Analysis of Drake Sized ACCC^{TM} Core Subjected to Bending

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Contents

- Material property predictions
- Numerical work
  - Finite Element (FE) model of the ACCC core subjected to bending
- Experimental work
  - Compression tests with Acoustic Emission (AE)
  - Flexure tests with AE
    - An analytic expression for the stress state within the ACCC rod subjected to bending
- What lies ahead…

Work Based Upon

1. **B Burks, D Armentrout, M Kumosa, "Failure Prediction Analysis of an ACCC Conductor Subjected to Thermal and Mechanical Stresses," *IEEE Transactions on Dielectrics & Insulators*, in press.**

   Summary – Multiple loading conditions (thermal stressing, uni-axial tension, and bending) were numerically investigated. Bending around mandrels was identified as a possible cause for concern.

2. **B Burks, D Armentrout, J Buckley, M Baldwin, M Kumosa, "Hybrid Composite Rods Subjected to Excessive Bending Loads," *Composites Science and Technology*, in press.**

   Summary – Parameters affecting the stress state during the mandreling process were investigated. Compressive strengths of the ACCC core, and Carbon Fiber core were experimentally measured.

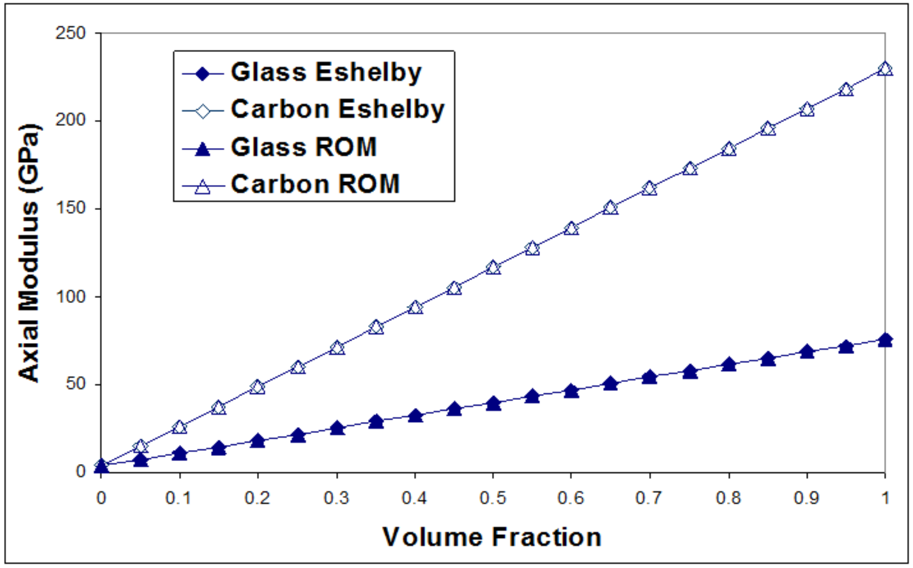
3. **B Burks, *Short-term failure analysis of the Aluminum Conducting Composite Core Transmission Lines*, MS Thesis.**

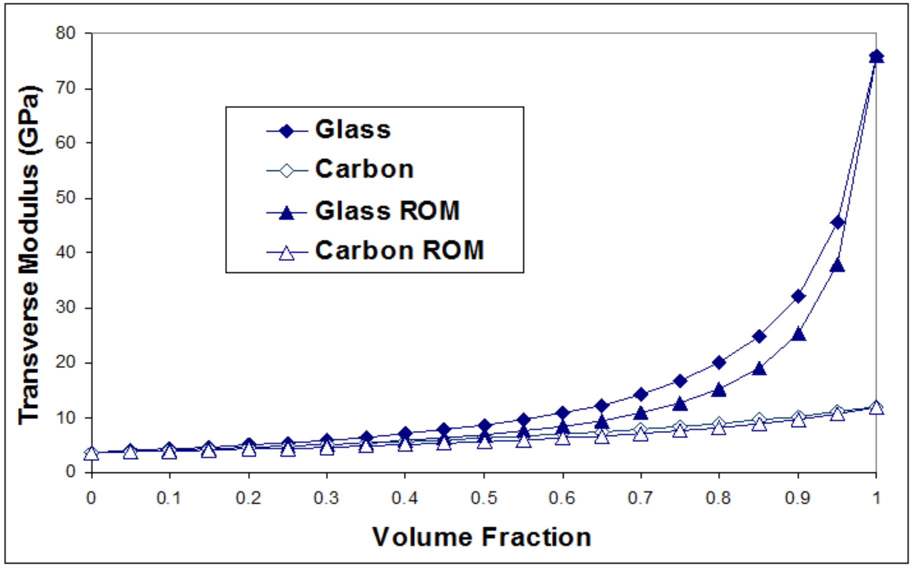
   Summary – Numerical and experimental investigation of the ACCC core.

Material Property Predictions

- Key to accurate numerical analysis
- Uni-directional (UD) composite materials offer the additional challenge of transverse isotropy
- Many authors have proposed methods for predicting material properties of UD composites
  - Rules of Mixture [7-8]
    - Simplistic, easily implemented, not always accurate transversely
  - Mori-Tanaka formulation of the Eshelby method [9-11]
    - Rooted in an elasticity solution, more rigorous implementation
    - Exhibits better agreement with experimental data
- Volume fraction of fibers has a significant impact

Material Property Predictions





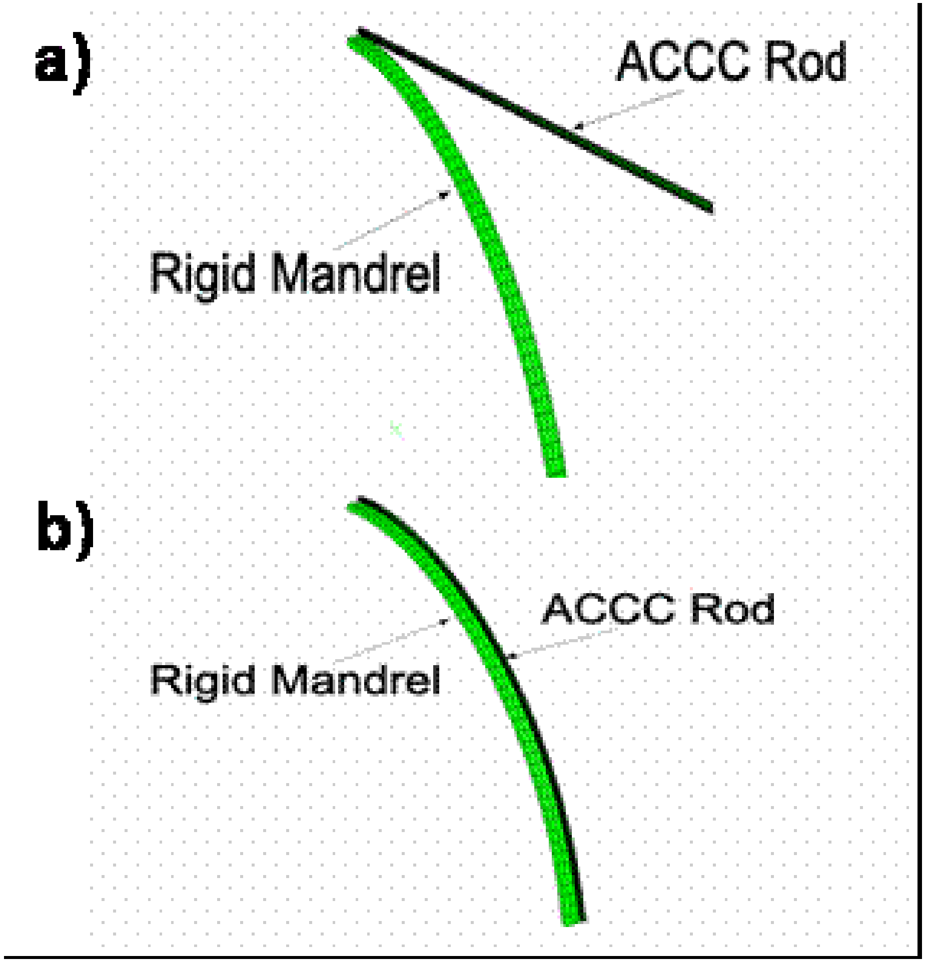
Material Property Predictions

Property	ECR / Epoxy	CF / Epoxy
Axial Modulus (GPa)	47.0	139.4
Transverse Modulus (GPa)	10.8	7.0
Axial Shear Modulus (GPa)	6.3	2.9
Axial Poisson's Ratio	.214	.270
Transverse Poisson's Ratio	.05	.01

