The Effect of Localized Damage on the Electrical Conductivity of Bare Carbon Fiber Tow and Its Use as a Non-Destructive Evaluation Tool for Composite Overwrapped Pressure Vessels

SLaMS Presentation

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Outline

- Goal
- Introduction
- Composite Overwrapped Pressure Vessels
- Problems
- Methods and Materials
- Results and Discussion
- Conclusions and Future Work

Goal

- Demonstrate the feasibility of performing resistance measurements in bare carbon fiber tows and identify a correlation between the percentage of surviving filaments, local changes in resistance measurements, and strength reduction.
- Develop a tool to estimate strength of carbon fiber tows from electrical resistance measurements.

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Introduction

- Composite materials are beneficial because of their high specific strength and low weight.
- Safety
  - Destructive testing and destructive testing
  - Non-Destructive Testing (NDT) and Non-Destructive Evaluation (NDE)
- Problem: Neither NDT nor NDE can provide sufficient data to determine life expectancy or quantify the damage state of a composite material.

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Introduction

- One method that has potential to do so is by monitoring the localized resistance measurement of the composite.
  - Schulte and Baron (1989)
  - Wang, X and Chung, D (1997)
  - Abry et al. (1998)
  - Park et al. (2002)
- Past research focused on single fiber and carbon fiber reinforced plastics (CFRP), and little research was done for failure prediction

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Introduction

- Why electrical resistance?
  - Carbon fiber filaments are conductive
  - The localized resistance measurement is a function of the number of filaments
  - As a whole, these filaments have a quantized resistance
- Electrical resistance measurement correlates to number of continuous filiments in the local region

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Composite Overwrapped Pressure Vessels

- "…is a combination of structural fibers and a resin that forms the overwrapped structure for a COPV. Continuous fibers provide tensile strength for structural integrity while the resin carries shear loads in the composite and maintains the fiber position."

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Composite Overwrapped Pressure Vessels

- Failure Modes

Failure Mode	Failure Result	Control Phase	Mitigation Method
Shearing of Boss	Catastrophic	Design /NDE	Statistical, NDI
Fatigue Crack Growth in Liner under Composite	Leakage	Design/NDE	Fracture Control (Safe-Life)
Crack Growth in Boss	Catastrophic	Design/NDE	Fracture Control (Safe-Life)
Over Pressurization	Catastrophic	System Design/Operations	Thermal Control and System Design
Stress-Rupture	Catastrophic	Design/Operations	Stress-Rupture Data
Corrosion/Stress-Corrosion of Liner under Composite	Catastrophic	Design/Mfg/Operations	Control of Chemical Environment
Corrosion/Stress-Corrosion of Boss	Catastrophic	Design/Mfg/Operations	Control of Chemical Environment
Embrittlement of Liner	Catastrophic	Mfg/Operations	Metallurgical Control, Control of Thermal and Chemical Environments
Corrosion of Matrix Resin or Fiber	Catastrophic	Mfg/Operations	Control of Chemical Environment
Embrittlement of Matrix Resin or Fiber	Catastrophic	Mfg/Operations	Control of Cure, Control of Thermal and Chemical Environments
Liner Buckling under Composite/fatigue	Leakage	Mfg/NDE	Adhesive Bonding Process Control, Bond-Line NDE
Impact/Mechanical Damage	Catastrophic	Mfg/NDE/Operations	Damage Control
Delamination (of mounting interface and bridging)	Catastrophic	Mfg	NDE

Courtesy of Lorie Grimes-Ledesma, Ph.D., NASA Jet Propulsion Laboratory, Pasadena, Calif.

Composite Overwrapped Pressure Vessels

- Stress Rupture
  - Conventional pressure vessels will leak before burst; however, COPVs have a tendency to burst before leak.
  - Despite years of effort, there still exist no comprehensive understanding concerning the rupture phenomena of COPVs
- Impact Damage

Composite Overwrapped Pressure Vessels

- Uses
  - Aerospace
  - Commercial Vehicles
- The increase in commercial use is dangerous because failure modes not well understood and manufacture, inspection, etc. are not as stringent as aerospace standards.

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Problems

- No method to quantify damage of composite materials
- A failure mechanism that is not understood
- Pressure to develop solutions to energy needs

The electrical resistance method can be used to correlate a change in resistance to a change in strength and can be used as a tool to predict failure.

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Methods and Materials

- Carbon Fiber
  - Hexcel® IM7 (Hexcel Corporation, Stamford, CT) continuous, Polyacrylonitrile (PAN) based, carbon fiber was used.
  - Intermediate modulus fiber and is commonly used in the production of COPVs for aerospace applications.
  - A specimen is composed of 12,000 carbon fiber filaments, and is also referred to as a tow or strand

HexTow® IM7 12 K Filament Carbon Fiber	SI Units
Diameter	5.2µm
Density	1.78 g/cm^3
Tensile Modulus	276 GPa
Tensile Strength	5,655 MPa
Electrical Resistivity	1.5 x 10^{-3} Ω-cm

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Methods and Materials

- Standards
  - ASTM D2343 “Standard Test Method for Tensile Properties of Glass Fiber Strands, Yarns, and Rovings Used in Reinforced Plastics,”
  - ASTM D4018 “Standard Test Methods for Properties of Continuous Filament Carbon and Graphite Fiber Tows.”

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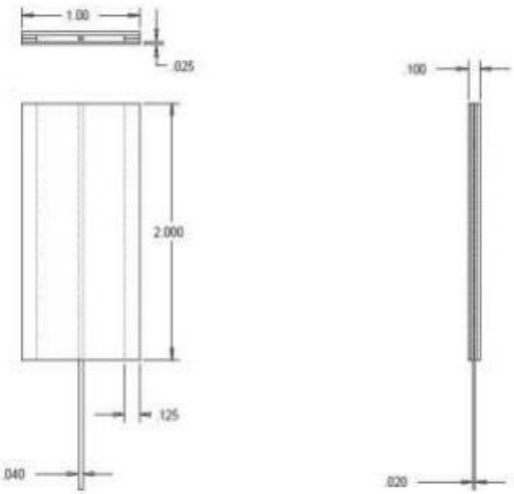
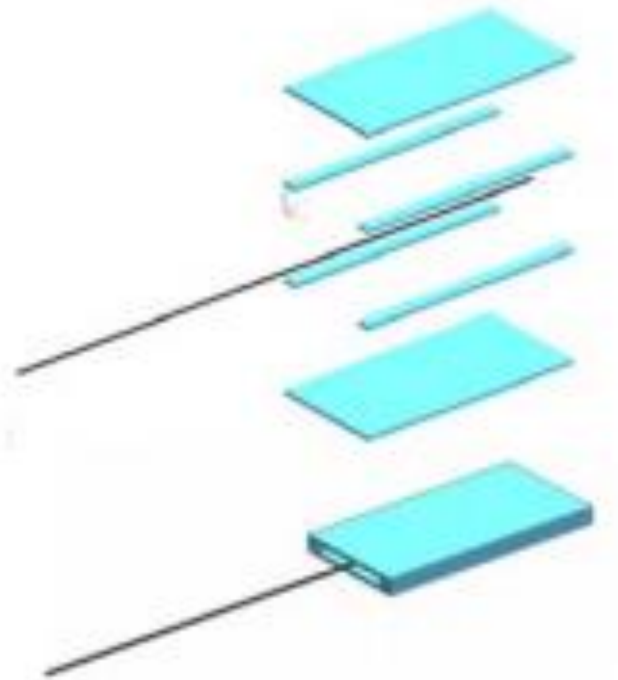
Tabbing



$$L_{min} = F^{tu}h/2F^{su}$$

where:

L_{min} = minimum required bonded tab length, mm [in.];
F^{tu} = ultimate tensile strength of coupon material, MPa [psi];
h = coupon thickness, mm [in.]; and
F^{su} = ultimate shear strength of adhesive, coupon material, or tab material (whichever is lowest), MPa [psi].



