NCSX Peer Review
Cable Conductor Material Properties

May 6, 2004

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Material Property Test Program

- **Purpose:**
  - To evaluate and determine by testing the mechanical properties of the modular coil copper rope conductor.
  - Test data will be be used to develop the Design Criteria for the modular coil conductor

Specimen Fabrication Part I

Jim Chrzanowski

Specimen Preparation

- **Specimens were prepared and vacuum impregnated at PPPL.**
- **Four types of test specimens were fabricated**
  - Single bare conductor (Flexural and compression)
  - 2 x 5 bare bundle (Transverse compression)
  - 4-turn insulated coil (Tensile and Fatigue)
  - Full insulated bundle- 40 turn (Bending/ flexural)

Specimen Preparation-
Conductor Properties

- **Conductor**
  - Compacted copper rope (oxygen-free copper)
  - Bare dimensions (0.310 in. x 0.351in. +/- 0.010 in.)
  - 2640 strands of 34 gauge wire– (nom. Dia. 0.0063 in.)
  - Construction:
    - (44) @ 2.5 in. RHL/ (5) @ 3.5 in. RHL/ (9) @ 5.5 in. LHL
    - (44) @ 2.5 in. LHL/ (5) @ 3.5 in. LHL/ (3) @ 5.5 in. RHL
  - Cable Manufacturing Preparation:
    - Clean: No oil type lubricates used in any of the drawing or forming operations
    - Regular (unclean): Normal fabrication process used lubricate during initial processing

Specimen Preparation-
Conductor Properties

- **Properties of Wire:**
  - Tensile Strength (typical) - Soft **35,000 psi**
  - Yield Strength (typical, 1% offset)- Soft **10,000 psi**
  - Elongation (Typical,% in 10")- Soft **10-25%**
  - Percent Copper (Minimum, including silver)- **99.95%**
  - Electrical Conductivity (IACS-Minimum)- **100%**
  - Resitivity (Maximum, ohms-circ mil/ft)- **10.371**
  - Area (Nom. CMA)- **39.7**
  - DC Resistance- **269.8 Ohms/ 1000 ft.**
  - Nom. Weight- **0.1201 lbs./1000 ft.**