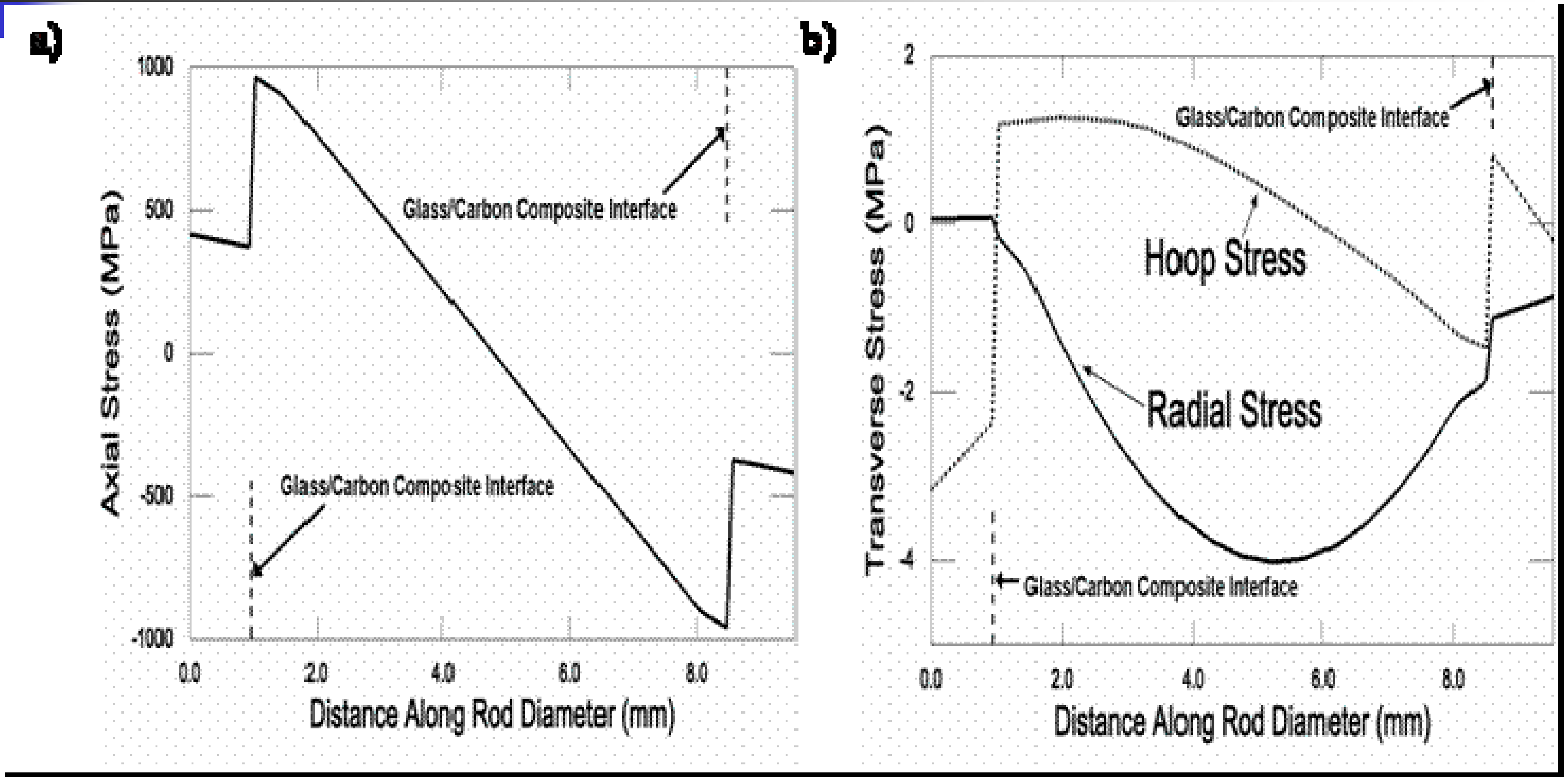
v_F = 60 % for both composite materials

FE Wrapping Model

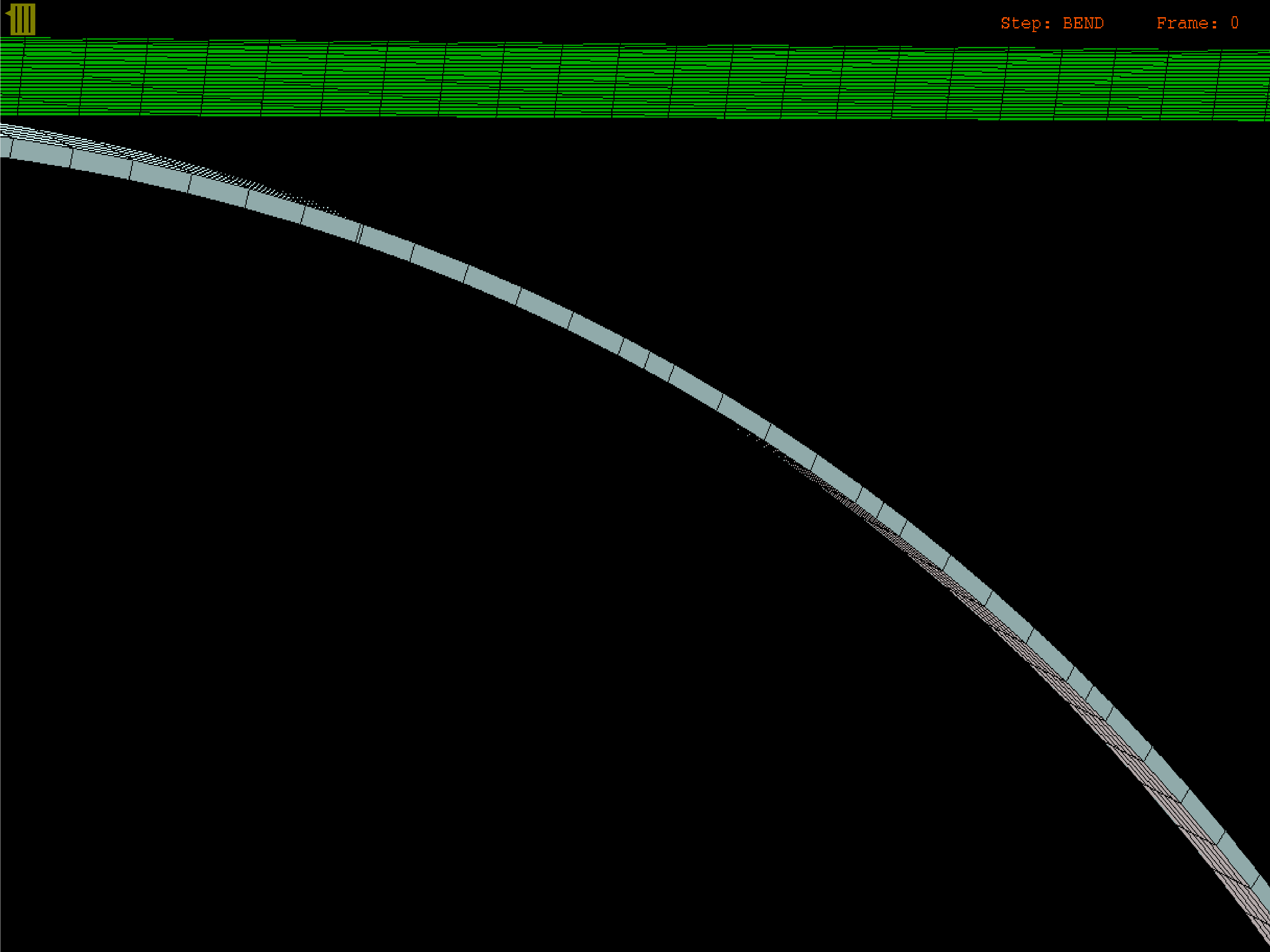
- Developed an Implicit FE model to investigate wrapping of the ACCC core around a mandrel
- Abaqus® FE solver
- Reduced integration continuum elements [12-13]
- Boundary Conditions
- Penalty based contact definition