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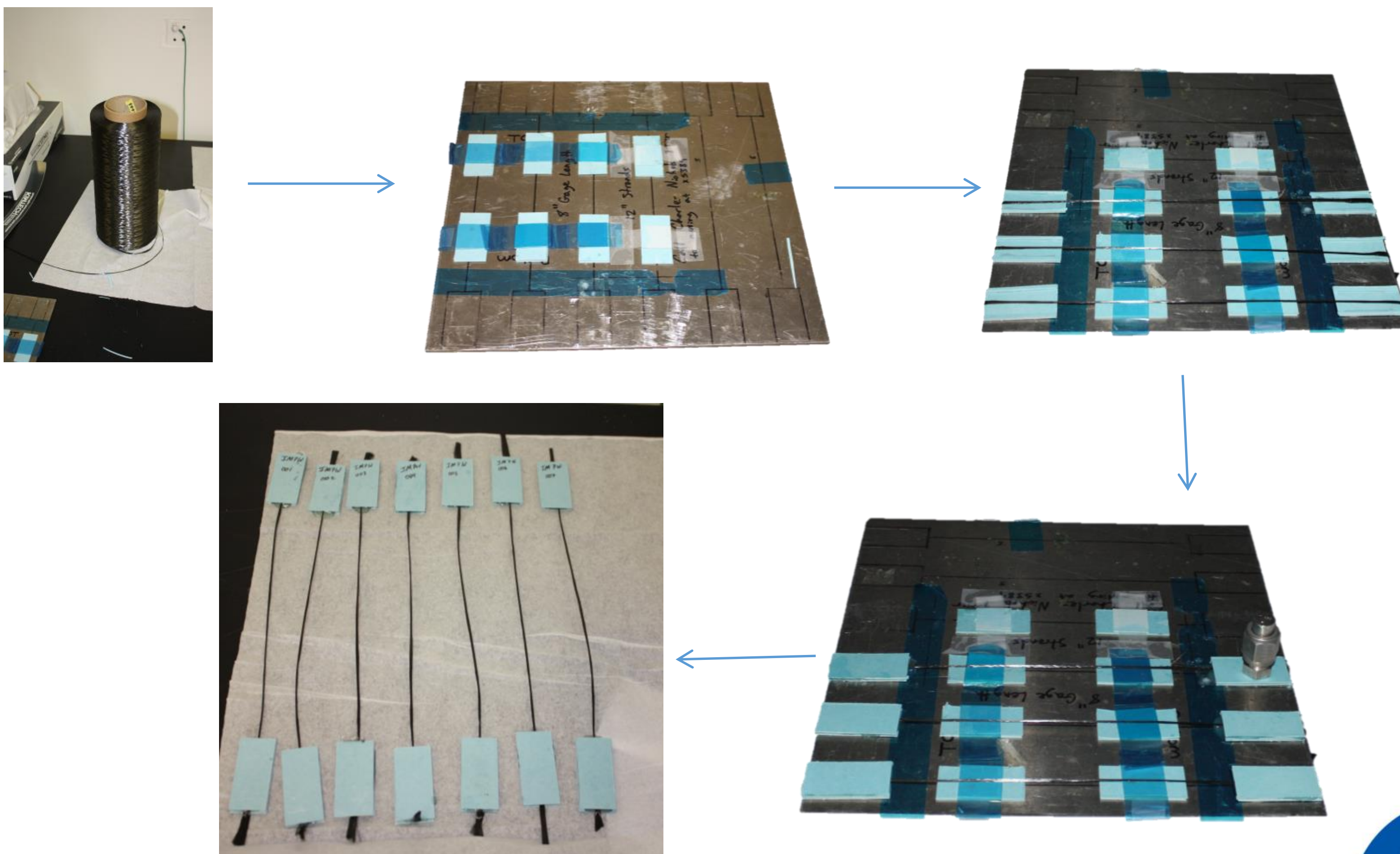
Specimen Preparation



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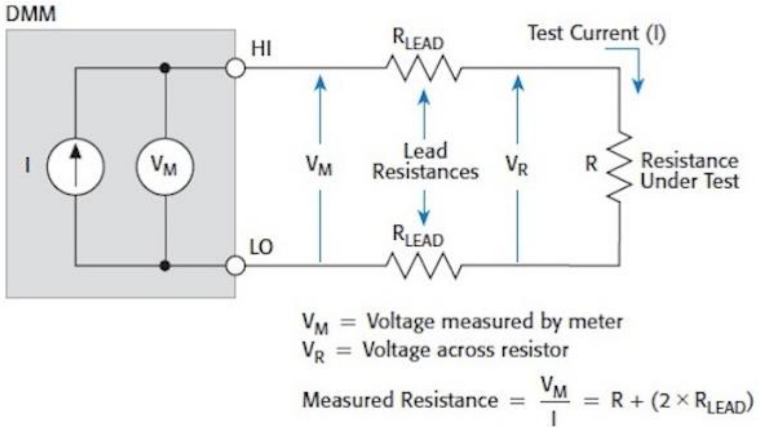
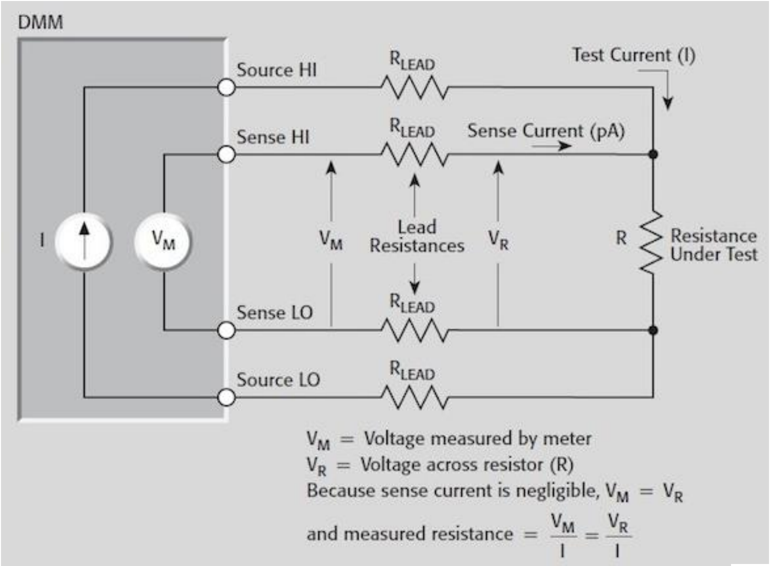
Resistance Measurement

