Silicon Carbide Multilayer Piping for High Temperature sCO_2 Brayton Cycle

Presenter

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Introduction

- Advanced power-generation systems permit higher turbine inlet temperatures than current systems
  - Nuclear – Gen IV (500-900°C)
  - Fossil – Oxy-fuel (1100°C)
  - Solar – Gen3 CSP (≥700°C)
- Suitable energy conversion systems needed
- sCO_2 EC systems have been selected as a prime candidate to pair with advanced power-generation systems
- Improvements in piping and other supporting components are needed to support sCO_2 EC systems, especially if higher temperatures and pressures are desired

Presentation Overview

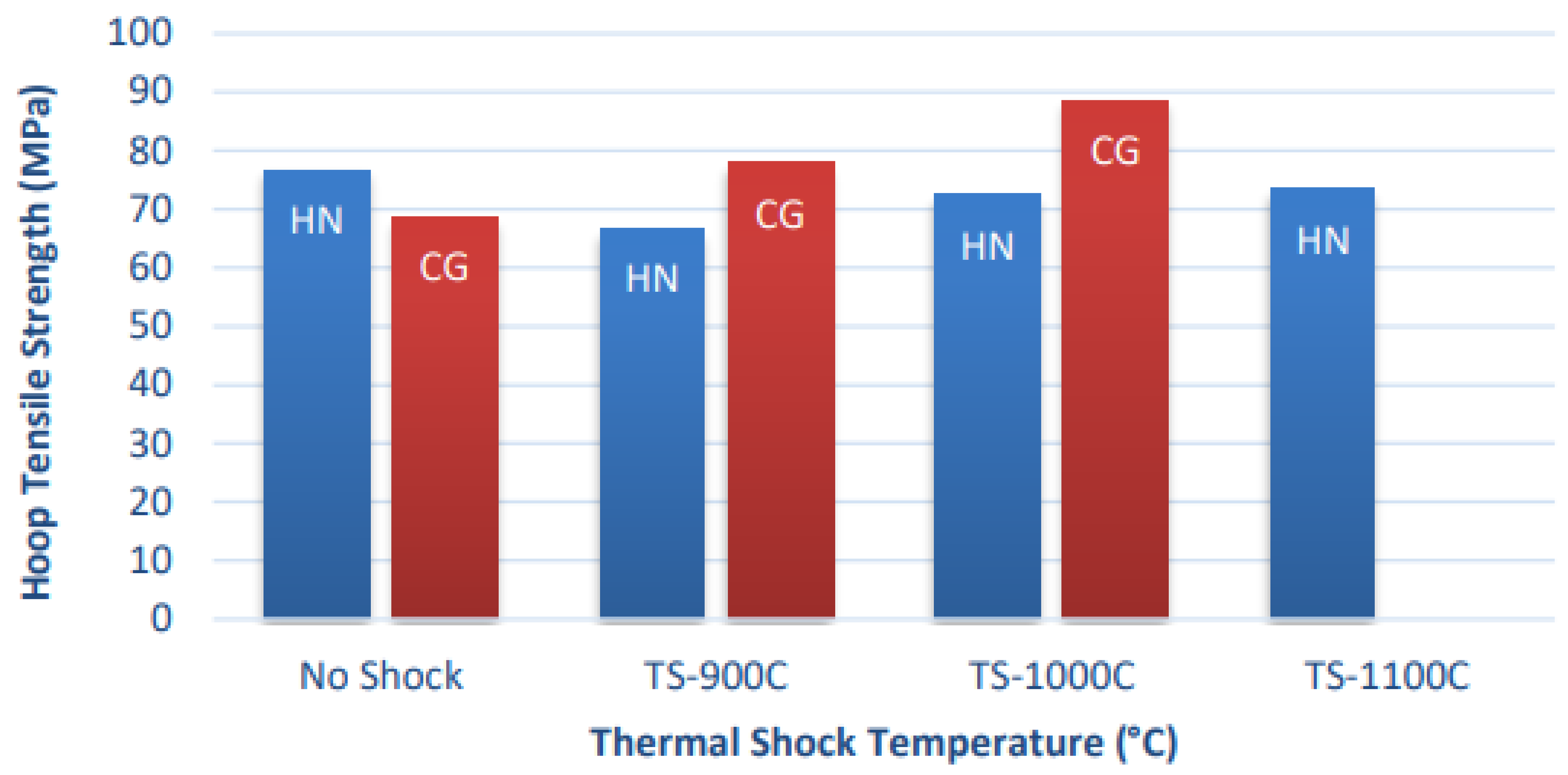
- Motivation for Piping Advancement
- Technology Overview
- Technology Advancement
  - Finite Element Model
    - Material Characterization
    - Preliminary Tubular Tests
    - Additional Tubular Tests
    - Results and Conclusions
  - Corrosion Testing
    - Overview
    - Results
- Summary