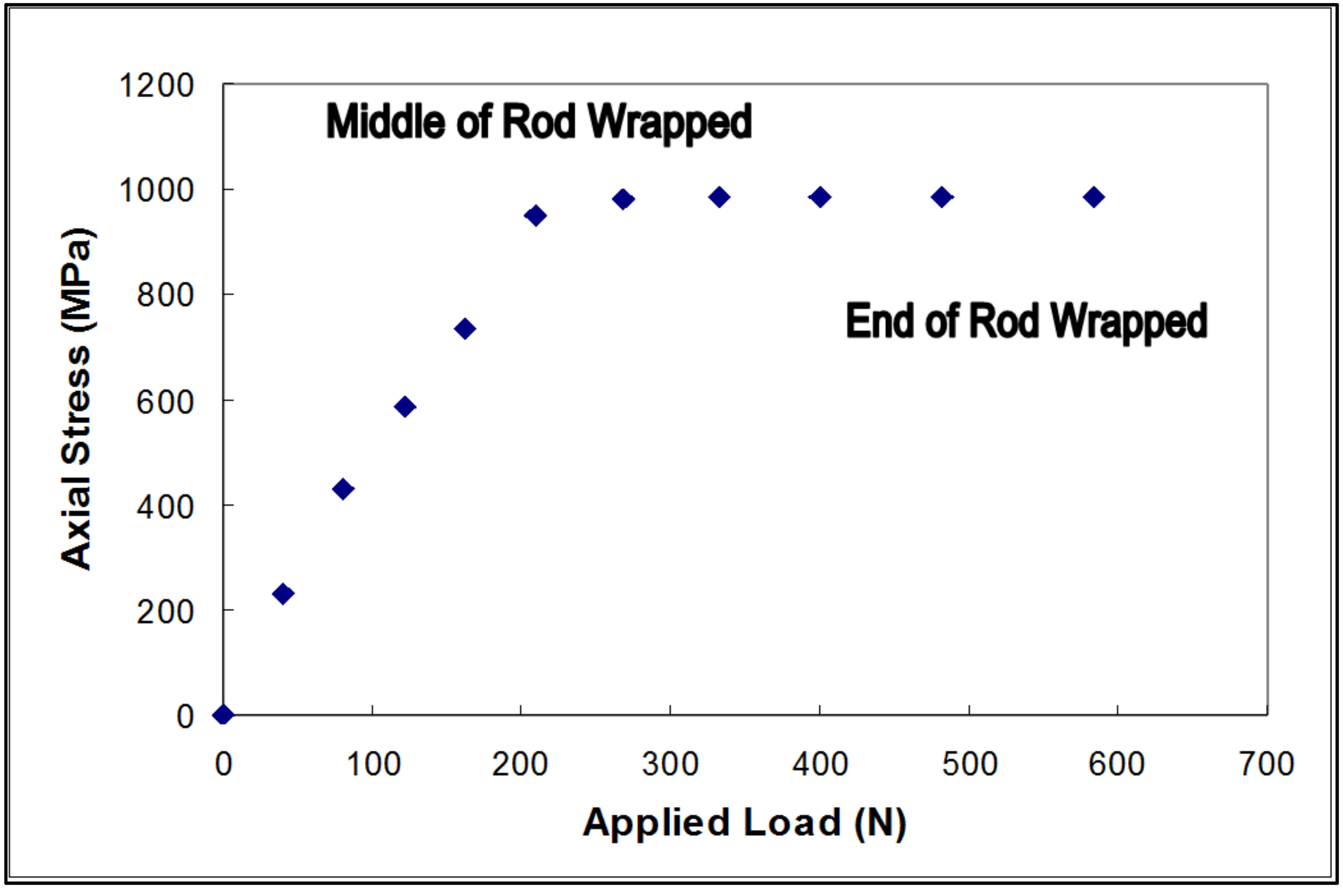
FE Wrapping Model



Internal stresses for 1 m diameter mandrel


Step: BEND
Frame: 0

FE Wrapping Model

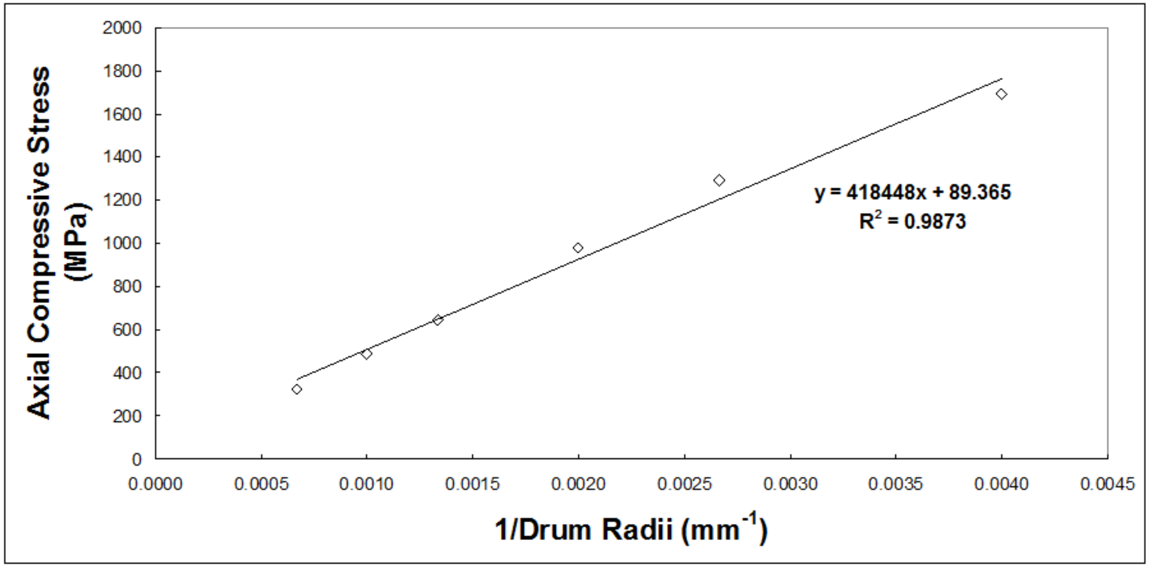


Axial stress vs. load for 1 m diameter mandrel

Mandrel Size Effect

- Investigate the effect that the size of the mandrel upon which the core is wrapped around has on the axial compressive stress state
- Six different mandrel diameters considered:
  - 500 mm, 750 mm, 1000 mm, 1500 mm, 2000 mm, and 3000 mm
- Geometries
- Extracted the maximum axial compressive stress from each analysis