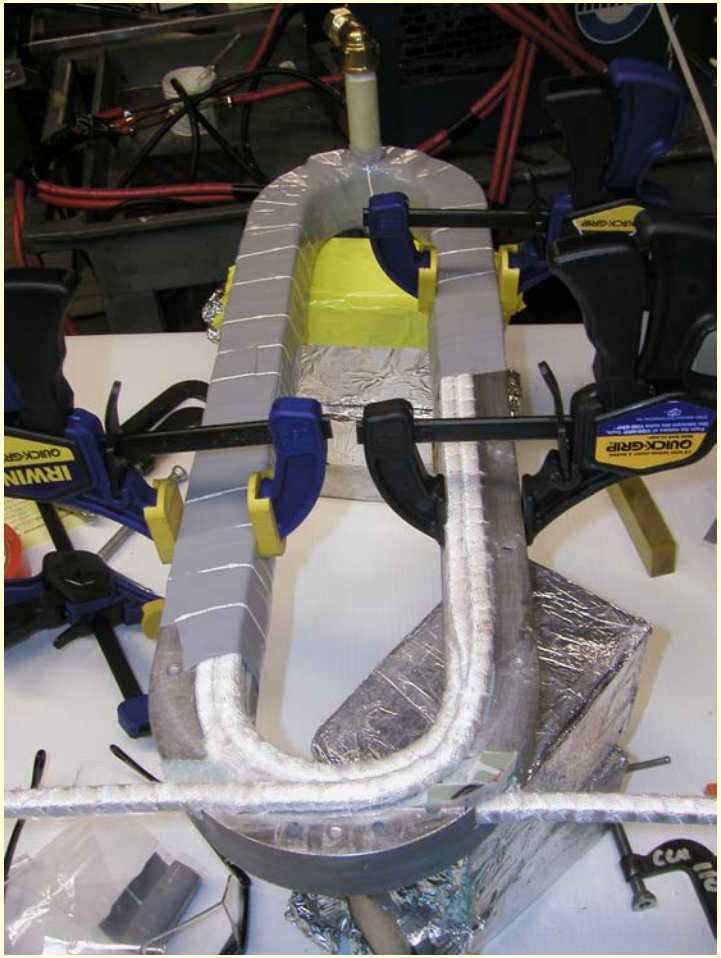
Specimen Preparation

- **Epoxy System:**
  - **CTD-101K *(Well characterized for ITER)***
  - Product of *Composite Technology Dev. Inc.*
  - 3- Component epoxy system
  - Excellent performance at cryogenic temperatures with a long pot life and low viscosity
  - **Cure Cycle**
  - 5 hours @ 110 ° C (Cure)
  - 16 hours @ 125 ° C (Post cure)

Specimen Preparation

- **Single Conductor-** Transverse bend, longitudinal compression & shear
  - Conductors were bare with no insulation
  - VPI'd using CTD-101K in straight 40 inch lengths
- **4-Turn Coils-** Longitudinal tensile and fatigue
  - Conductors were insulated with (1) ½ lapped layer of 0.004 inch thick S-2 glass
  - Conductor was wound into (2) different length racetrack coils
  - Coils were VPI'd using CTD-101K

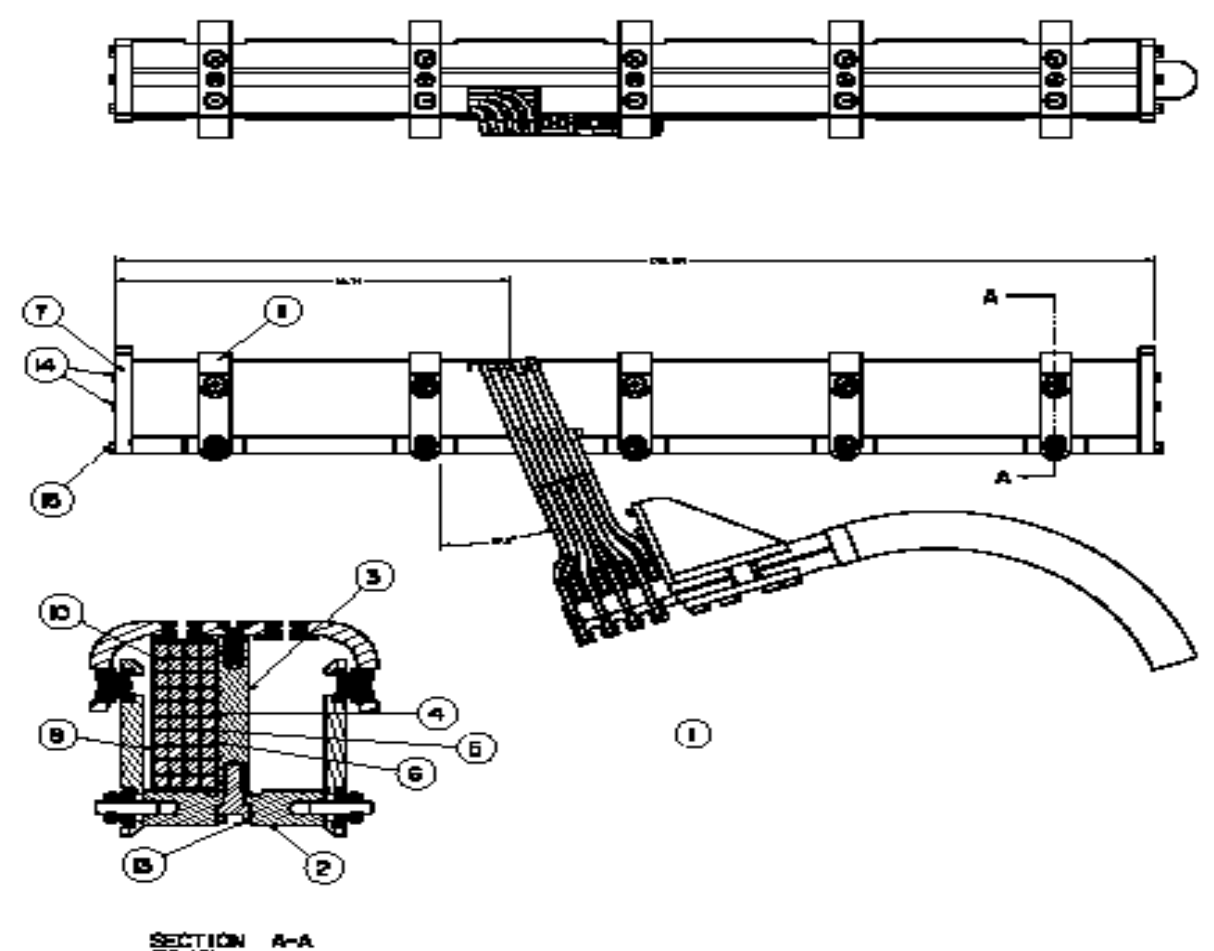
Specimen Preparation- Tensile/Fatigue Tests