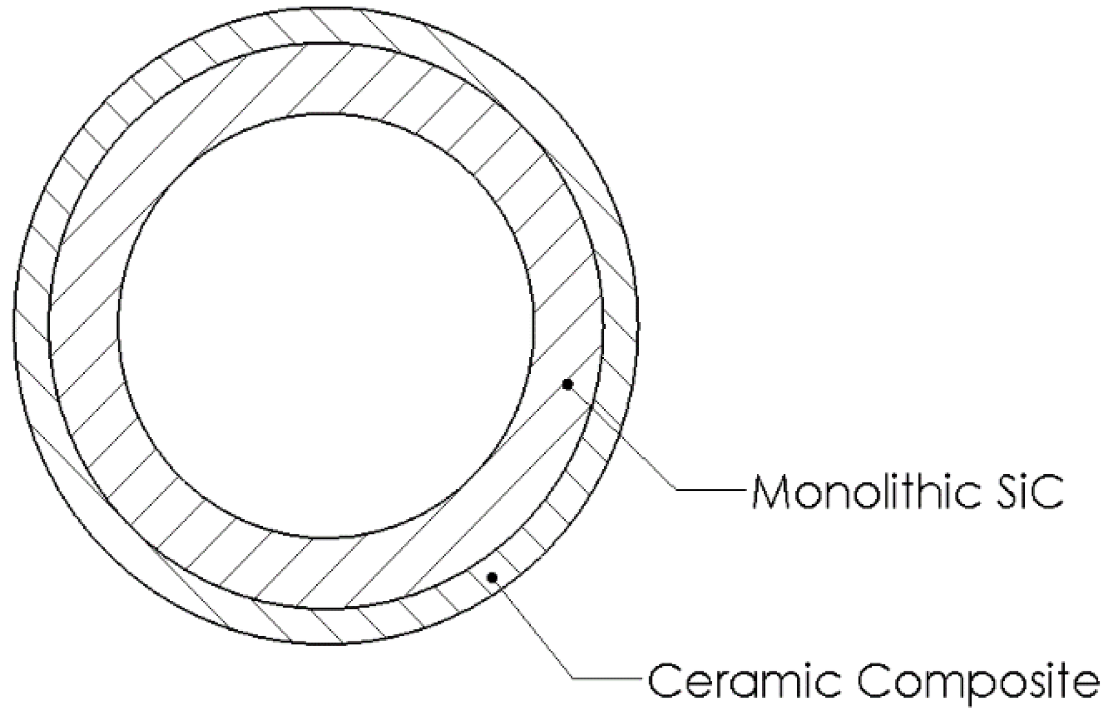
Motivation for Piping Advancement

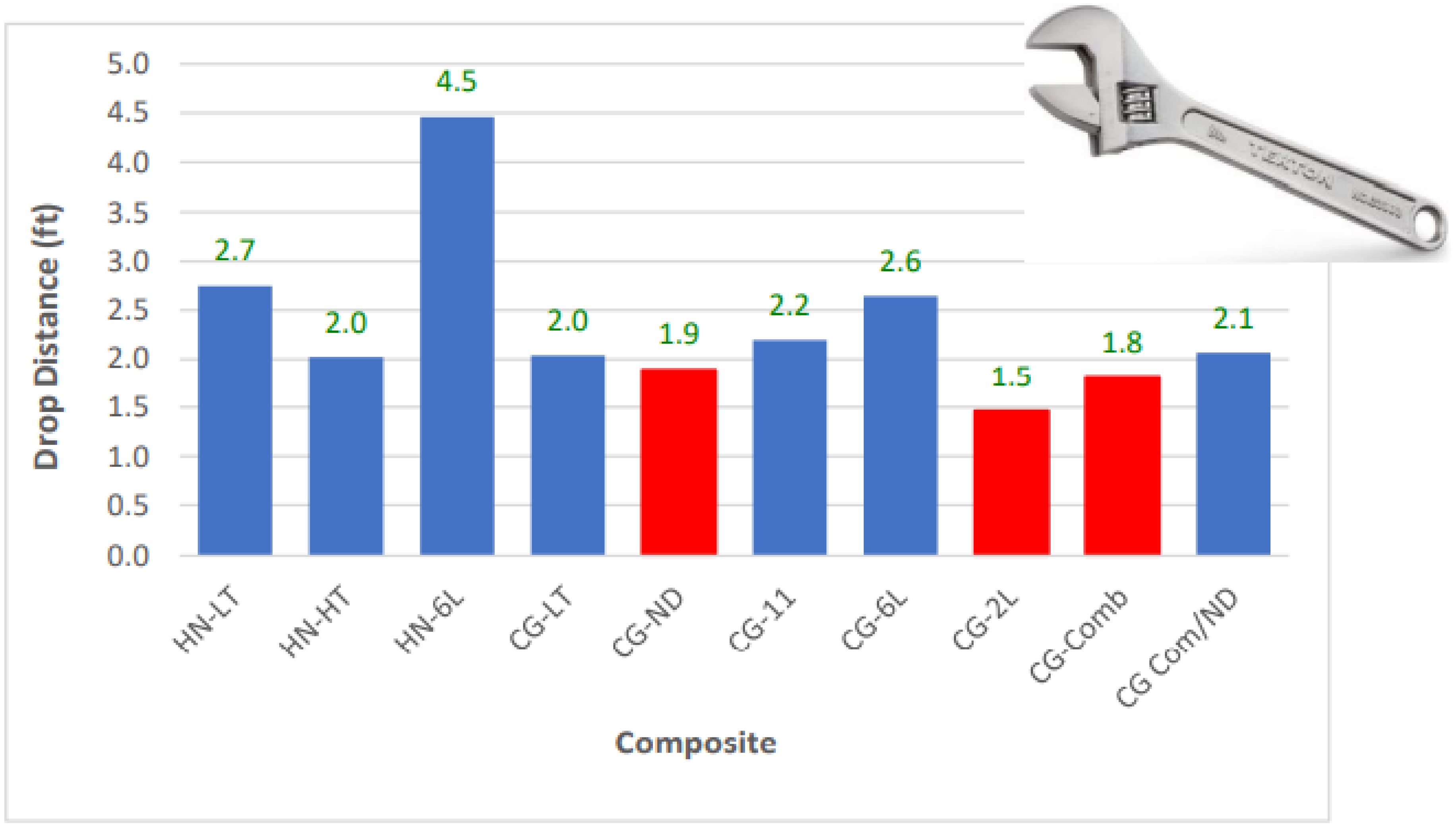
- Improved cycle performance at high temperatures
  - Efficiencies of greater than 50% in sCO_2 can only be achieved at turbine inlet temperatures above 700°C
  - Efficiencies of greater than 55% may be achieved for inlet temperatures of 800°C and higher
- Behavior of alloys under sCO_2 conditions and cost/availability
  - Increased creep
  - Increased corrosion

Technology Overview

- “Multilayer” Architecture
  - Monolith Silicon Carbide (SiC)
  - Ceramic Matrix Composite (CMC) $SiOC_f/SiOC$
- Filament wound, Polymer Infiltration & Pyrolysis (PIP)
- Results in a structure that is
  - Hermetic
  - Tough







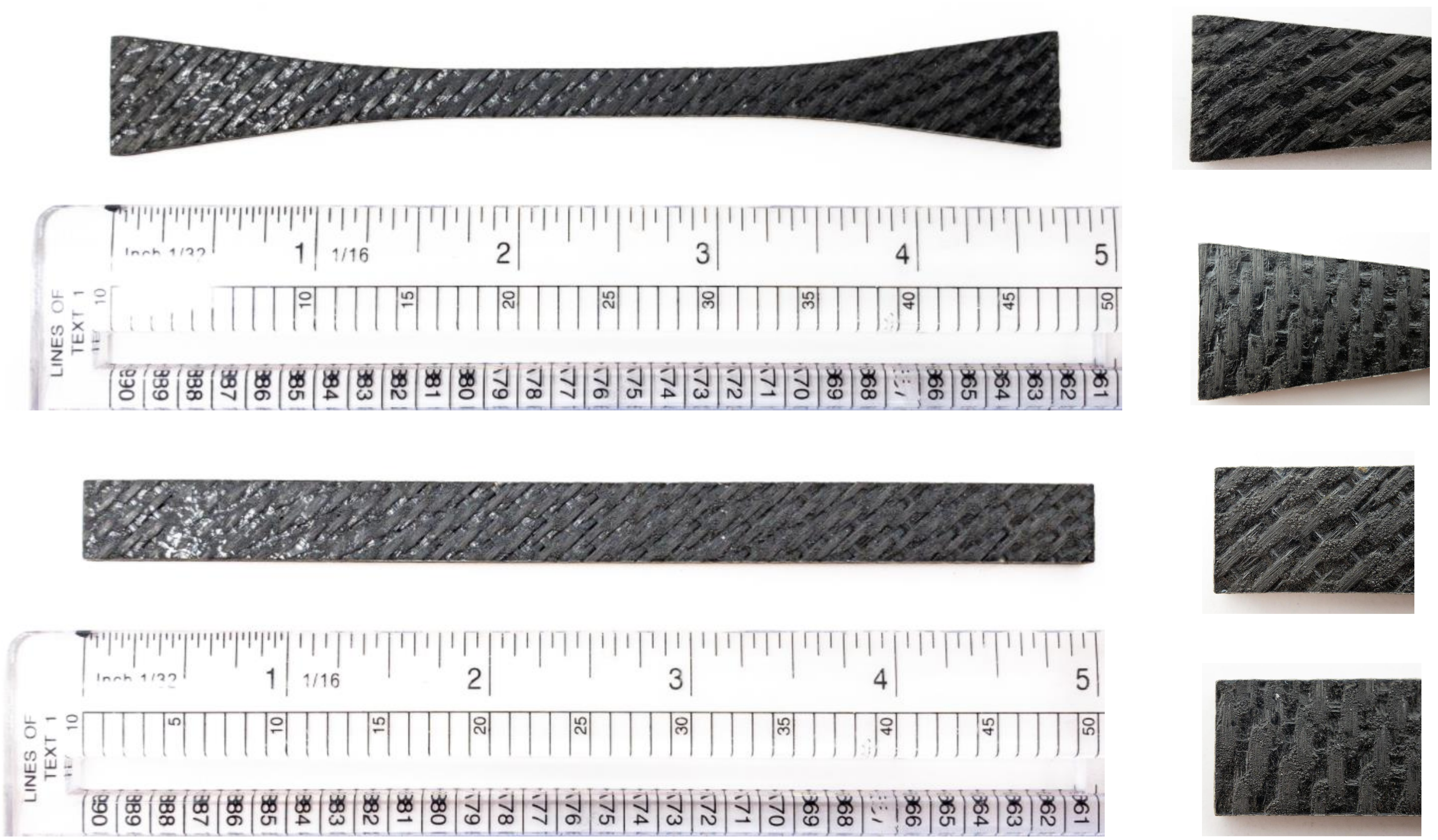
Technology Advancement

- Two main areas
  - Finite Element Model of Multilayer Tube – Materials Research and Design (MR&D)
    - Pipe Size (OD/ID)
    - Monolith Thickness
    - Composite Layer Thickness
    - Composite Fiber Architecture
      - Number of Layers
      - Wind Angle
      - Tension
  - Additional High Temperature (900°C) CO_2 Corrosion Testing – Sandia National Laboratories (SNL)
    - Hexoloy SE
    - Hexoloy SA