Mandrel Size Effect

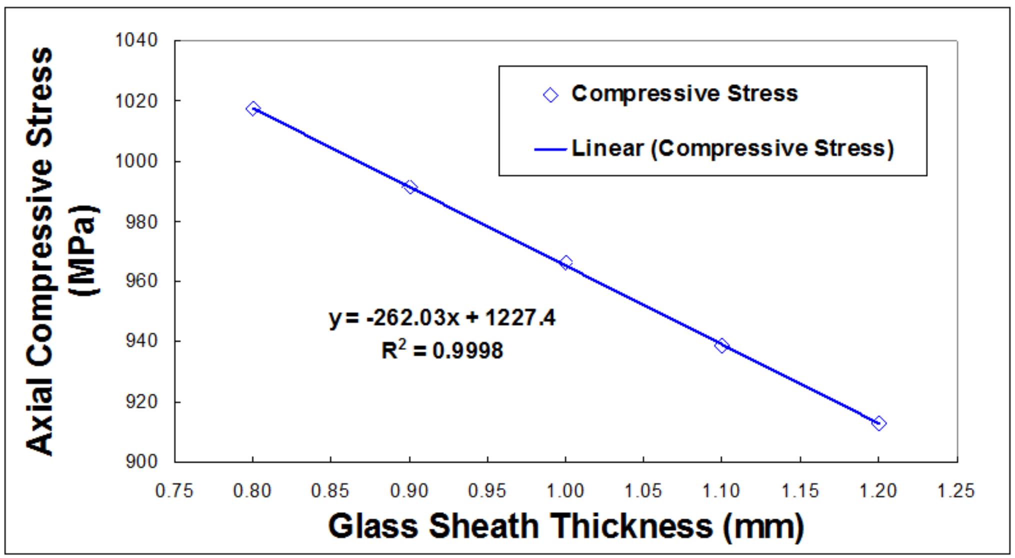


- Inverse relationship between axial compressive stress and mandrel radius
- Smaller diameter mandrels result in the ACCC rods being put in a larger stress state

Glass Composite Thickness Effect

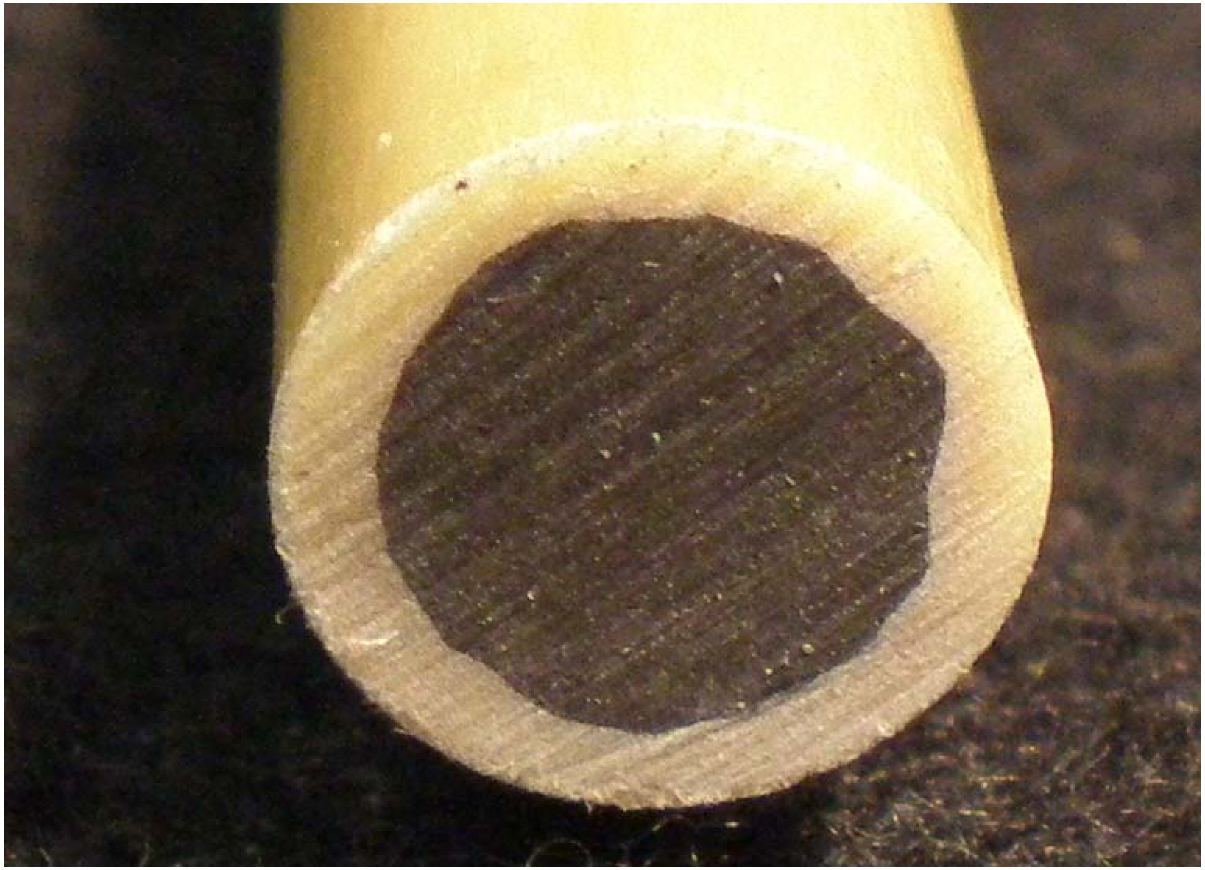
- Investigate the effect that the thickness of the ECR glass fiber composite layer has on the axial compressive stress state
- Used the 1 m mandrel model with varying glass composite thicknesses
  - Outer diameter of the ACCC rod remained fixed at 9.53 mm (simulate Drake sized ACCC core)
- Five geometries considered

Glass Composite Thickness Effect



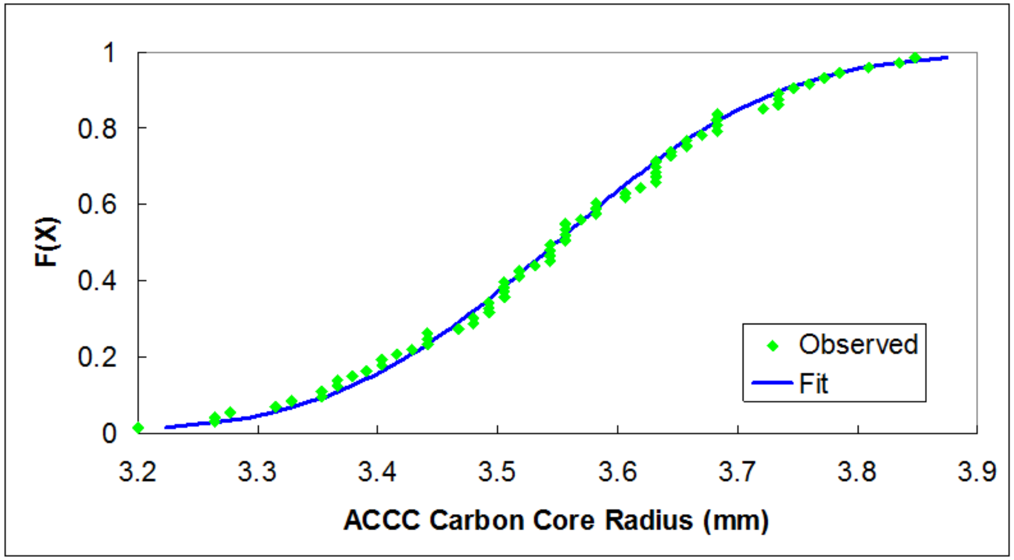
- Linear relationship with the glass sheath thickness and the axial compressive stress at the interface
  - Explained by relationship of bending stress with distance from the neutral axis
- 11% reduction in stress with a thickness increase of .4 mm