- HP4338B milliohmmeter
- Four-Point Method was used





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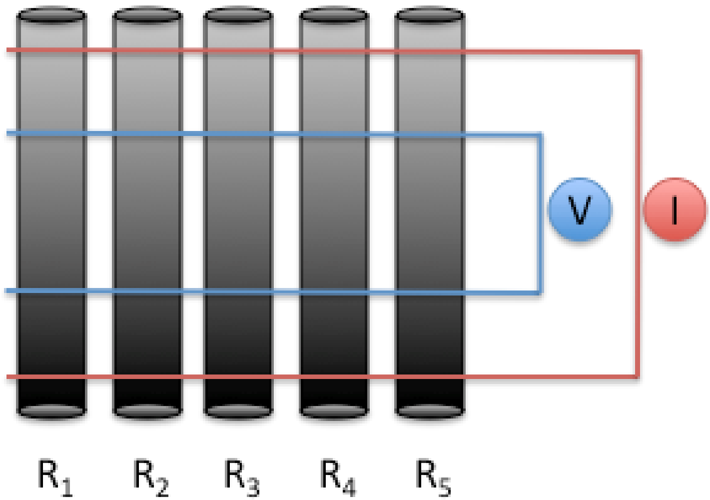
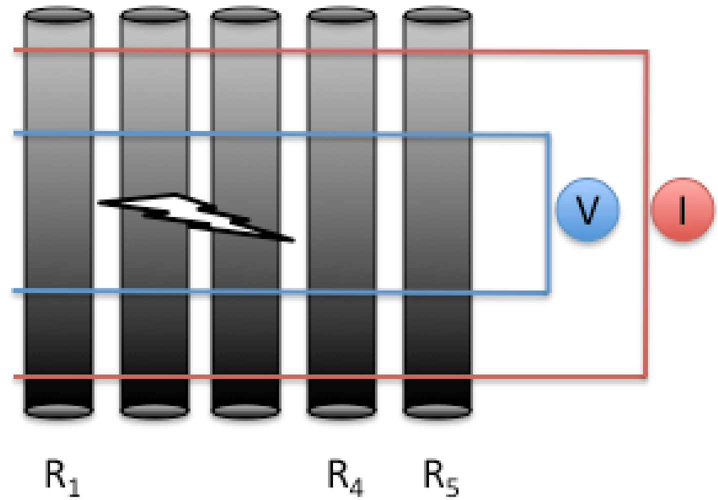
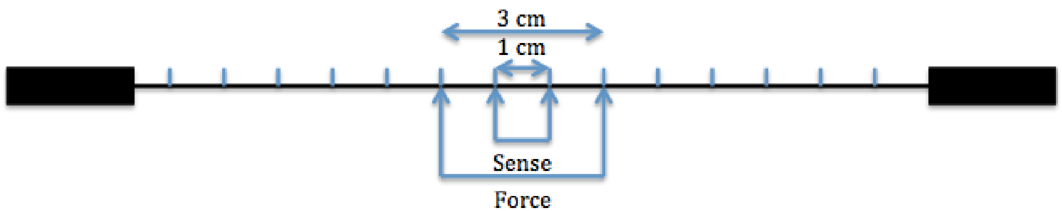
Resistance Measurement





$$I = \frac{V}{R}$$

$$1/Rtot = \sum_{1}^{n} 1/Rn$$



Experimental

- Load Profile

Step	Duration/Rate
1.) Preload (approx. 5 N)	10 minutes
2.) Ramp to 133.5 N	20 N/min
3.) Hold	10 minutes
4.) Ramp 44.5 N	20 N/min
5.) Hold	10 minutes
6.) Repeat 4.) - 5.) to failure	

This load hold profile was used in order to make measurements at various stress levels or stress ratios.

Experimental

Test apparatus showing the Instron tensile tester, miliohmmeter, and data acquisition system.

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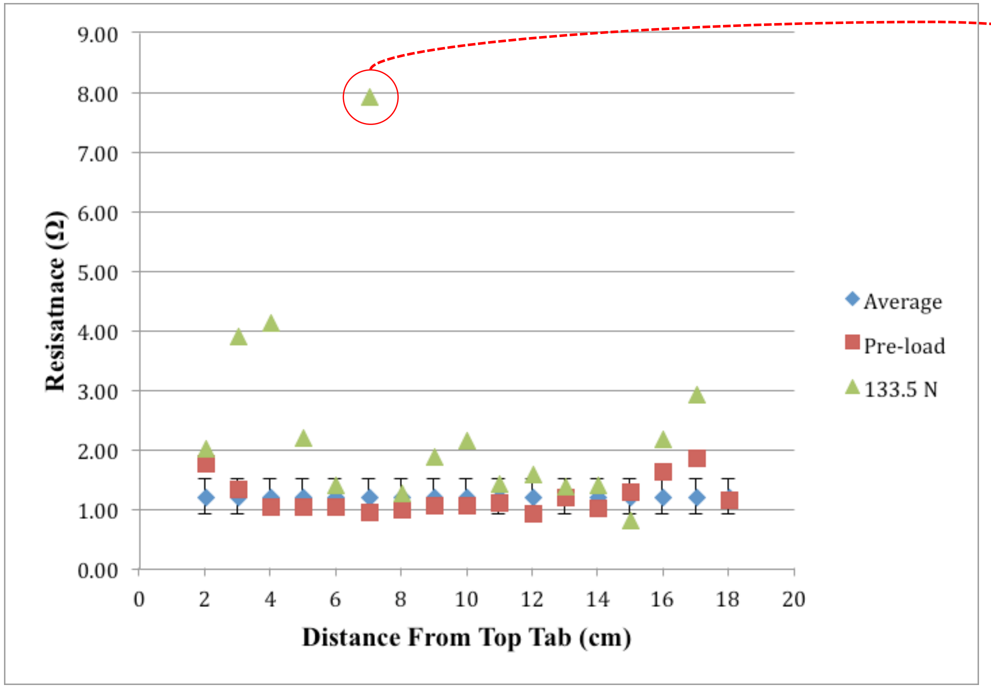
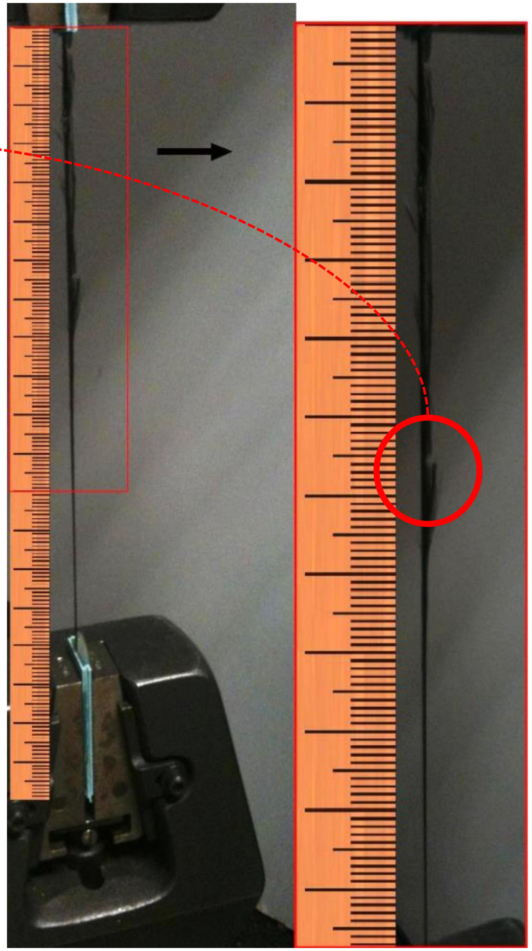
Results and Discussion

- Nine specimens were analyzed
  - 2: Ramp to failure
  - 1: 133.9 N failure
  - 3: 222.9 N failures
  - 3: 266.9 N failures
- Stress and strain data
- Resistance data