Maximum Use Temperature	1900°C
Flexural Strength (MPa) @ Room Temp @ 1450°C @ 1600°C	 280 270 300
Density (g/cc)	3.05
Apparent Porosity (%)	5-10
Modulus of Elasticity (GPa) @20°C @1300°C	 420 363
Thermal Conductivity (W/mK) @ 1200°C	34.8
Coefficient of Thermal Expansion	4.02 x 10^-6/°C

Finite Element Model – Material Characterization

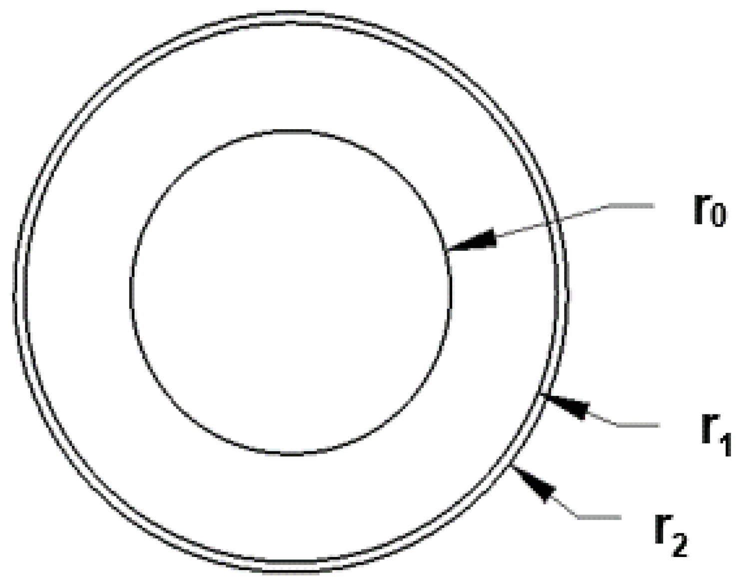
- Micromechanical Predictions
  - Materials
  - Fiber Volume Fraction
  - Fiber Interface
  - Fiber Winding Angle
  - Stress State of Monolithic Pipe
- Measured Properties
  - Fiber
  - CMC Matrix

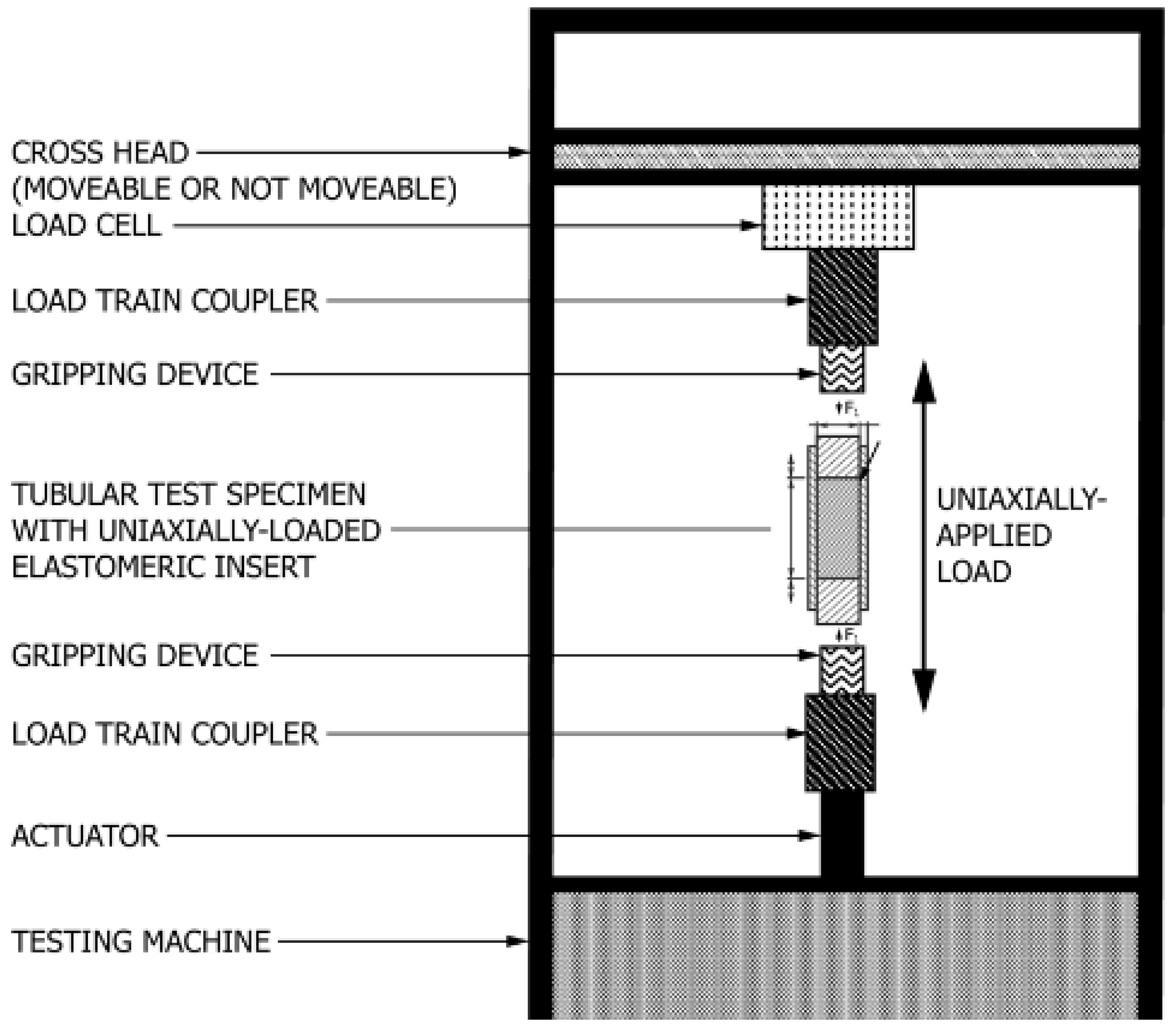


Layup	Measured Modulus	Predicted Modulus	Measured Strength	Predicted Strength
0/90	11.6 MSI	13.6 MSI	19.3 ksi	101.5 ksi
+45/-45	11.1 MSI	13.1 MSI	9.8 ksi	35.2 ksi

Finite Element Model – Preliminary Tubular Tests

- Hoop Stress
  - Force over area exert circumferentially in both directions on every particle in the cylinder wall
- Monolithic Tubes & Multilayer Tubes