Randomness in Geometry

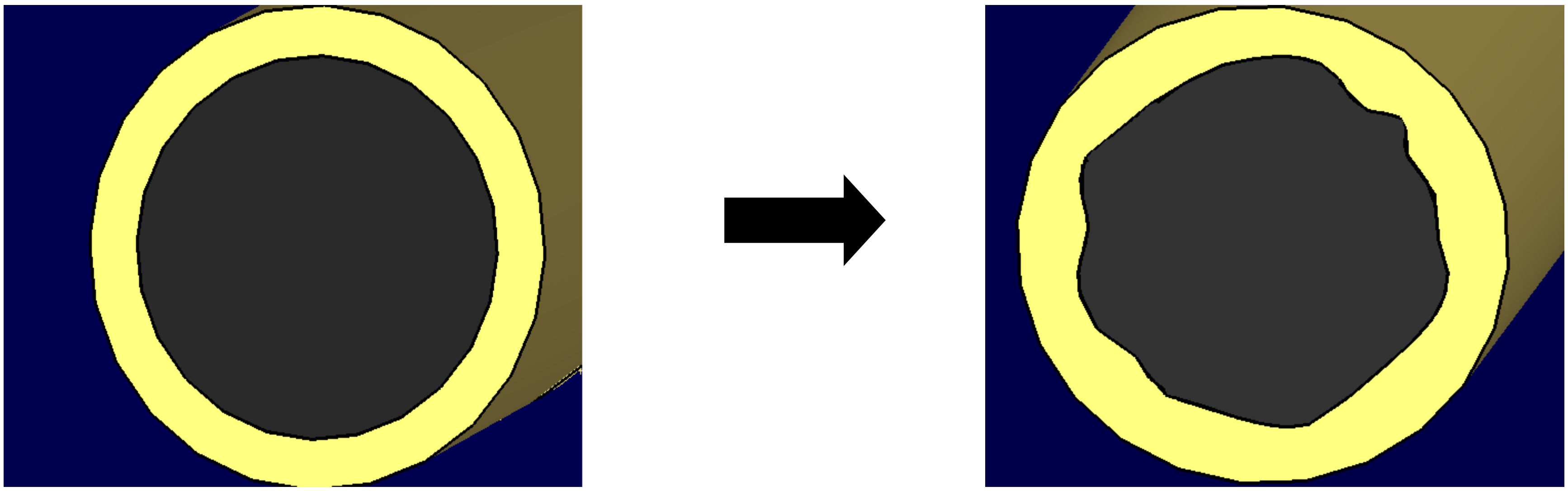


Randomness in Geometry

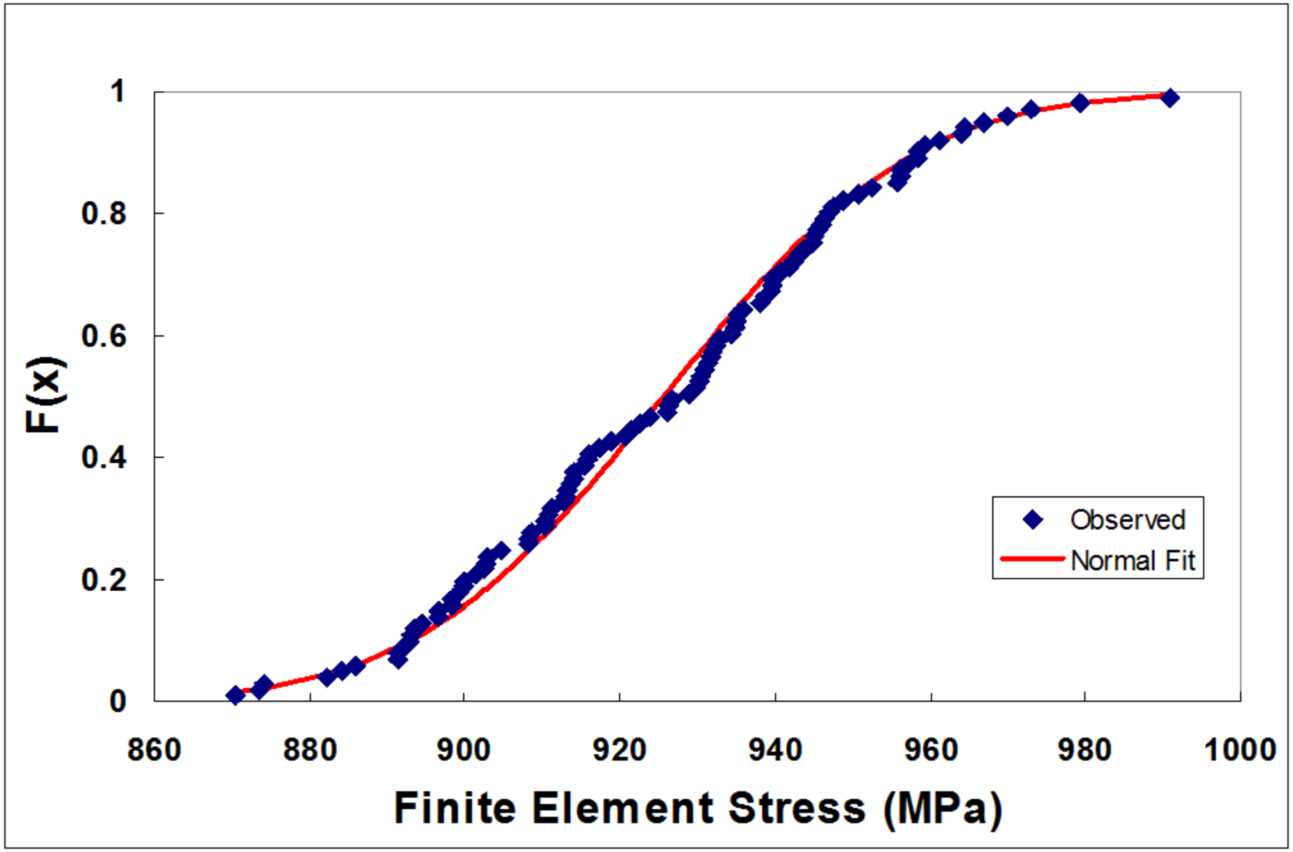
- Evaluate the effect that the geometric irregularities had on the axial compressive stress state via Monte Carlo sampling
- 72 measurements made of average carbon fiber diameter to gain a distribution
  - Fit well by a normal distribution with a mean of 3.55 mm and a standard deviation of .15 mm at the 1% sig. level [14] (K-S_{TEST} = .057; n = 72; K-S_{CRIT} = .192)



