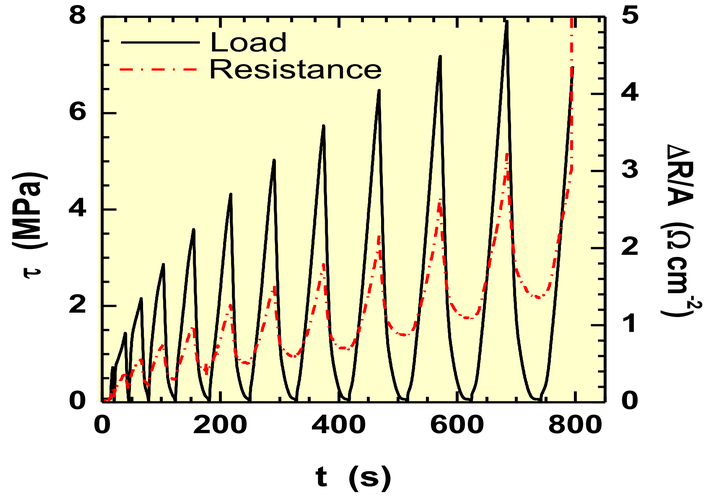
- The baseline resistance behavior is similar to that in the tensile test for this failure mechanism, with distinct regions of increased damage accumulation throughout the cycles.

COMPOSITE FAILURE - CYCLIC



- As observed in the tensile composite failure, minimal damage is sustained at lower stress levels. At stress levels prior to failure, the corresponding fiber breakage leads to rapid increases in damage.

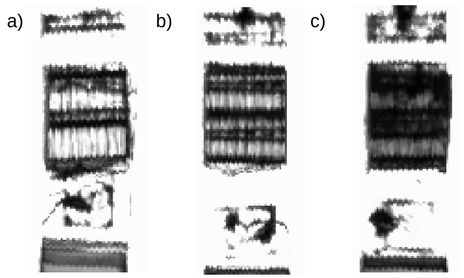
COMBINED FAILURE - CYCLIC



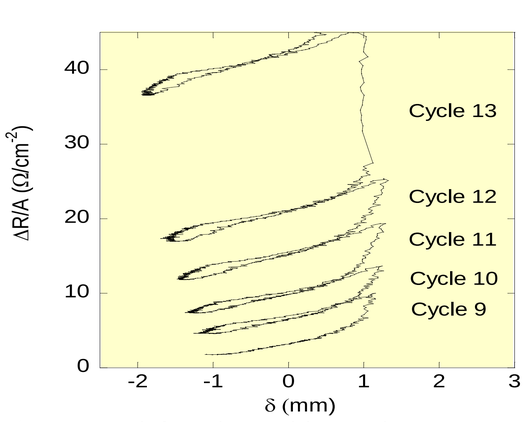
- The resistance behavior of combined failures for cyclic testing is similar to that of the tensile case, with the progressive damage accumulation throughout the test.

ULTRASONIC NDE

- C-Scan images of specimens at different loading configurations provides a means to visualize the level of damage sustained to the joints.
- Dark regions represent voids in the joint.
- In (a), horizontal dark lines represent cross-fibers binding the unidirectional glass fiber in the composite and not actual damage.

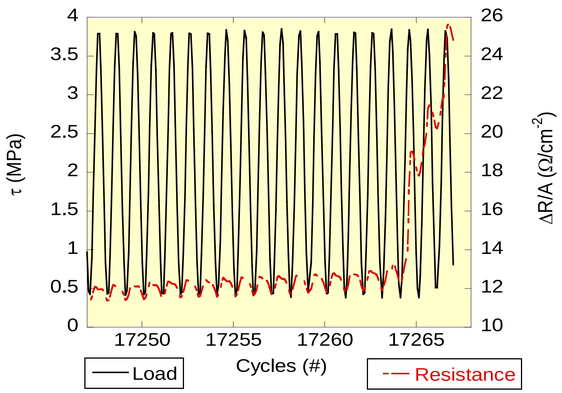


DAMAGE ACCUMULATION



- New crack formation, and hysteresis are apparent in the resistance / deformation behavior.

FATIGUE TESTING



- Specimens fatigued to failure show the sensitivity of the sensing capabilities; note the upward trend of the resistance baseline prior to failure.

FUTURE WORK

- Carbon nanotube reinforced adhesives show promise for *in situ* damage sensing of hybrid joints.
- Future work will center on manufacturing specimens to fail in a cohesive fashion.
- In order to sense cohesive failure, cracks through the bulk of the adhesives will be promoted with the addition of microspheres.
- An additional area of interest will look at the characterization of specimen failures for fatigue testing.

ACKNOWLEDGEMENTS

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