Specimen	Layers	Debond Layer	# of Samples	Specimen Length (in.)	Avg. r_0 (in.)	Avg. r_1 (in.)	Avg. r_2 (in.)	Avg. Monolith thickness (in.)	Avg. CMC thickness (in.)	Max Pressure (psi)	Max Pressure Std Dev. (psi)	Max Hoop Stress (psi)
100X2	2	No	3	3.125	0.366	0.499	0.532	0.133	0.033	9081	615	30307
100D2		Yes	5		0.366	0.5	0.535	0.134	0.035	8710	528	28890
100X4	4	No	5	3.375	0.366	0.499	0.564	0.133	0.065	8670	545	28867
100D4		Yes	5		0.365	0.499	0.558	0.134	0.059	9984	374	32955
100X6	6	No	5	3.625	0.366	0.501	0.589	0.135	0.088	9294	897	30644
100D6		Yes	5		0.368	0.503	0.586	0.135	0.083	9376	619	30924
Average										9186	596	30431
125D2	2	Yes	5	4.125	0.366	0.627	0.665	0.261	0.038	15316	323	31098
125X4	4	No	4	4.375	0.365	0.628	0.701	0.263	0.073	14619	590	29502
125D4		Yes	5		0.365	0.626	0.699	0.261	0.073	16164	379	32788
125X6	6	No	8	4.625	0.366	0.629	0.733	0.263	0.103	15781	571	31887
125D6		Yes	5		0.366	0.63	0.731	0.264	0.101	15793	1401	31902
Average										15535	653	31435

Finite Element Model – Additional Tubular Tests

- Multilayer Tubes of Various Configurations
  - “Standard” Parameters
  - Hoop Fiber Architecture
  - Combined Fiber Architecture
  - Altered Wind Patterns
  - Increased Fiber Tension
  - Increased Monolith Wall Thickness
- Monolithic and Composite Only Tubes
- FEA Simulations
  - Updated SiC and CMC elastic properties from prior simulations
  - 10 FEA simulations performed

Configuration	Description	Notes on FEA
125NCG-4X21L	1.25" OD Monolith, Nicalon CG, 4 Layers, +/-55° Architecture, 2:1 Wind Pattern, 1 lb Tension	2 FEA cases (with and without pre-stress)
125NCG-4H21L	1.25" OD Monolith, Nicalon CG, 4 Layers, +/-87° Architecture (Hoop Wind), 2:1 Wind Pattern, 1 lb Tension	1 FEA case (with pre-stress)
125NCG-4C21L	1.25" OD Monolith, Nicalon CG, 4 Layers, Combined Architecture ((+/-55°, Hoop (87°), Hoop (87°), 55°)), 2:1 Wind Pattern, 1 lb Tension	*Mixed angle design; not analyzed.*
125NCG-4X11L	1.25" OD Monolith, Nicalon CG, 4 Layers, +/-55° Architecture, 1:1 Wind Pattern, 1 lb Tension	*Same as Tubes 1 and 2 for FEA purposes*
125NCG-4X81L	1.25" OD Monolith, Nicalon CG, 4 Layers, +/-55° Architecture, 8:1 Wind Pattern, 1 lb Tension	*Same as Tubes 1 and 2 for FEA purposes*
125NCG-4X21H	1.25" OD Monolith, Nicalon CG, 4 Layers, +/-55° Architecture, 2:1 Wind Pattern, High Tension (3 lb)	1 FEA case (with pre-strss)
125NCG-4X21L-ND	1.25" OD Monolith, Nicalon CG, 4 Layers, +/-55° Architecture, 2:1 Wind Pattern, 1 lb Tension, No De-Bond Coating	*Same as Tubes 1 and 2 for FEA purposes*
125NCG-4X21L-COMP	1.25" OD Monolith, Nicalon CG, 4 Layers, +/-55° Architecture, 2:1 Wind Pattern, 1 lb Tension, Composite Only	2 FEA cases (with and without pre-stress)
150NCG-4X21L	1.50" OD Monolith, Nicalon CG, 4 Layers, +/-55° Architecture, 2:1 Wind Pattern, 1 lb Tension	1 FEA case (with pre-stress)
150HEXOLOY	1.50" OD Monolith Only	1 FEA case (without pre-stress)
125HEXOLOY	1.25" OD Monolith Only	1 FEA case (without pre-stress)

Finite Element Model – Results and Conclusions

- Tested Results vs. Model
  - Model slightly overpredicted multilayer and composite
- Adding CMC to Monolith offers a slight reduction in SiC hoop stress, or equivalently, a slight increase in expected failure pressure
- ID and OD are the primary parameters that control expected failure pressure
- Fiber architecture*, wind pattern, and fiber tension have little effect on the expected failure pressure

Configuration	Description	# of Samples	Specimen Length (in.)	Avg. r_0 (in.)	Avg. r_1 (in.)	Avg. r_2 (in.)	Avg. Monolith thickness (in.)	Avg. CMC thickness (in.)	Max Pressure (psi)	Max Pressure Std Dev. (psi)	Max Hoop Stress (psi)	Predicted Max Pressure (psi)	% Difference
125NCG-4X21L	Standard Wind	5	3.6	0.495	0.626	0.69	0.131	0.064	7154	671	31136	7235	1%
125NCG-4H21L	Circumferential Wind	7	3.6	0.494	0.626	0.686	0.132	0.06	6936	437	29816	7633	10.05%
125NCG-4C21L	Combined Wind	7	3.6	0.496	0.626	0.687	0.13	0.061	7158	521	31467		
125NCG-4X11L	1/1 Wind Pattern	3	3.6	0.498	0.626	0.687	0.128	0.061	7112	145	31740		
125NCG-4X81L	1/8 Wind Pattern	3	3.6	0.49	0.626	0.689	0.136	0.064	6649	353	27830		
125NCG-4X11L/4X18L	1/1 & 1/8 Wind Patterns	6	3.6	0.494	0.626	0.688	0.132	0.062	6881	350	29785		
125NCG-4X21H	High Tension Standard Wind	7	3.6	0.496	0.626	0.678	0.13	0.052	7139	318	31345	7436	4.16%
125NCG-4X21L-ND	No-Debond Standard Wind	7	3.6	0.494	0.626	0.687	0.132	0.062	6381	813	27436		
Average									6926	451	**30069**		
125HEXOLOY	Monolith Only	2	3.1	0.492	0.626	NA	0.134	NA	6799	199	**28747**	6799	0.01%
125NCG-4X21L-COMP	Composite Only Standard Wind	7	2.1	0.625	0.625	0.689	NA	0.064	1457	150	22473	1270	-12.85%
150NCG-4X21L	Standard Wind - Increased Wall Thickness	3	4.7	0.494	0.755	0.819	0.261	0.064	12371	578	30861	12569	1.60%
150HEXOLOY	Monolith Only - Increased Wall Thickness	1	4.3	0.492	0.753	NA	0.261	NA	7978	x	20089	11913	49.32%