Specimen Preparation

- **2 x 5 Bundle-** Transverse Compression
  - Conductors will be bare with no insulation
  - Conductors will be VPI'd as a 2 x 5 bundle using CTD-101K (Mold near completion)
- **Full Bundle-** 40 turn (Bending/flexural)
  - Using Tee mold- construct a full 40-turn bundle with turn and ground wrap insulation as being proposed for modular coils.

Full Bundle Specimen



Material Testing
Part II

Tom Kozub

Specimen Load Orientation

- Transverse Bending/Shear
- Transverse Compression
- Longitudinal (Axial) Compression
- Longitudinal Tensile
- Longitudinal Shear

Material Properties Measured

- Modulus
- Yield Strength
- Ultimate Strength
- Fatigue Strength

Material Conditions

- **Temperature**
  - Room temperature
  - Liquid nitrogen temperature (77 degrees K)
- **Conductor**
  - Clean copper wire
  - Lubricated copper wire

General Test Notes

- Not all combinations of specimen orientation, properties, configuration, and conditions were performed.
- Only certain specific measurements performed.
- Additional measurements need to be performed in future testing.

3- Point Flexural Tests

3-Point Flexure Tests
Beyond Yield

- **Test Description:**
  - Bare epoxy impregnated conductor specimens were cycled four times below or just to yield.
  - Specimens were then cycled to nearly an inch beyond yield.
  - Specimens were tested at room temp.
  - Specimens were tested at LN2 temp.