133.5 N Load Failure





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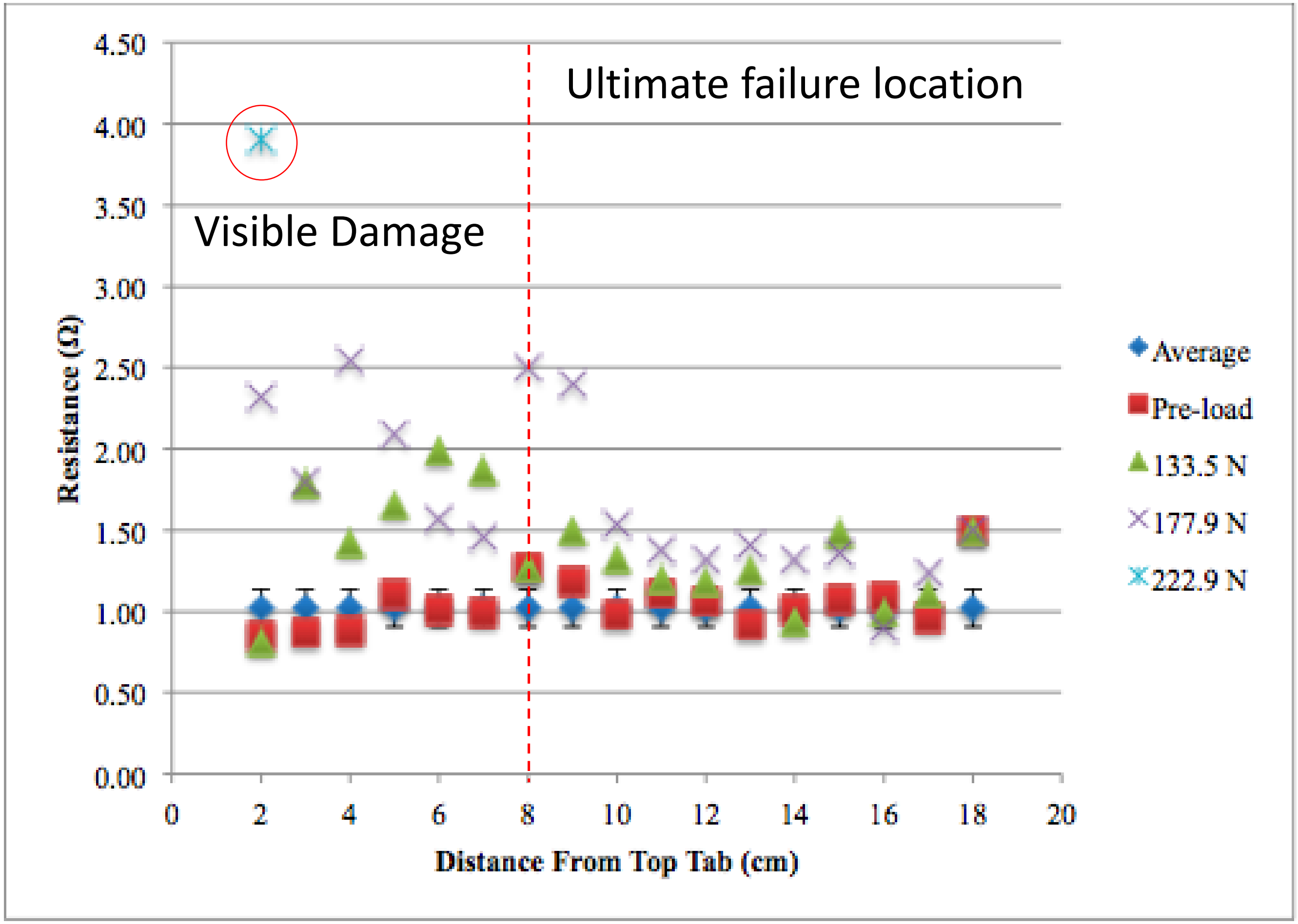
222.9 N Load Failures



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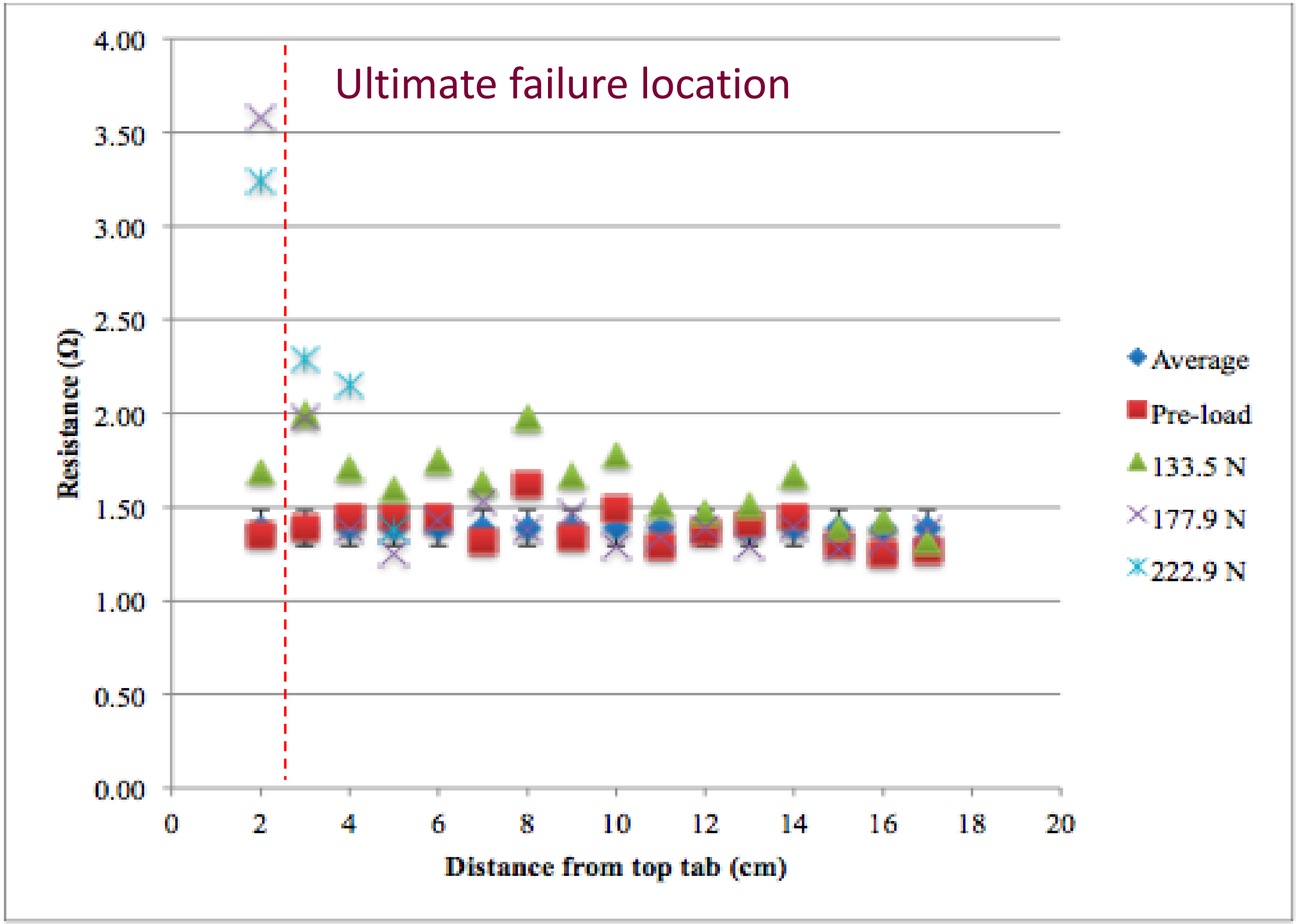
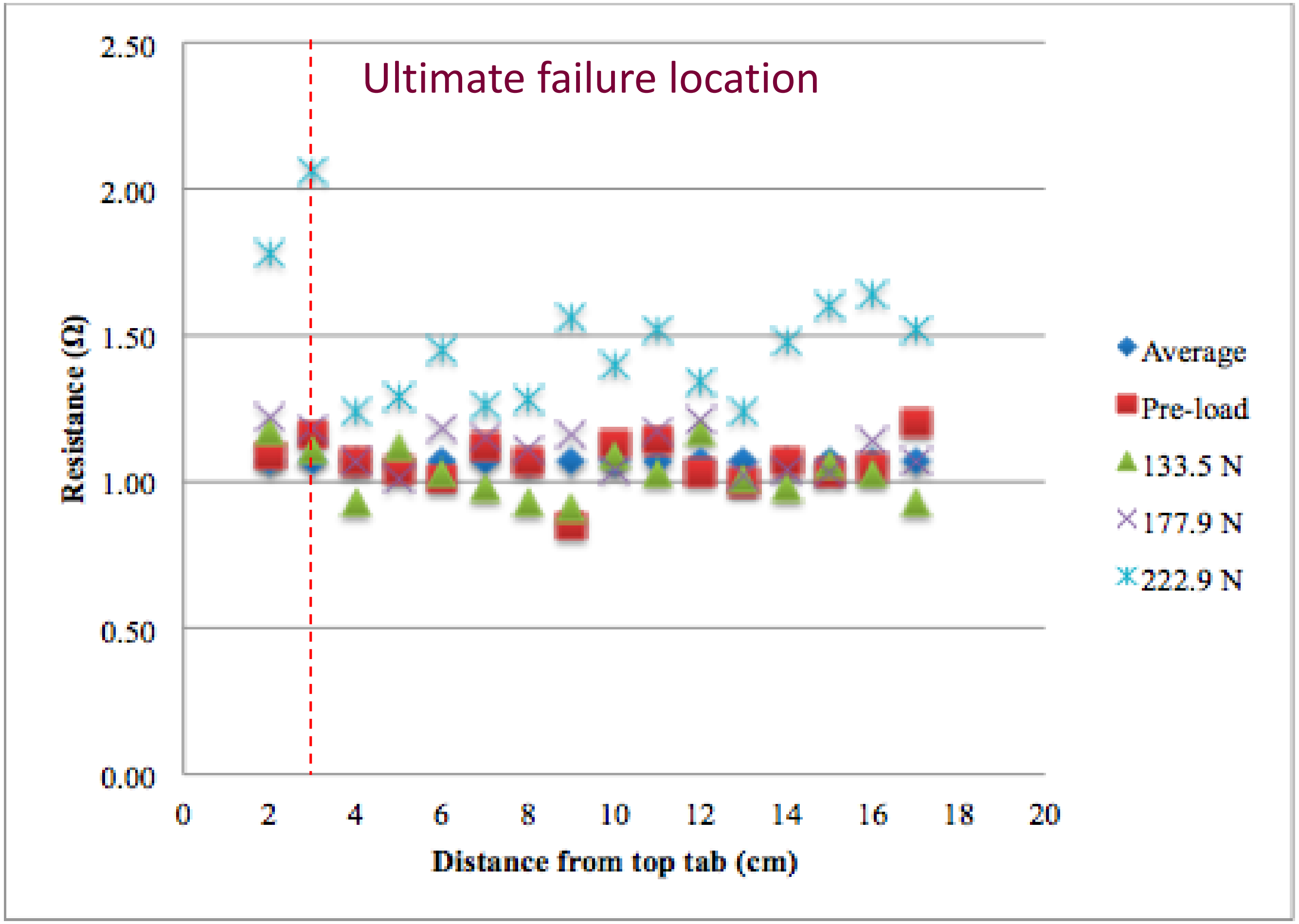
The average was 1.02 Ω with a standard deviation of 0.12 Ω.