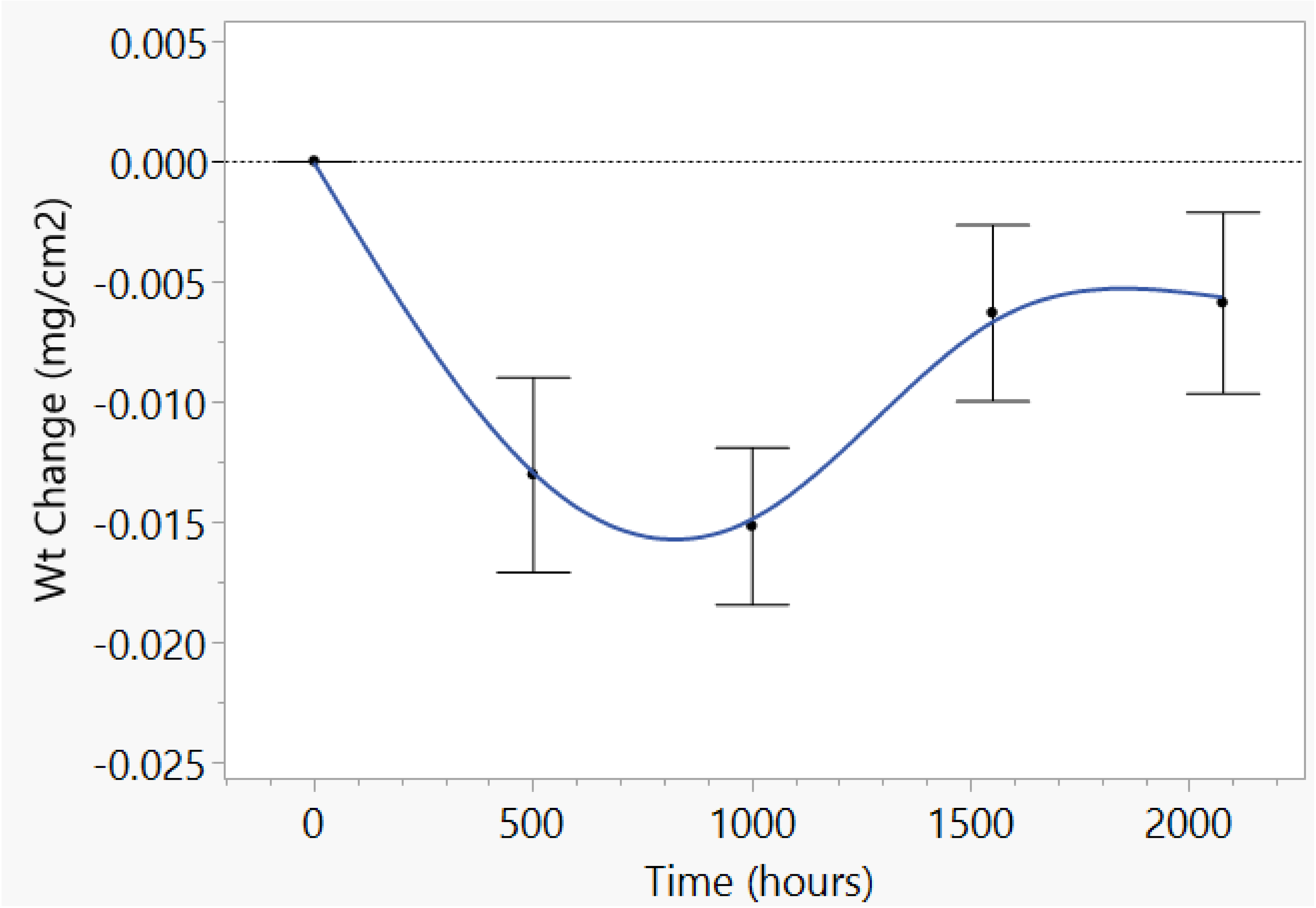
* Fiber architecture has a significant effect on CMC strength

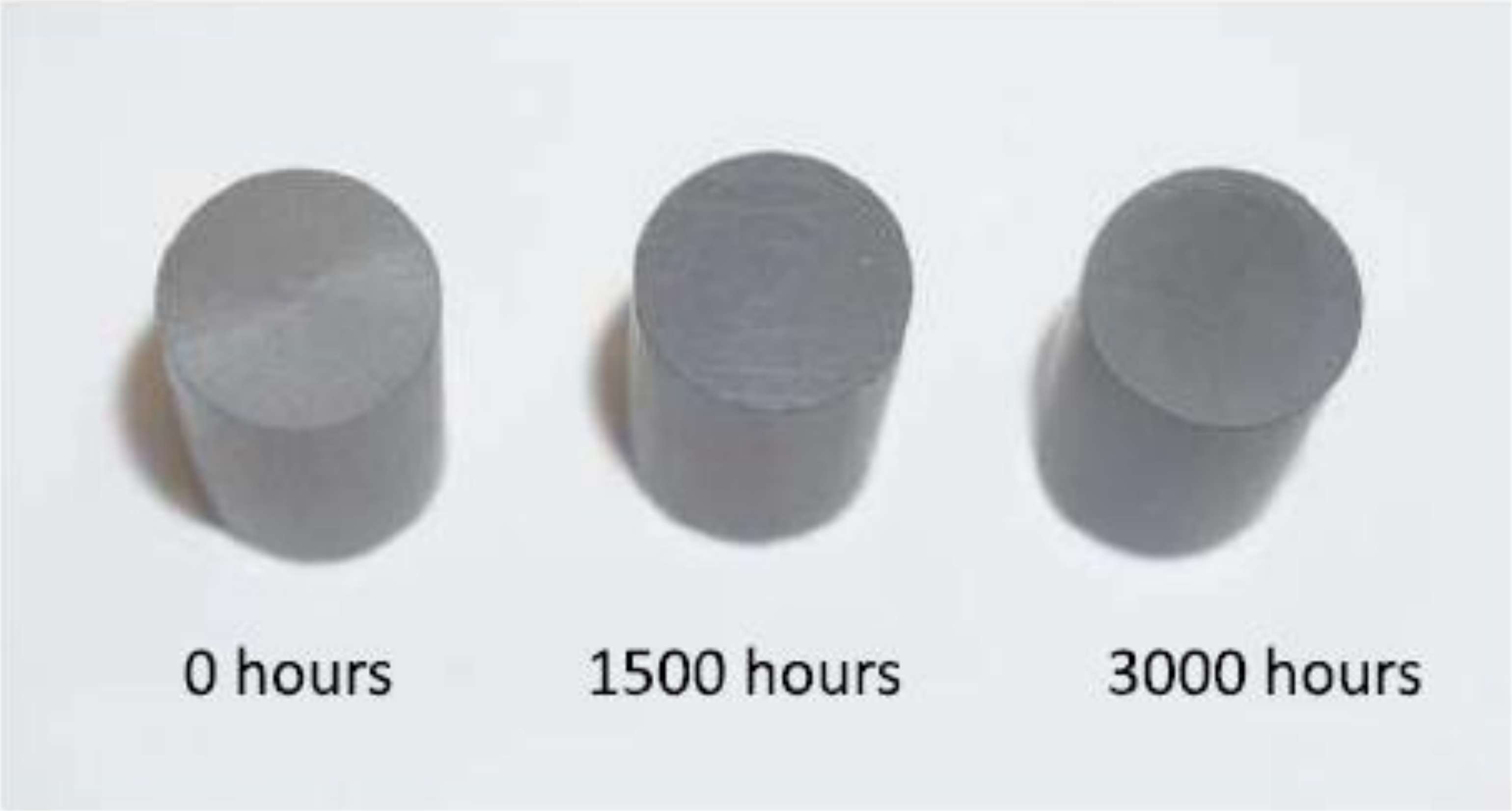
Corrosion Testing - Overview

- Tests performed at Sandia National Laboratories (SNL)
- Two SiC types both of which are used for multilayer tubes were tested
  - Hexoloy SE©
  - Hexoloy SA©
- Exposed to industrial-purity CO_2 at 900°C for durations up to 3000 hours
- Characterization using precision scale and SEM/EDS