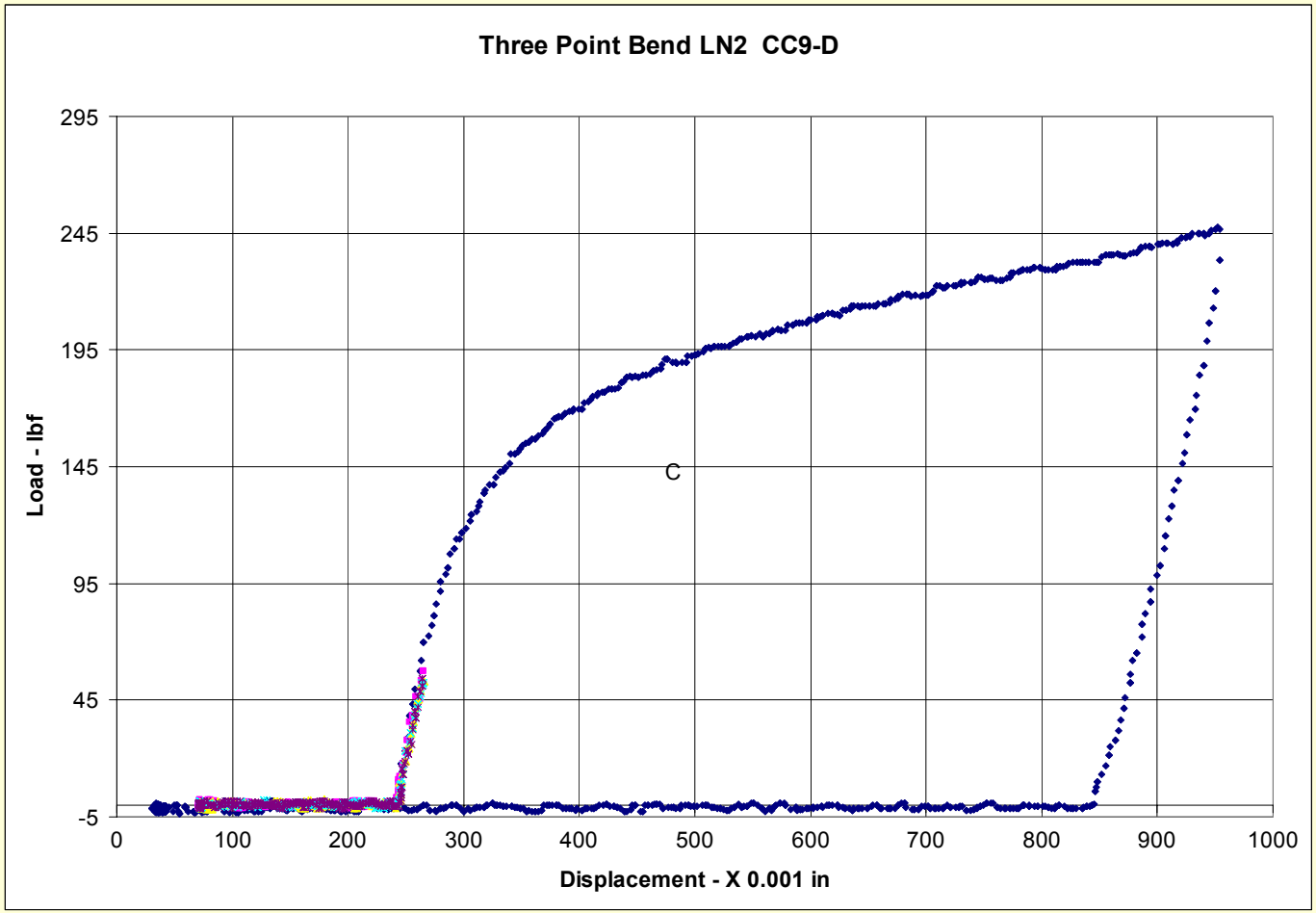
3- Point Flexural Test Fixture with Liquid Nitrogen