Randomness in Geometry

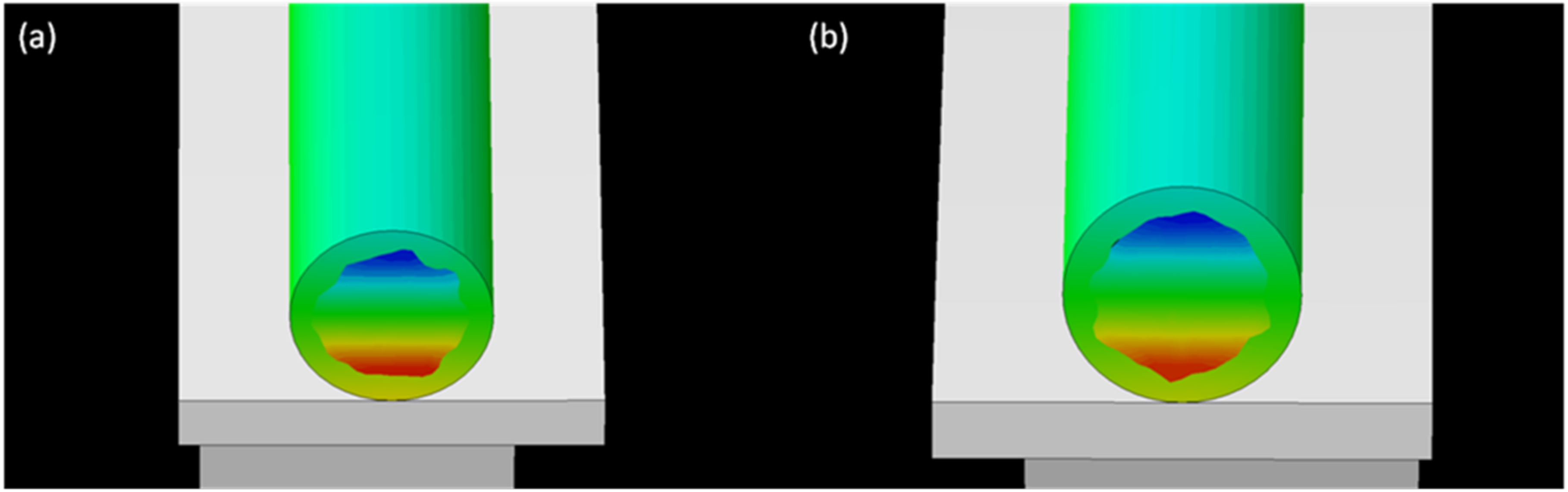


Randomness in Geometry



For 1 m diameter mandrel

Randomness in Geometry

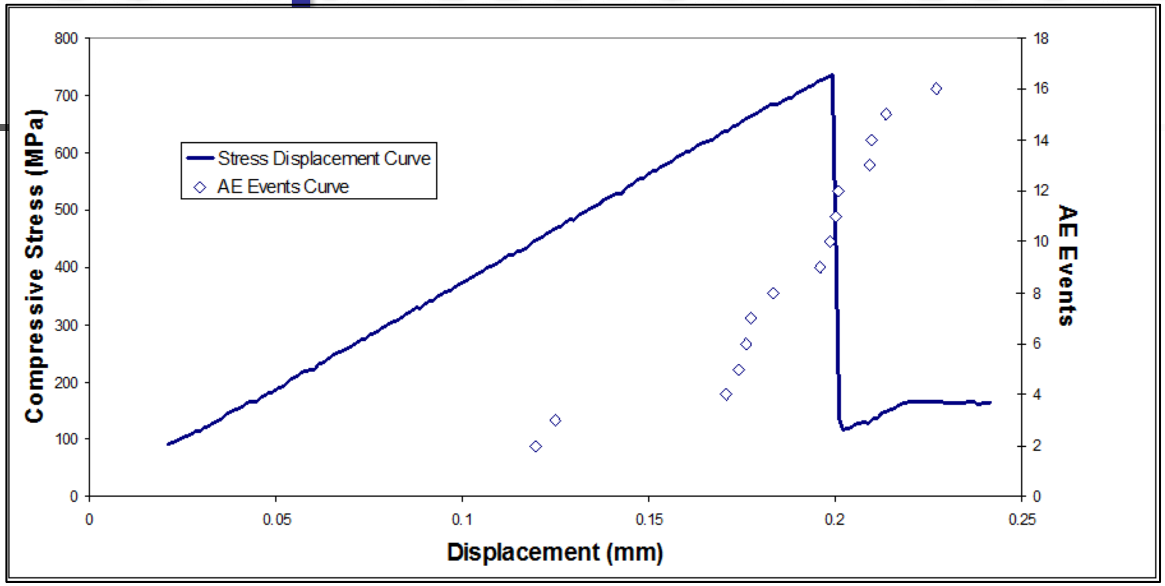


Compression Testing

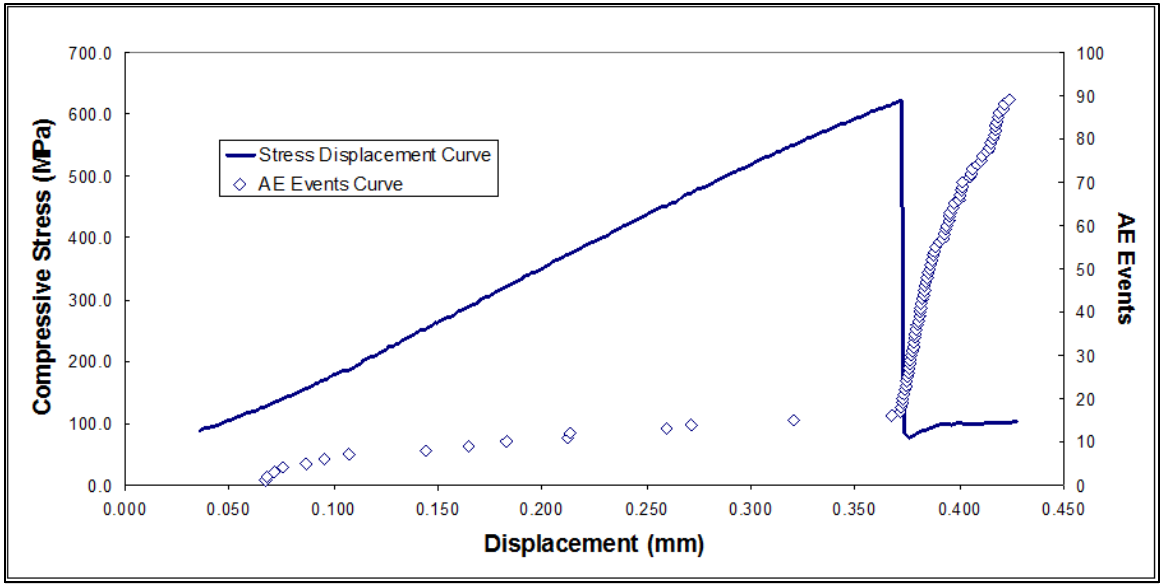
- Tests were run per ASTM D695 [15] to evaluate axial compression characteristics of ACCC cores
- Tested both full ACCC composite specimens, and carbon fiber composite specimens with AE monitoring
  - Different specimen lengths; same aspect ratio
- Sample preparation was key