222.9 N Load Failures



The average was 1.39 Ω with a standard deviation of 0.10 Ω.

222.9 N Load Failures



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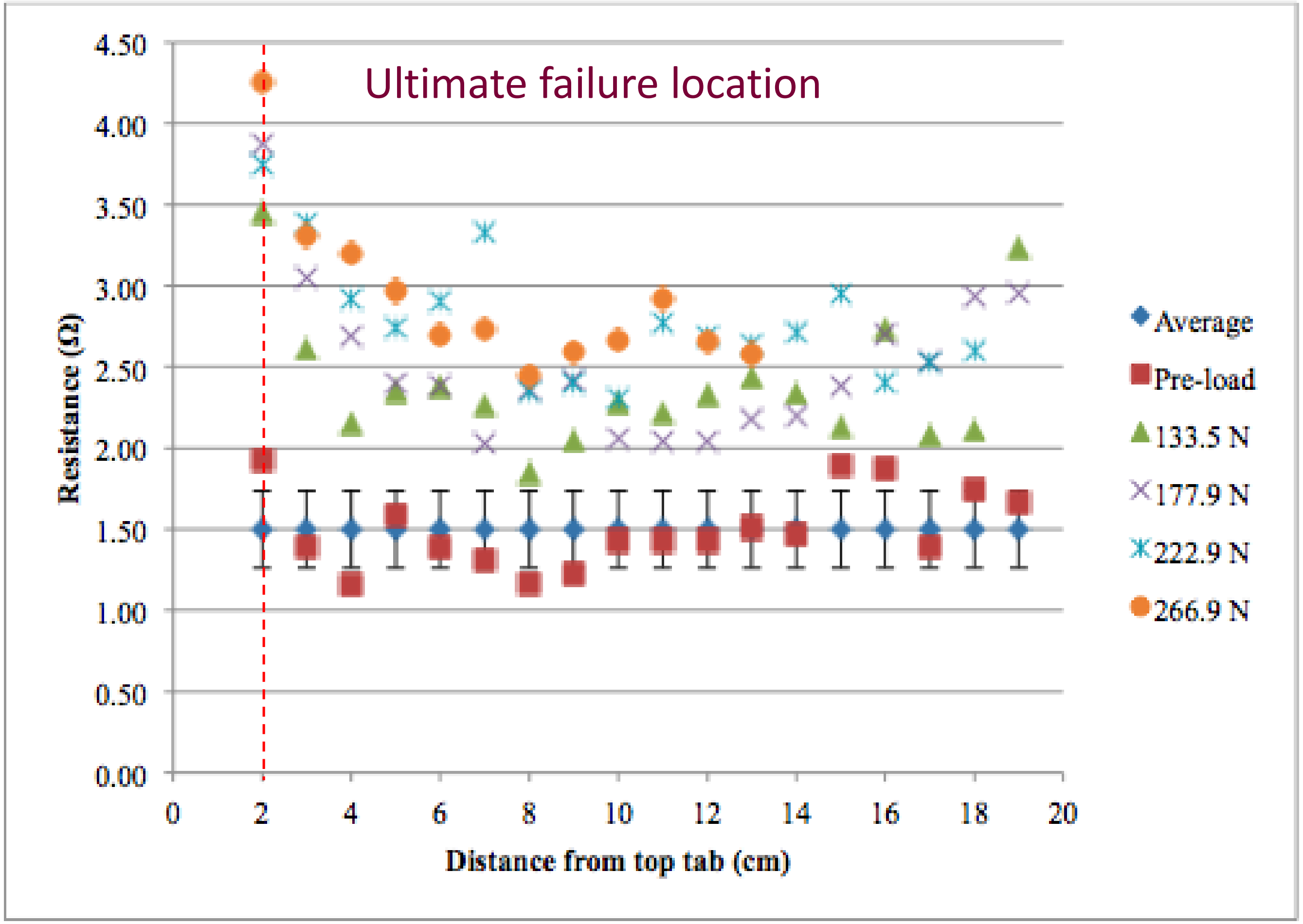
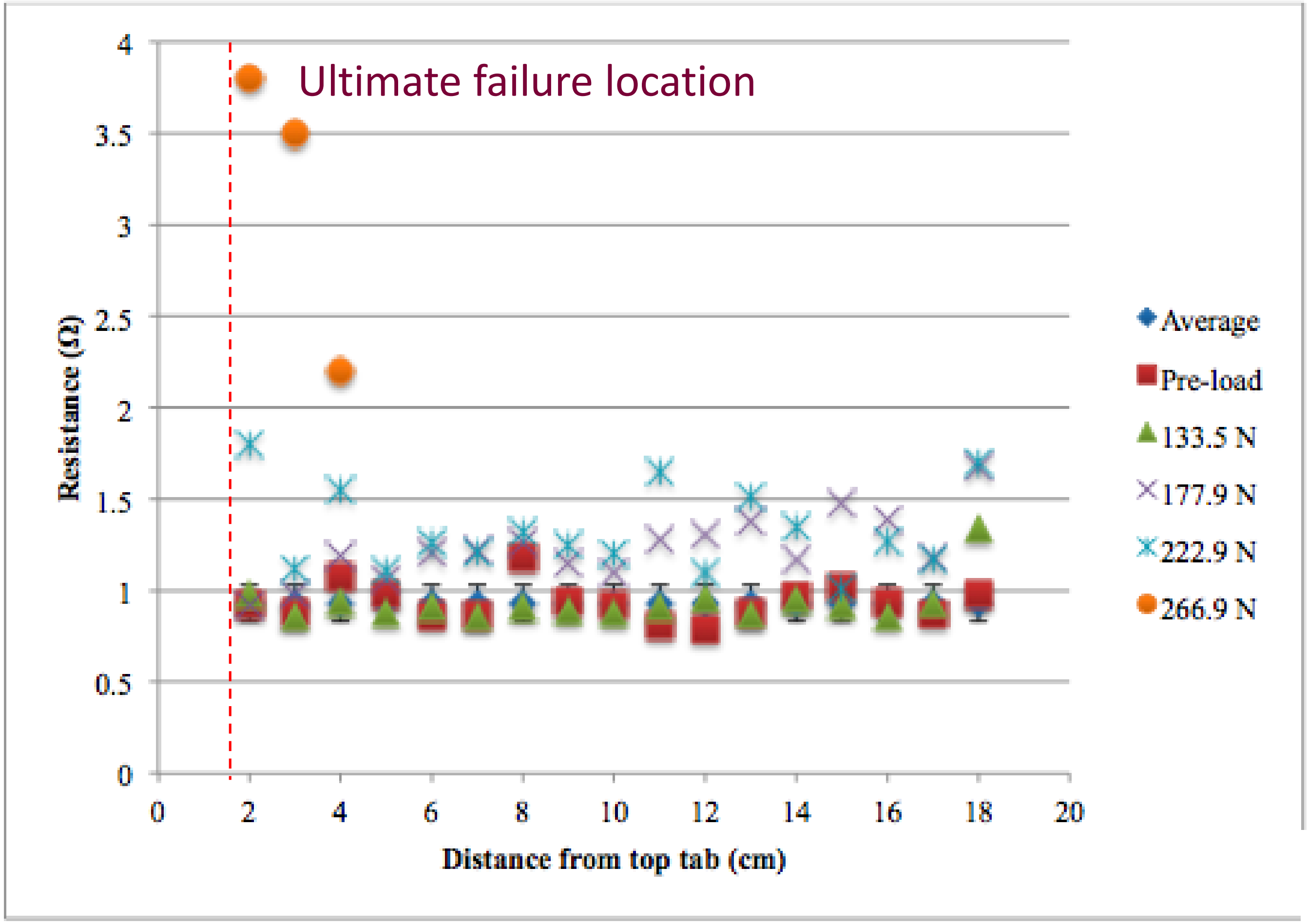
The average was 1.07 Ω with a standard deviation of 0.08 Ω.

266.9 N Load Failures



The average was 1.50 Ω with a standard deviation of 0.24 Ω.