3- Point Flexural Test Specimens

Room Temperature Specimens

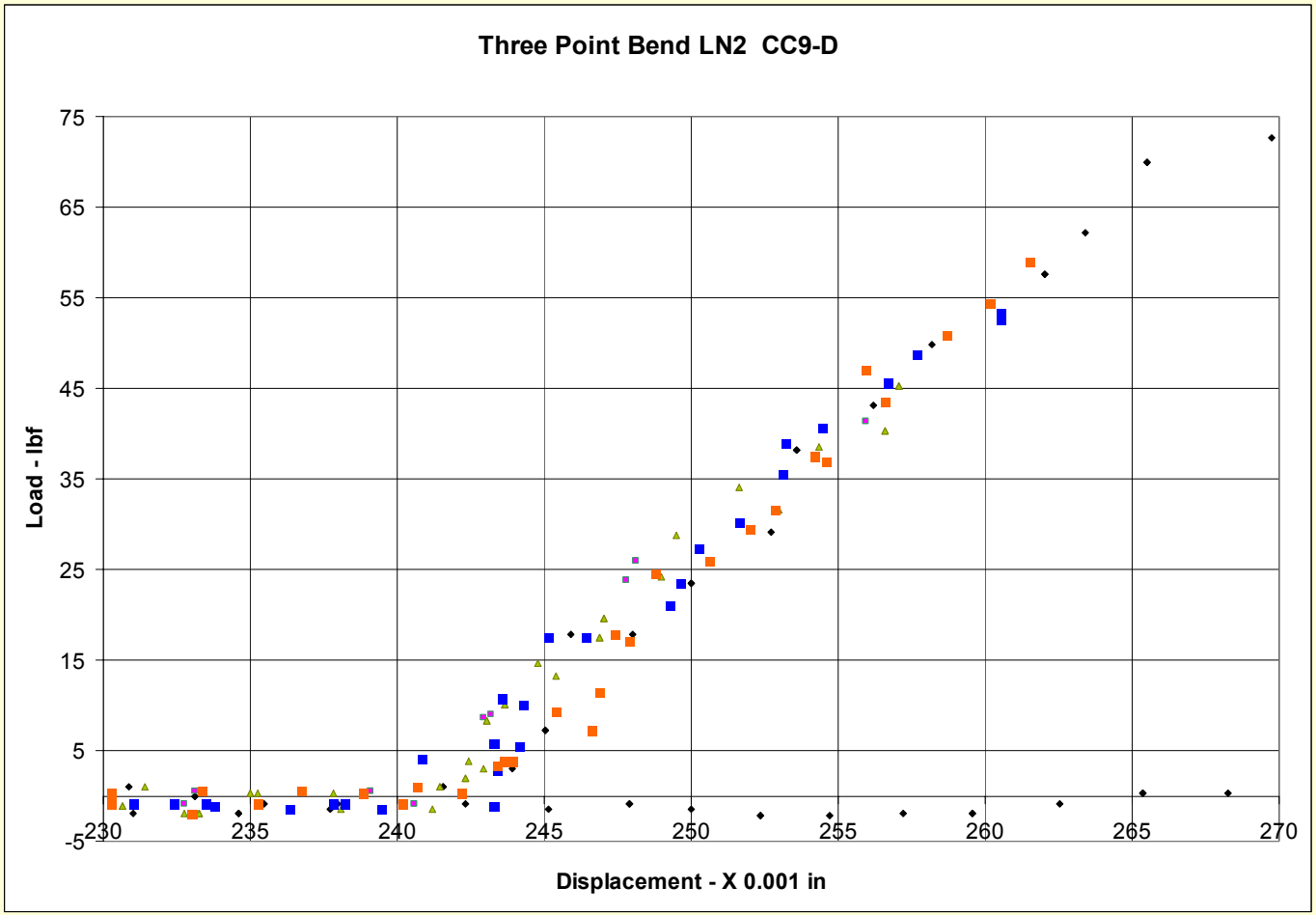
3- Point Flexural Test

LN2 Sample Data- 5 Cycles



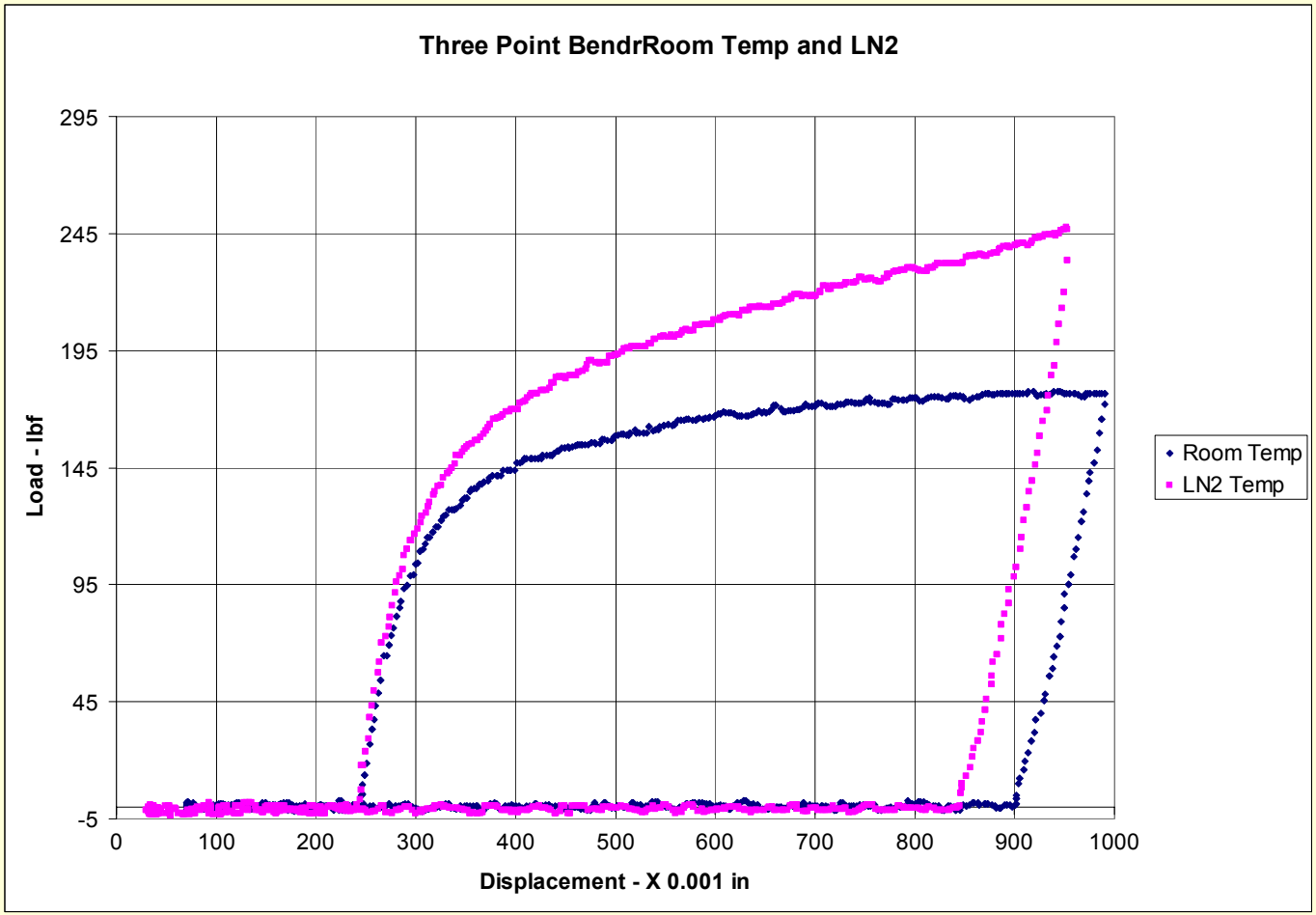
3- Point Flexural Test

Detail of Elastic Region



3- Point Flexural Test

Comparison of RT and LN2



Tangent Modulus of Elasticity
(ASTM D-790)

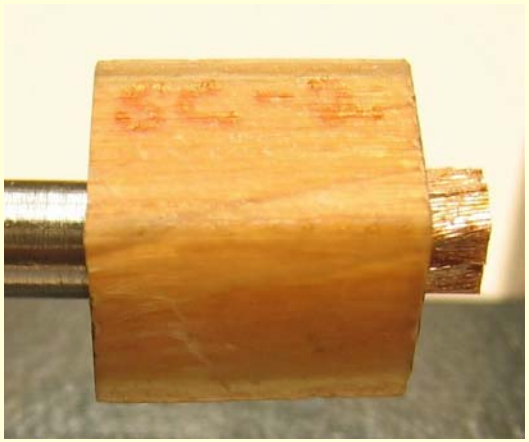
Specimen Material	Area Used For Modulus	Specimen Temperature	Modulus Average	Modulus Std Dev
		Deg. C	10E6 psi	10E6 psi
Bare Cu	Full	25.5	9.7	0.81
Bare CU	Full	-196	11.3	0.69
Glass Wrap	Full	25.5	6.3	0.26
Glass Wrap	Full	-196	7.4	0.42
Glass Wrap	Cu Only	25.5	10.6	0.09
Glass Wrap	Cu Only	-196	11.7	0.14

Three Point Bend
Flexural Offset Yield Strength (at 1% offset)
[See ASTM D790]

Sample Temperature Deg. C	Number of Samples	Average Flexural Offset Yield Strength Ksi	Standard deviation Ksi
25.5	6	36.2	1.2
-196	3	45.2	1.1

Longitudinal Shear Strength Tests

- Test performed only at room temperature.
- Tested several length samples: 0.5”, 0.25”, 0.15”
- Tested several diameter punches: 0.187”,0.125”
- Various aspect ratios tested:
  - If the specimen length is to long with respect to the punch diameter – the material crushes before it shears and ultimately the specimen bursts.