Compression Testing

CF composite



ACCC composite



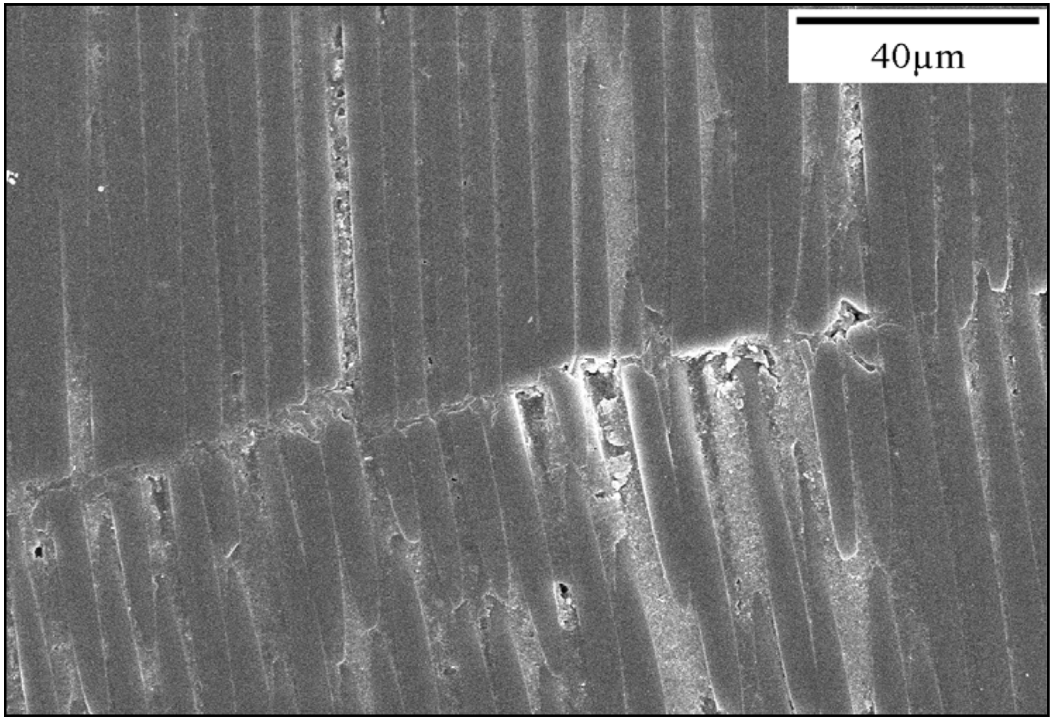
Compression Testing

	Compressive Strength (MPa) [μ±σ]	AE Events [μ±σ]
ACCC Composite	615 ± 62	95 ± 11
Carbon Fiber Composite	724 ± 44	21 ± 8

Compression Proof Tests

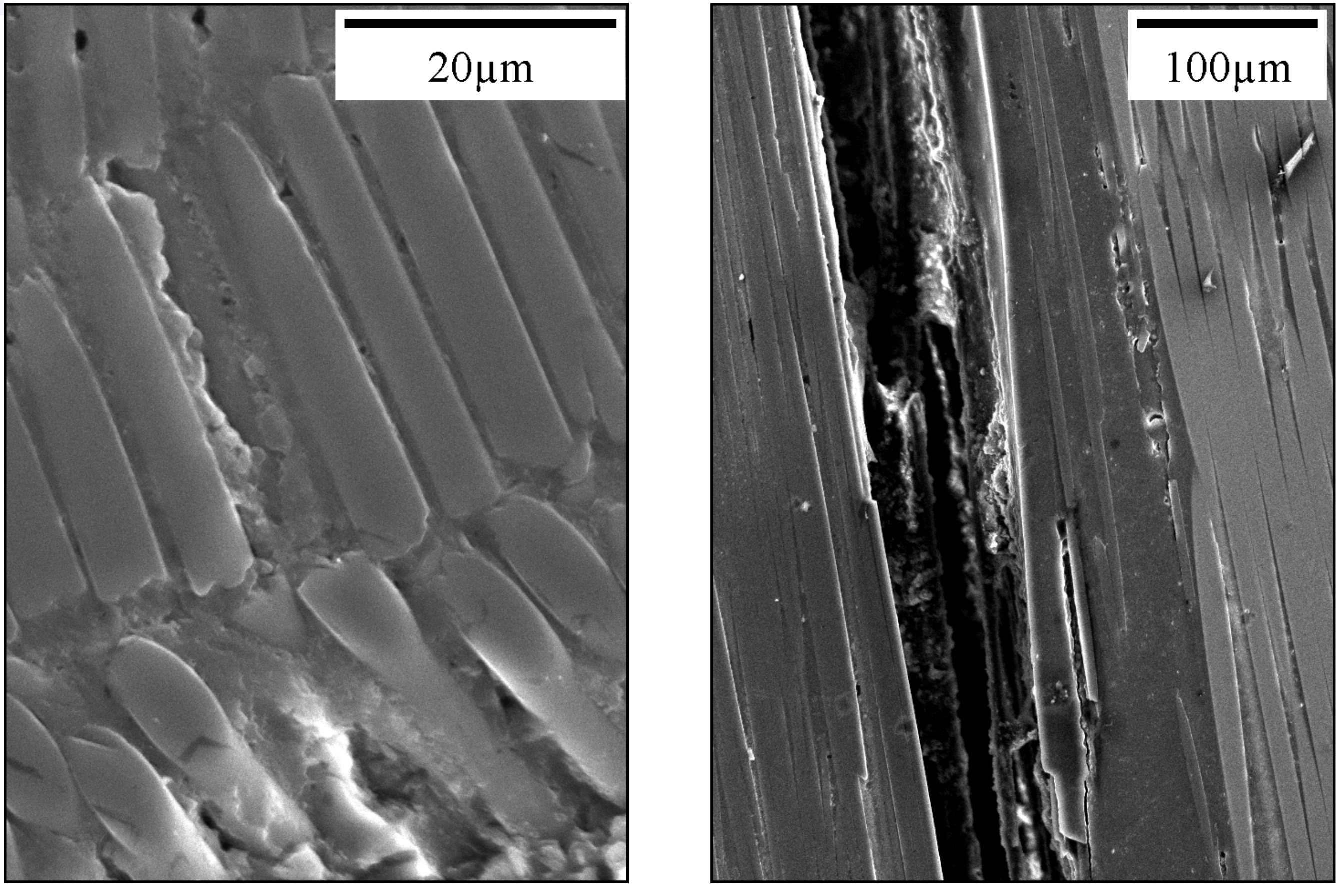
- Specimens were loaded to 80% of their loads at failure
- Split axially, polished, and examined with Scanning Electron Microscopy (SEM)
- Microstructure was compared to failed specimens