266.9 N Load Failures



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The average was 0.93 Ω with a standard deviation of 0.10 Ω.

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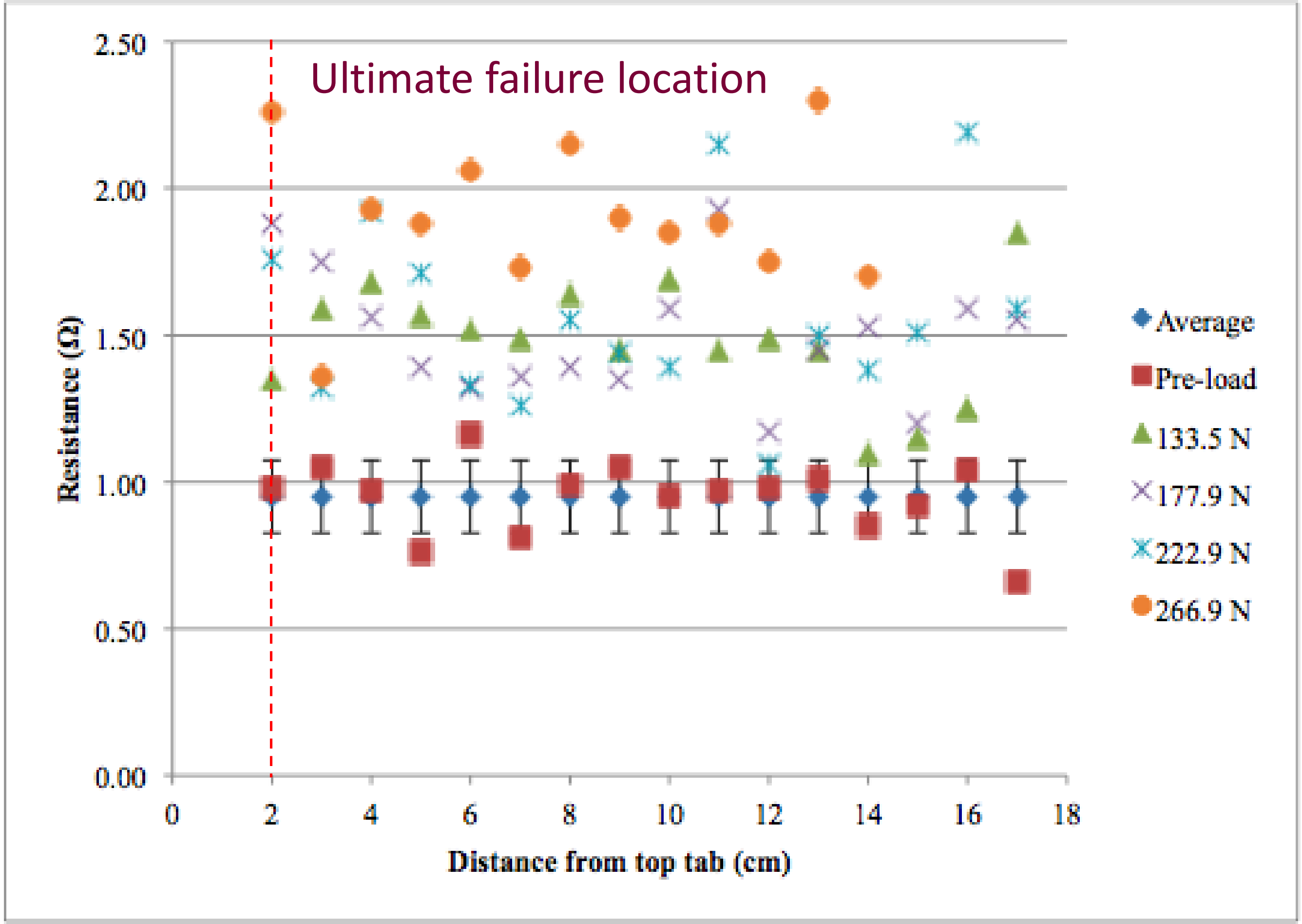
266.9 N Load Failures



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The average was 0.95 Ω with a standard deviation of 0.12 Ω.