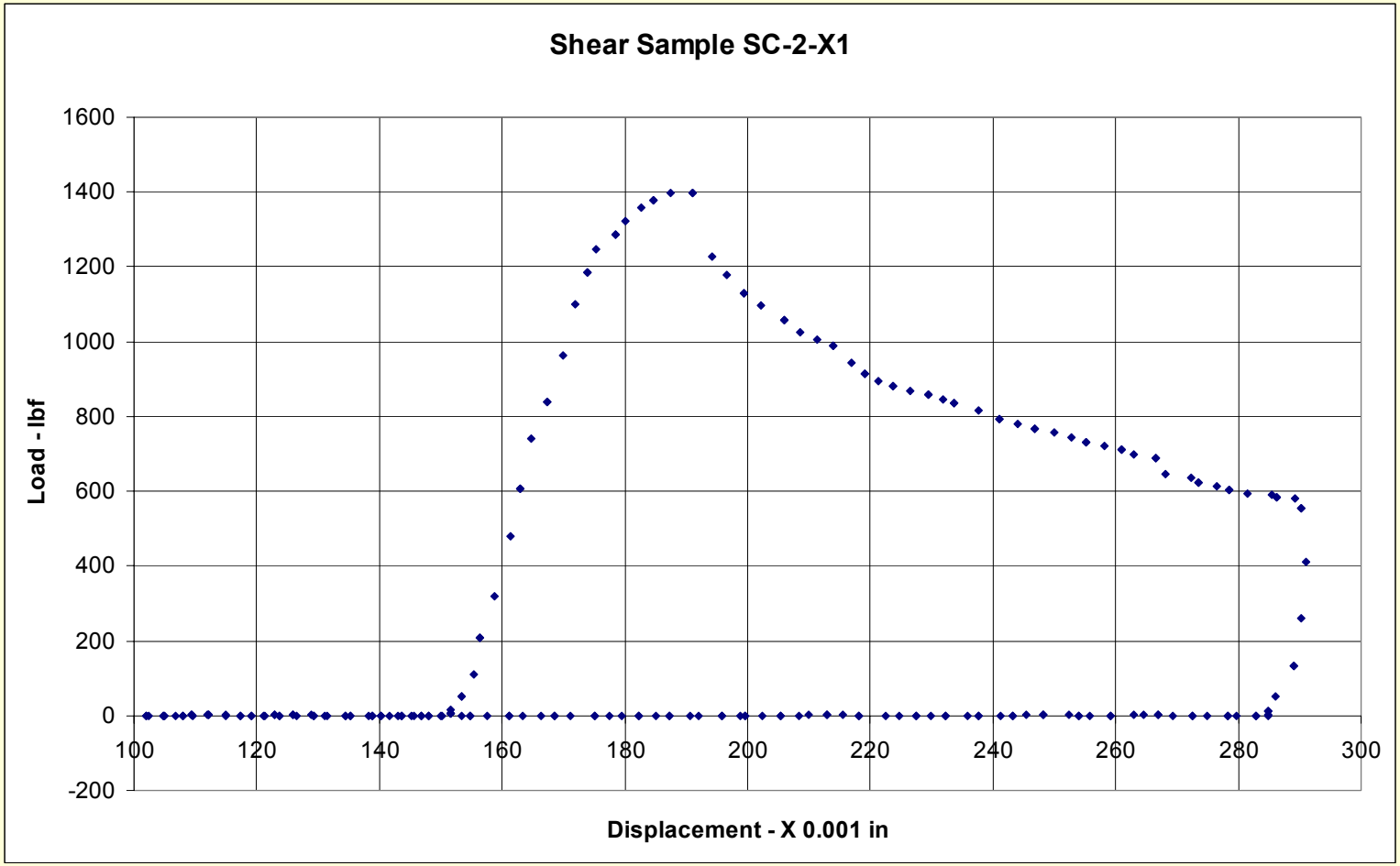


Plug Longitudinal Shear Specimens

Aspect Ratio Too Large

Correct Aspect Ratio

Longitudinal Shear Load – Displacement Curve



Longitudinal Shear
Yield and Ultimate Strength
All tested at Room Temperature

Sample	Yield Strength	Ultimate
	psi	psi
SC-2-X1	4169	4863
SC-2-X2	3584	4730
SC-1-X1	3510	4282
SC-3-X1	3467	4507
SC-4-X1	3806	4671
SC-5-X1	3510	4843
Average	**3674**	**4649**
Standard Deviation	**271**	**222**