Compression Testing



CARBON FIBER COMPOSITE ONLY

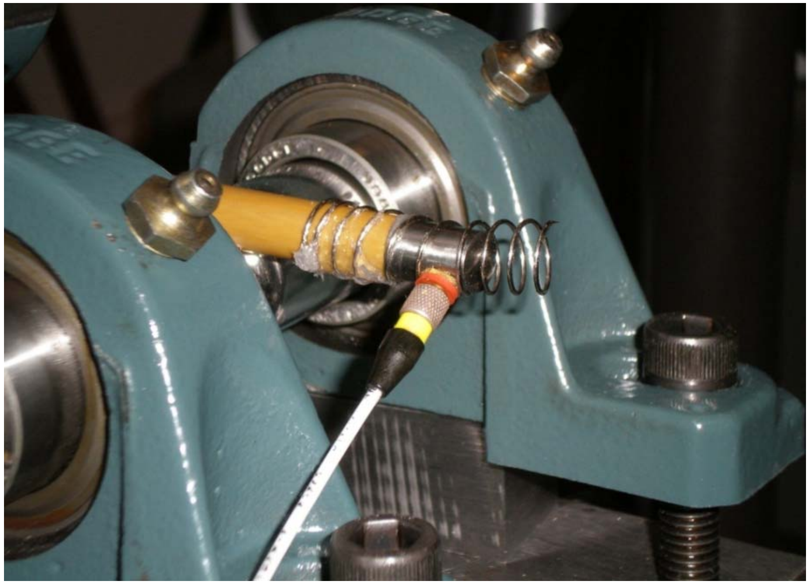
Compression Testing



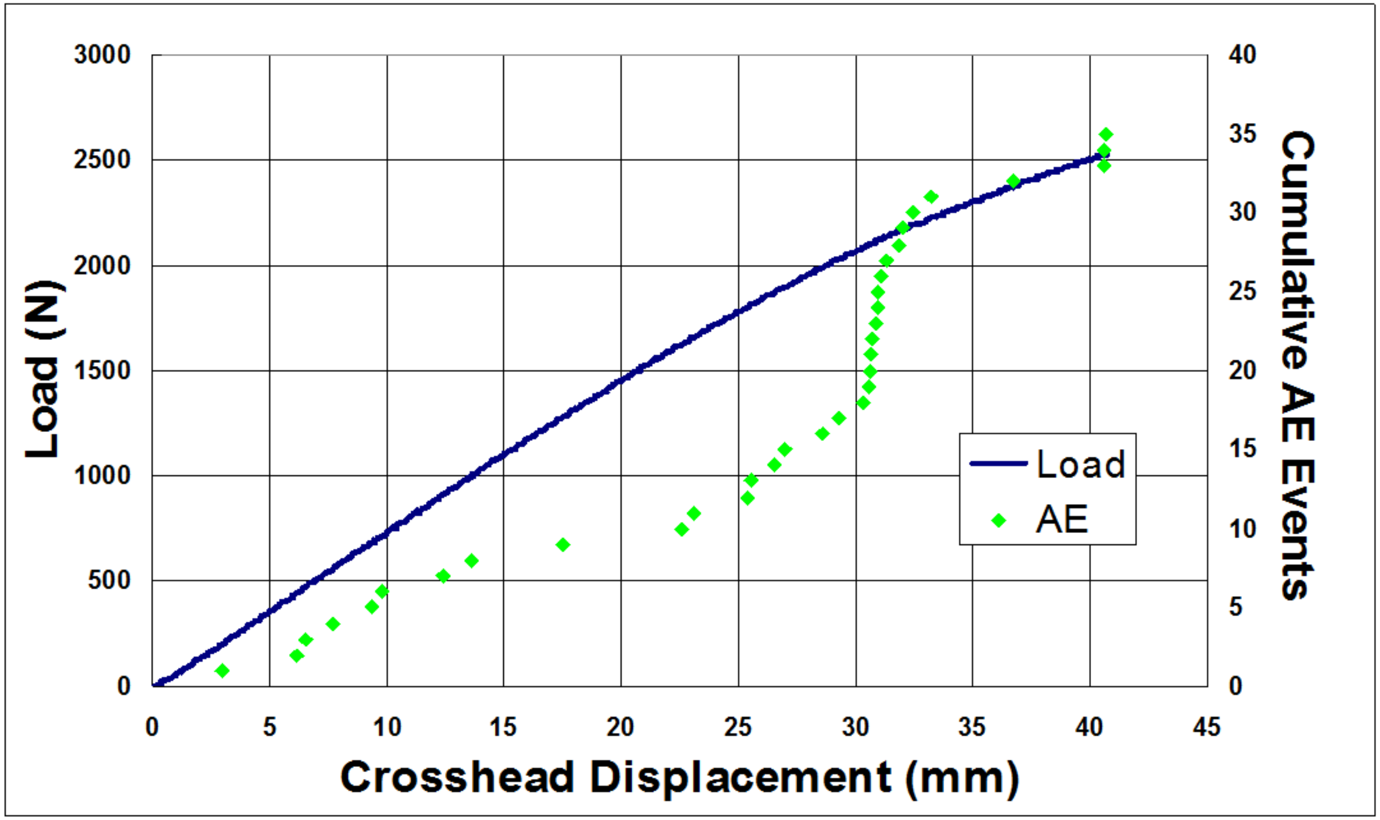
ACCC COMPOSITE

Four Point Bend (FPB) Testing

- FPB is ideal for flexure testing [16-18]
- Fixture Design
  - Rolling contact
  - Machined saddles to seat circular rod
  - Longer outer span to simulate mandreling process
  - Mechanical means of coupling the AE transducer to the specimen



Four Point Bend Testing



Four Point Bend Testing

- Bending generates primarily axial stresses
  - Confirmed through the FEM analysis in this research
- ACCC cores have 2 different materials, with 2 different axial stiffness

$$M_A = M_C + M_G$$

$$\frac{M_G}{I_G} = \frac{E_G}{R}$$

$$\frac{M_C}{I_C} = \frac{E_C}{R}$$

$$R = \frac{E_G I_G + E_C I_C}{M_A}$$

$$\sigma_{BEND} = \frac{Ey}{R}$$

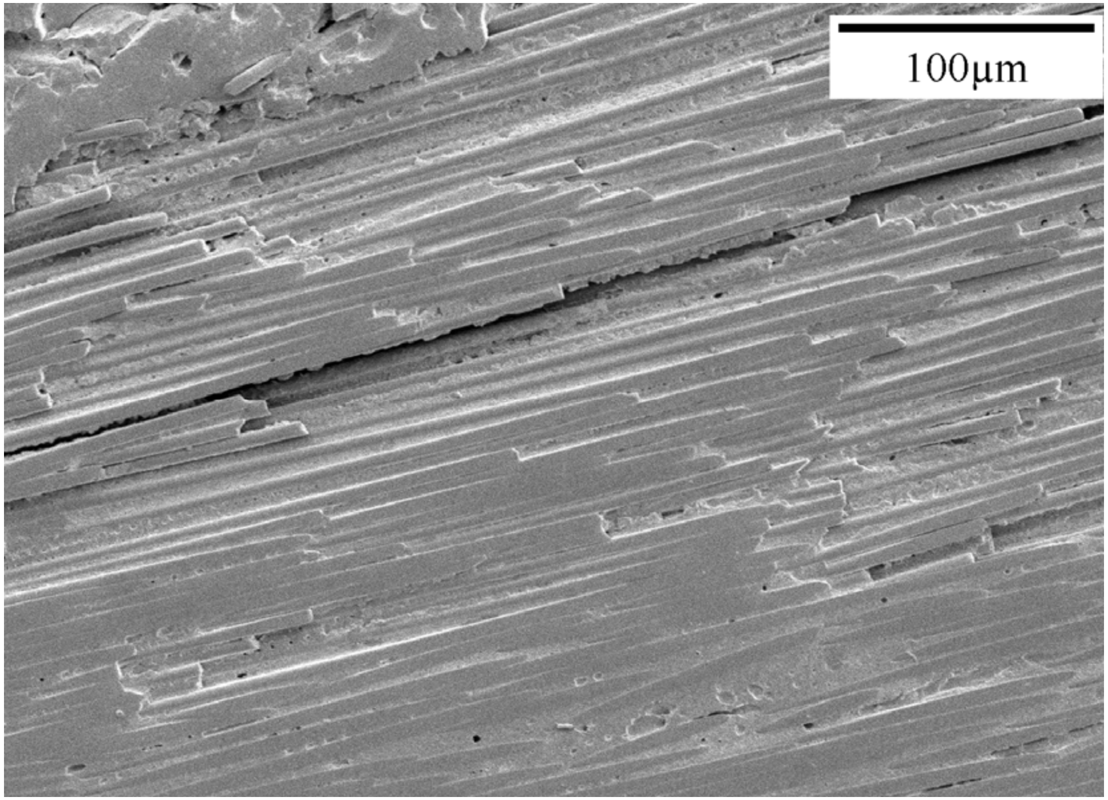
Four Point Bend Testing

***Max. axial stress state in the carbon fiber composite at the carbon fiber composite/ glass fiber composite interface**

	Average stress* (MPa)	COV
Onset of AE	1754	.09
Failure	2104	.02

Max. axial stress when wrapping on 1m diameter mandrel μ = 926 MPa (from FEM)

Four Point Bend Testing



Risk

- Using the First-Order Reliability Method (FORM) [19] the probability that an ACCC specimen will experience significant damage when being wrapped on a 1 m mandrel is $1.6 * 10^{-7}$
  - Only considers the randomness in geometry
  - Other factors could be more significant; they could also be less significant

Conclusions From This Research

- Damage during bending initiates from kinking of carbon fibers on the compressive side of the rods at the carbon-glass interface

- ACCC cores can be wrapped around 1 m mandrels with a low probability of damage (a “safety factor” of ~2)

Current Research

- Determining the effect of excessive bending on the residual tensile strengths of the ACCC core (damage tolerance model).
  - Will provide insight into the short-term performance of the ACCC core, if damage has occurred to the core.

Acknowledgements

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