Corrosion Testing – Results

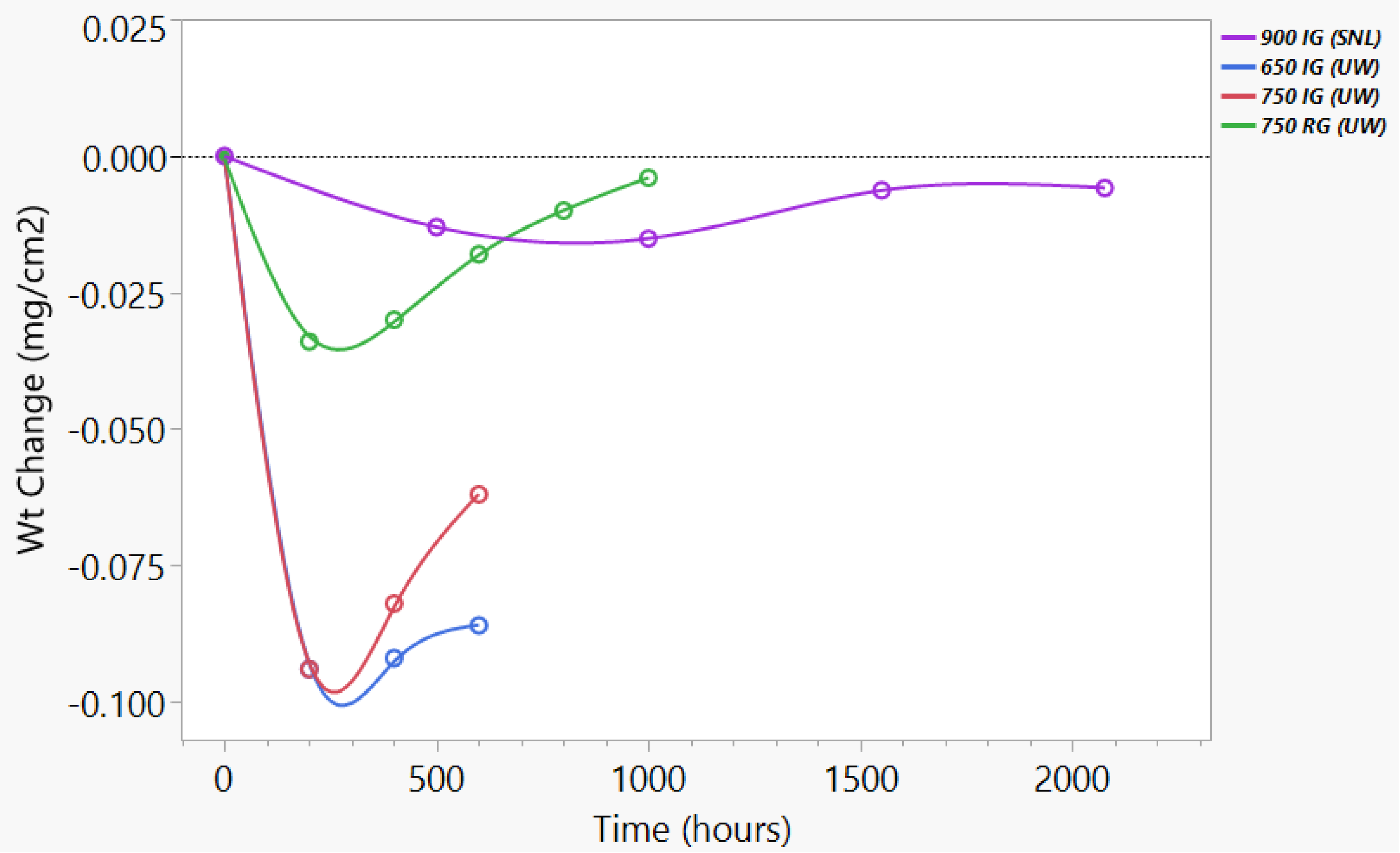
- Hexoloy SE and SA exhibited weight loss, bottoming out around 1000 hours, and rising up and leveling off at 1500 hours
- Surface chemistry change
  - Visual Difference
  - Hexoloy SA oxygen concentration increase from 1.4 atom percent (unexposed) to 36 atom percent at 1500 hours of exposure
  - Formation of surface oxide, SiO_2 (silica) - EDS
  - Hexoloy SE samples experienced the same oxide growth. Thickness of 2.5-3.0 micrometers at 3000 hours of exposure

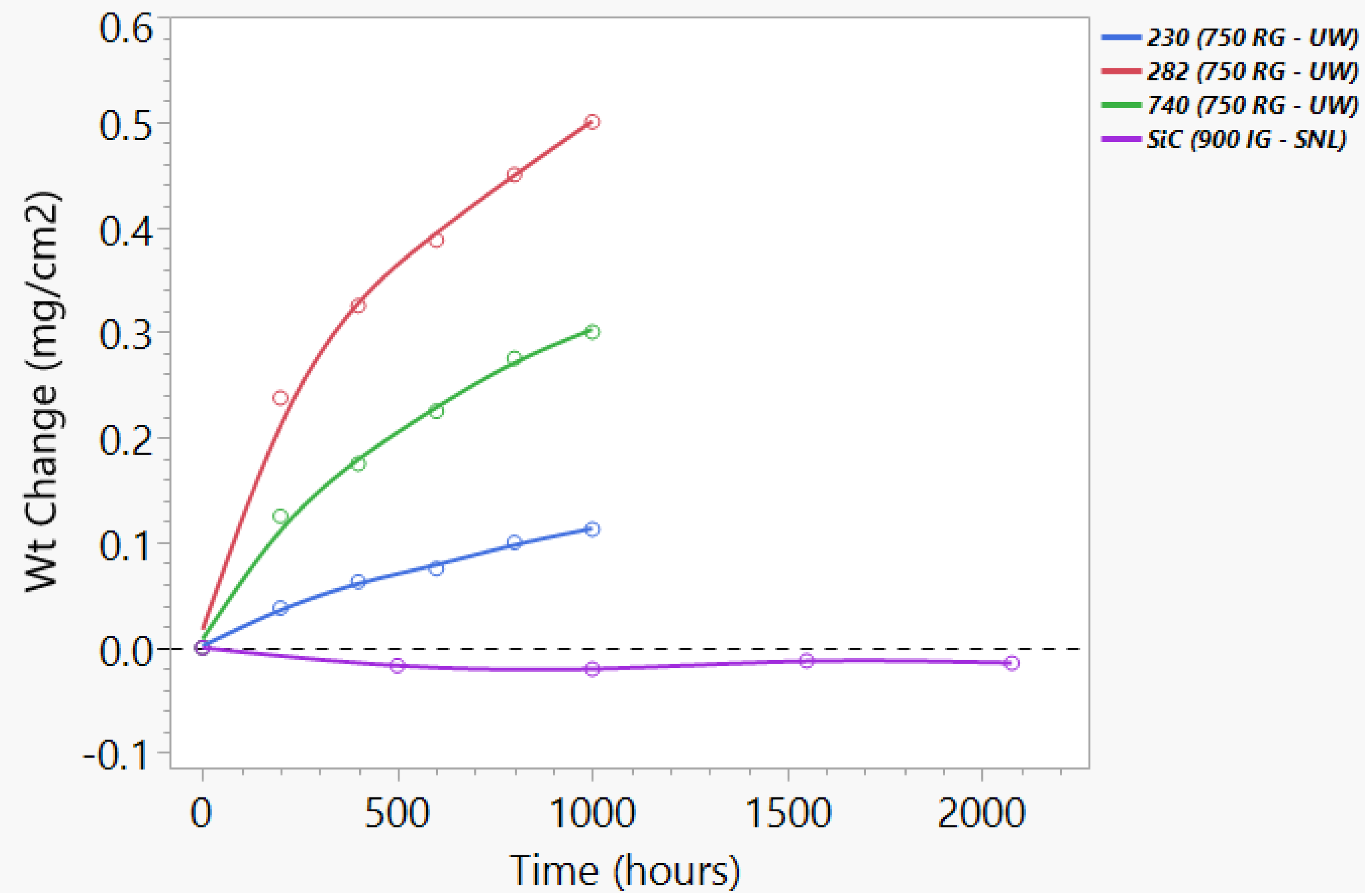




Corrosion Testing – Results (Cont.)