Observations

- Generally, the location of failure corresponds to the location of highest resistance.
- Three trends were noticed
  - Progressive increase in resistance to failure
    - High localized resistance
  - Sudden increase to failure
    - High localized resistance
  - Consistent lower resistance throughout gauge

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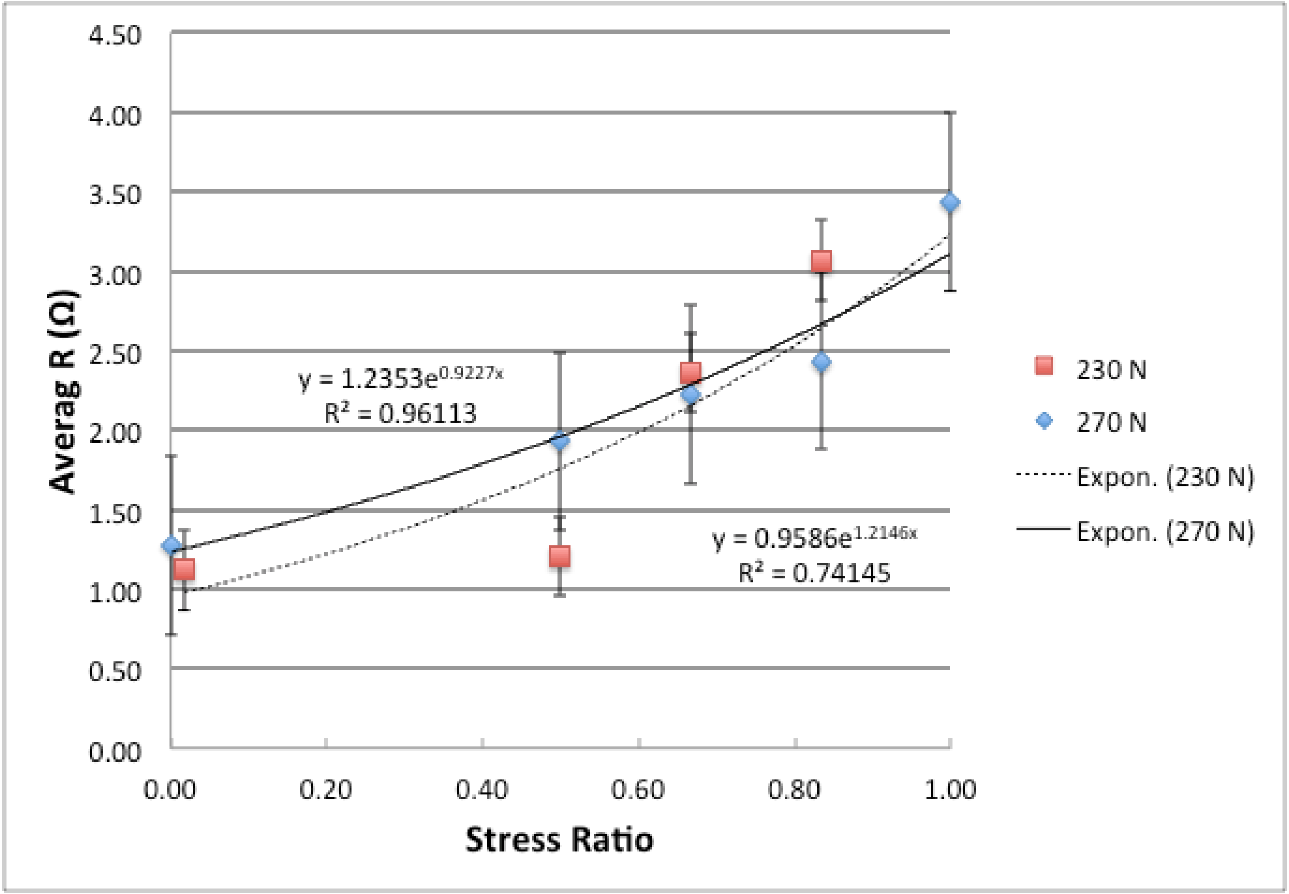
Change in Resistance

Exponential rise in the change in the average resistance measurement as the specimen approaches failure.



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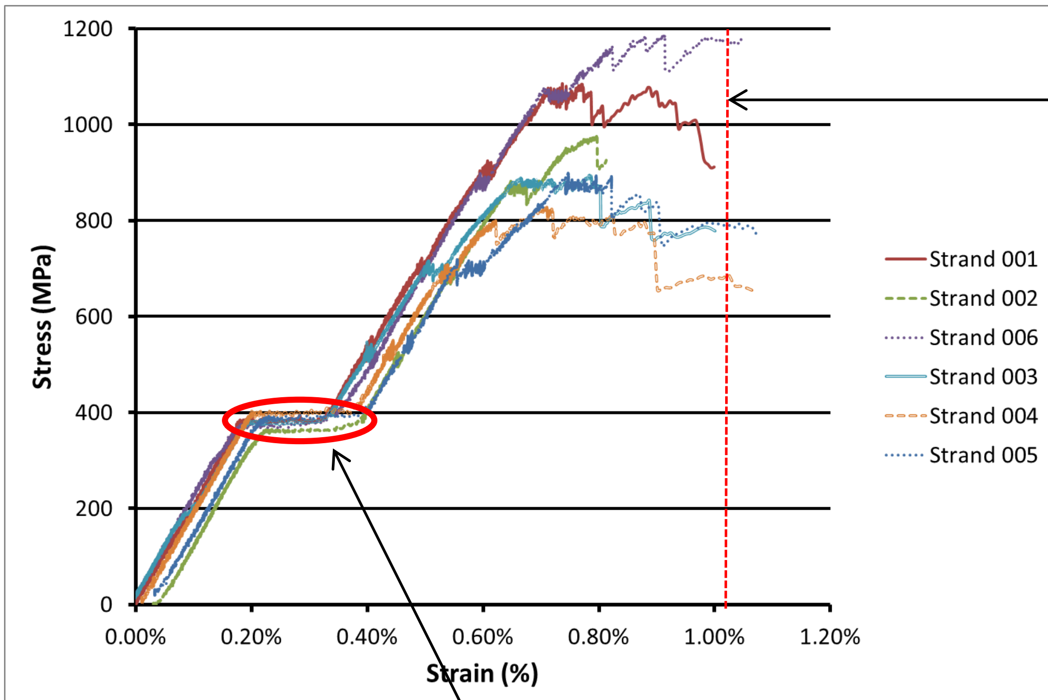
Stress vs. Strain

$$s = \frac{F}{A} \qquad e = \frac{DL}{L}$$



The reported strain to failure in the technical data sheet for IM7 provided by Hexcel was 1.9%. This deviation of 0.9% is a significant deviation from the reported value

This data is interesting because there was a significant elongation in the strand without an apparent change in localized resistance.