- Results mimic those of UW performed using RG and IG CO_2 at lower temperatures
  - Hypothesized that this weight change is caused by the impurities in either the SiC or CO_2 reacting leading to a weight loss followed by the formation of the SiO_2 layer and weight increase
- Nickel-based alloys in CO_2 experience weight gain
- SiC has been shown to have excellent chemical compatibility in high temperature CO_2 environments





Summary

- Finite Element Model was able to reliably (11%) estimate expected failure pressure and hoop stress of multilayer tubes
  - Optimize the component parts of the material system
- Corrosion tests continue to support the chemical combability of SiC in high temperature CO_2
- Multilayer tubes provide increased creep and corrosion tolerance compared to alloys
- Continued work in areas such as joining, code case development, surface coatings

Questions

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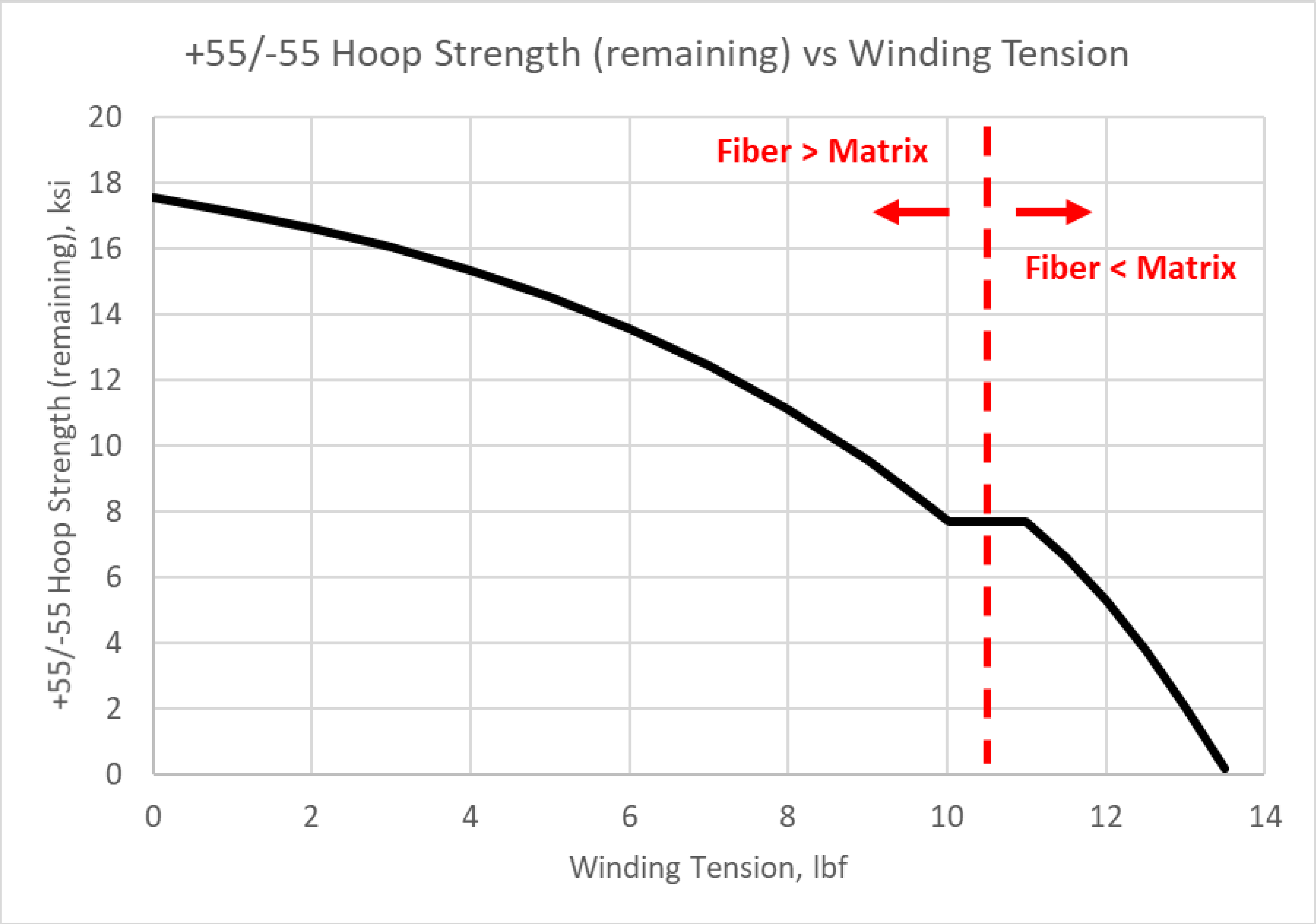
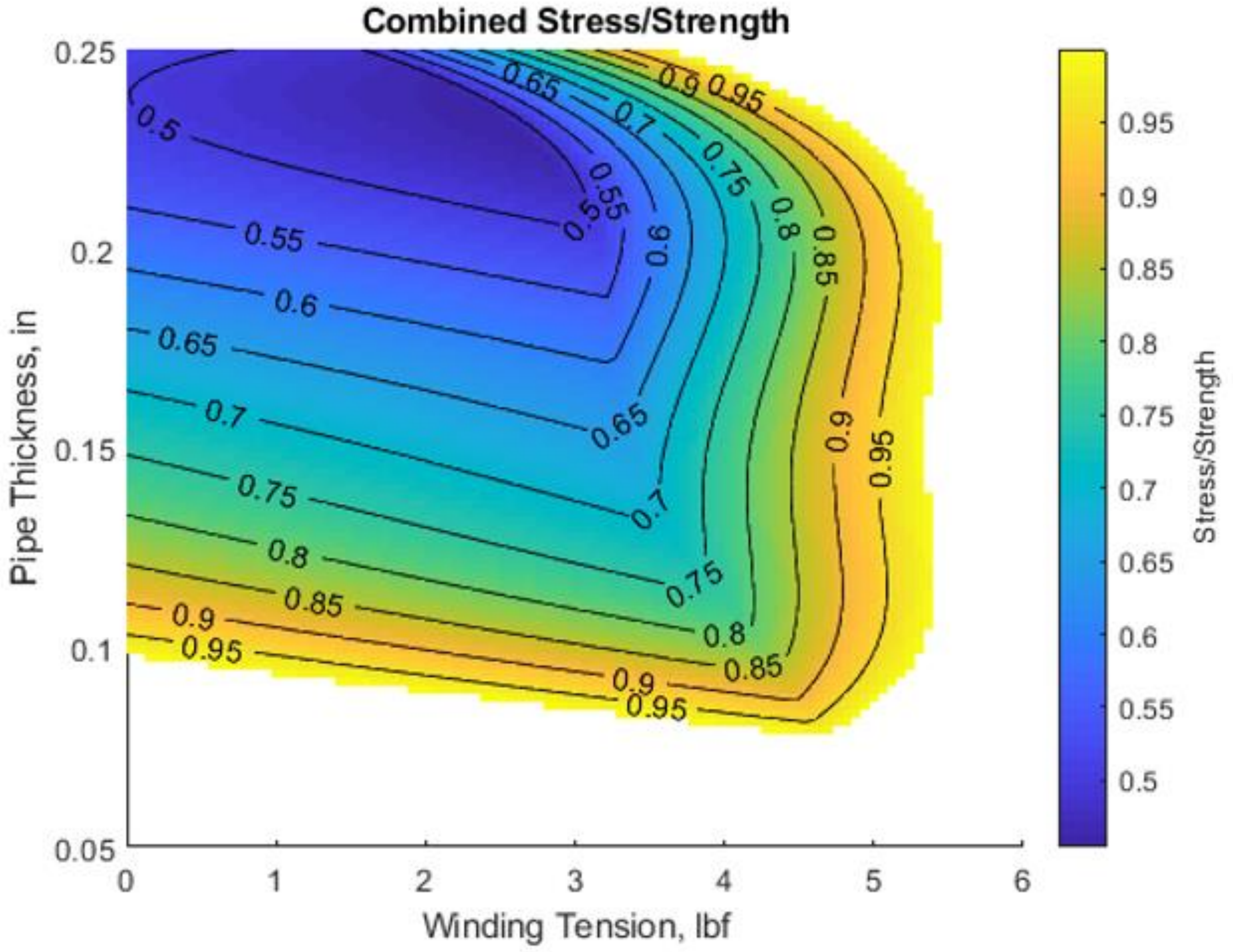
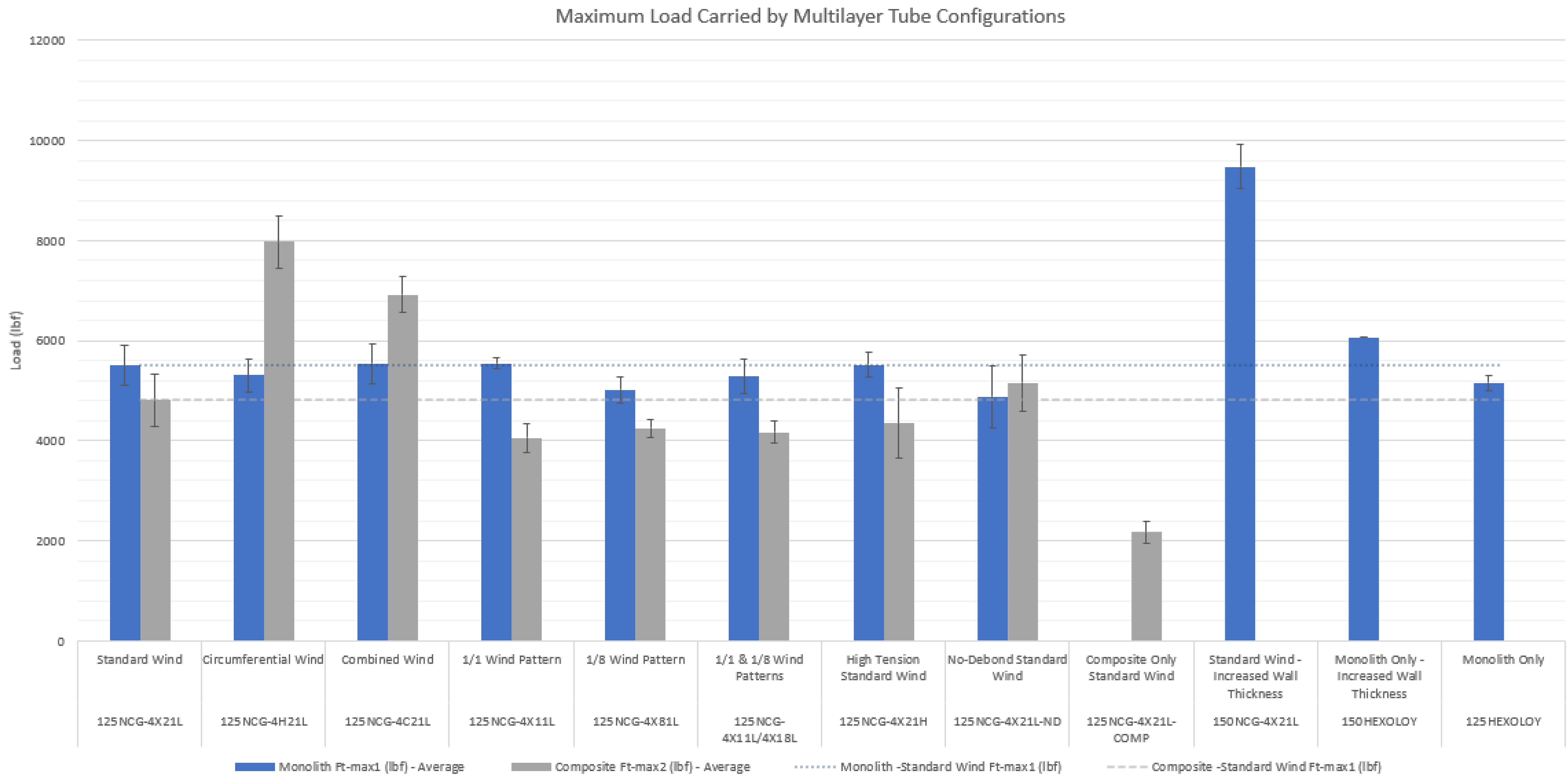
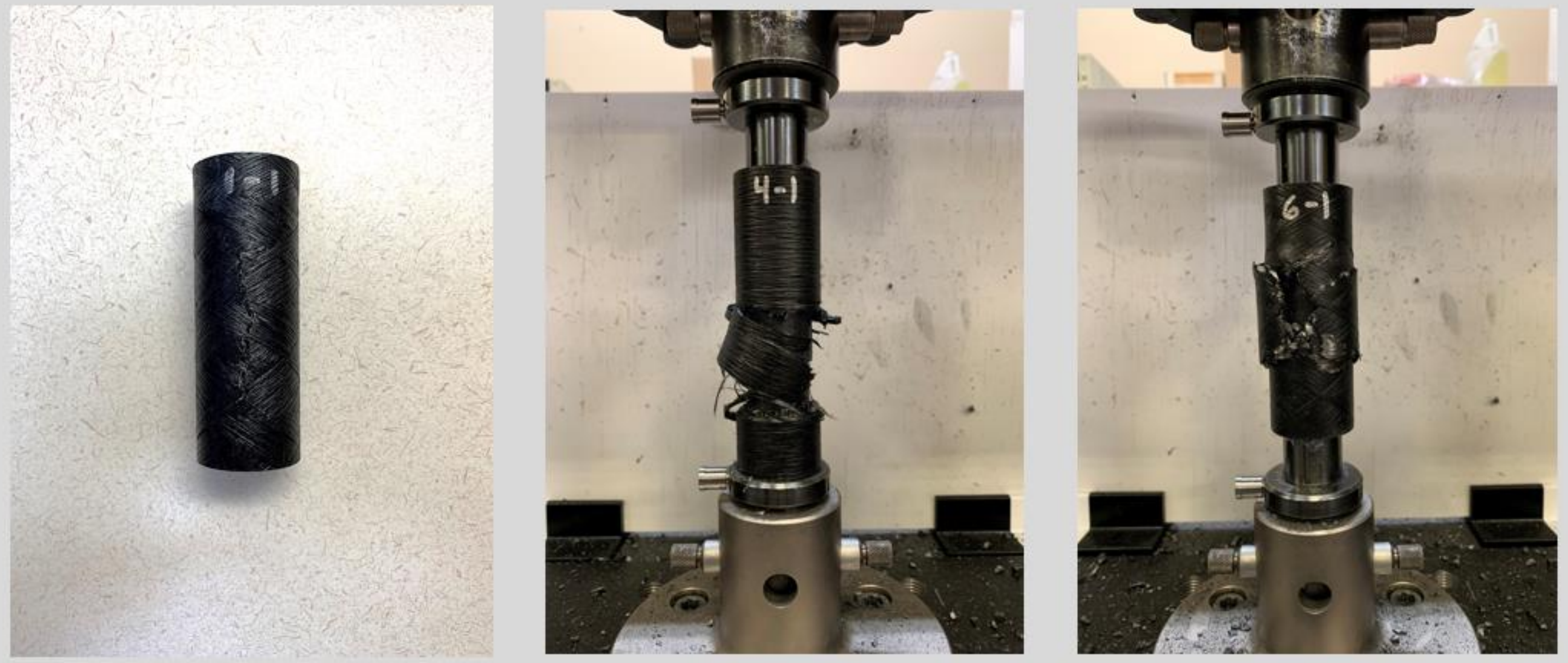
Finite Element Model – Modeling





Finite Element Model – Failure Characteristics





Standard Wind Circumferential Wind Combined Wind