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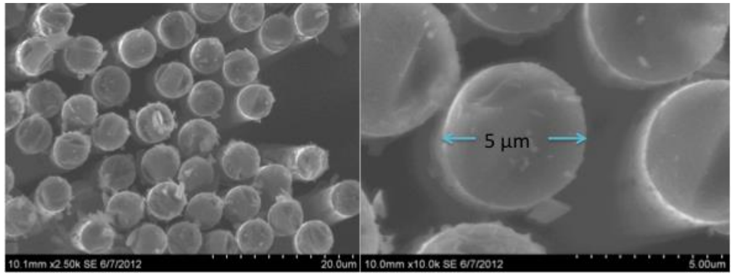
Theoretical Model

$$R(n) = \rho \frac{l}{An}$$

$$F(n) = \sigma_c An$$

Combination yields the relation between the load at which fracture occurs and the corresponding resistance

$$F(n) = \sigma_c \frac{\rho l}{R(n)}$$



Validation of fiber diameter

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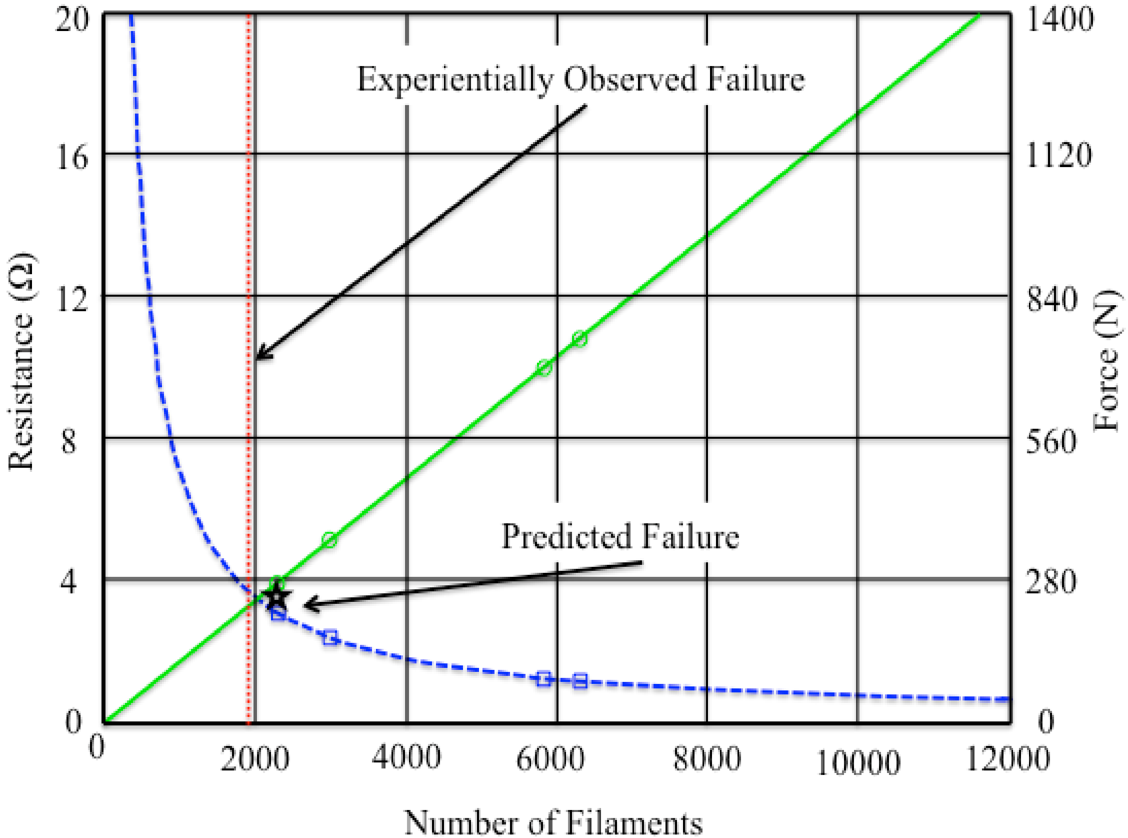
222.9 N Load Failures



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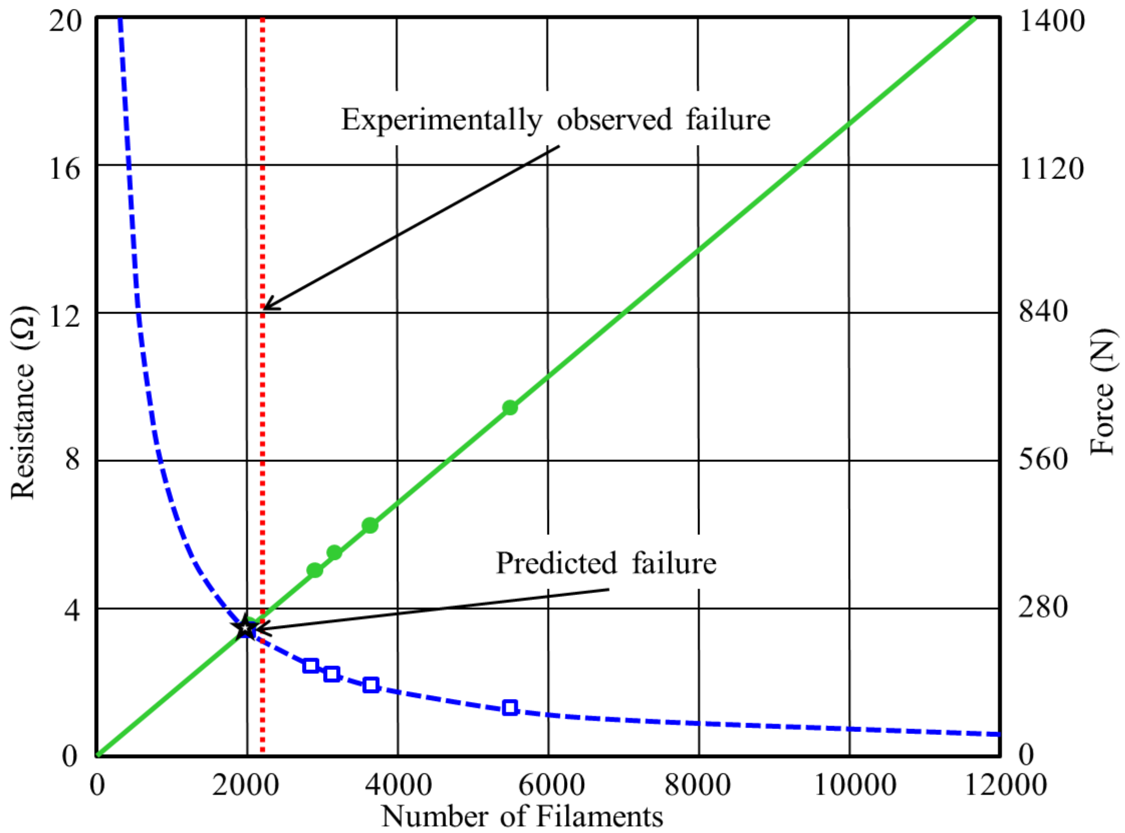
266.9 N Load Failures



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Conclusions and Future Work

- Demonstrated electrical resistance measurement can be used to evaluate damage in carbon fiber strand
- Demonstrated this is a highly localized effect
- Demonstrated agreement between experimental and theoretical values of surviving filaments and failure prediction

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Conclusions and Future Work

- Testing on epoxy impregnated strands
- True creep testing
- Determining how to make measurement on a COPV

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14. ABSTRACT

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• Safety
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• Problem: Neither NDT nor NDE can provide sufficient data to determine life expectancy or quantify the damage state of a composite material.

15. SUBJECT TERMS
Electrical Conductivity; Carbon Fiber; Non-Destructive Evaluation; NDE; Composite Overwrapped Pressure Vessel; COPV

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