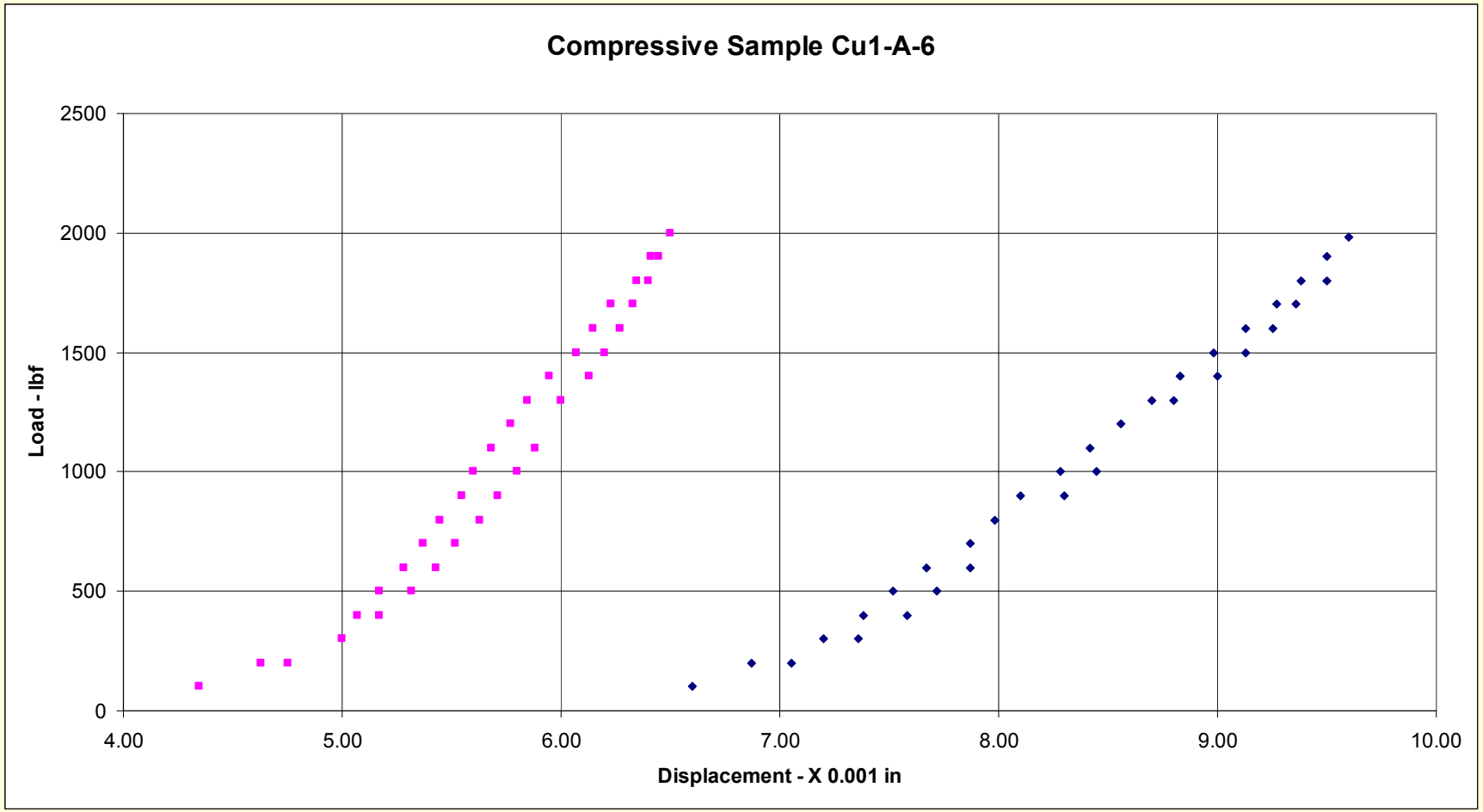
Longitudinal Compressive Tests

Longitudinal Compressive Test Description

- **Test Specimen:**
  - Resin impregnated bare conductor
  - Specimen length approximately 1.34”
  - Ends ground smooth and parallel
- **Test Resolution:**
  - Load: 1 lbf
  - Displacement: <0.0001”
- Tests were performed at **room temperature**

Longitudinal Compressive Test
Frame Deflection Corrections

Longitudinal Compressive Test
Copper Specimen Calibration



Longitudinal Compressive Test

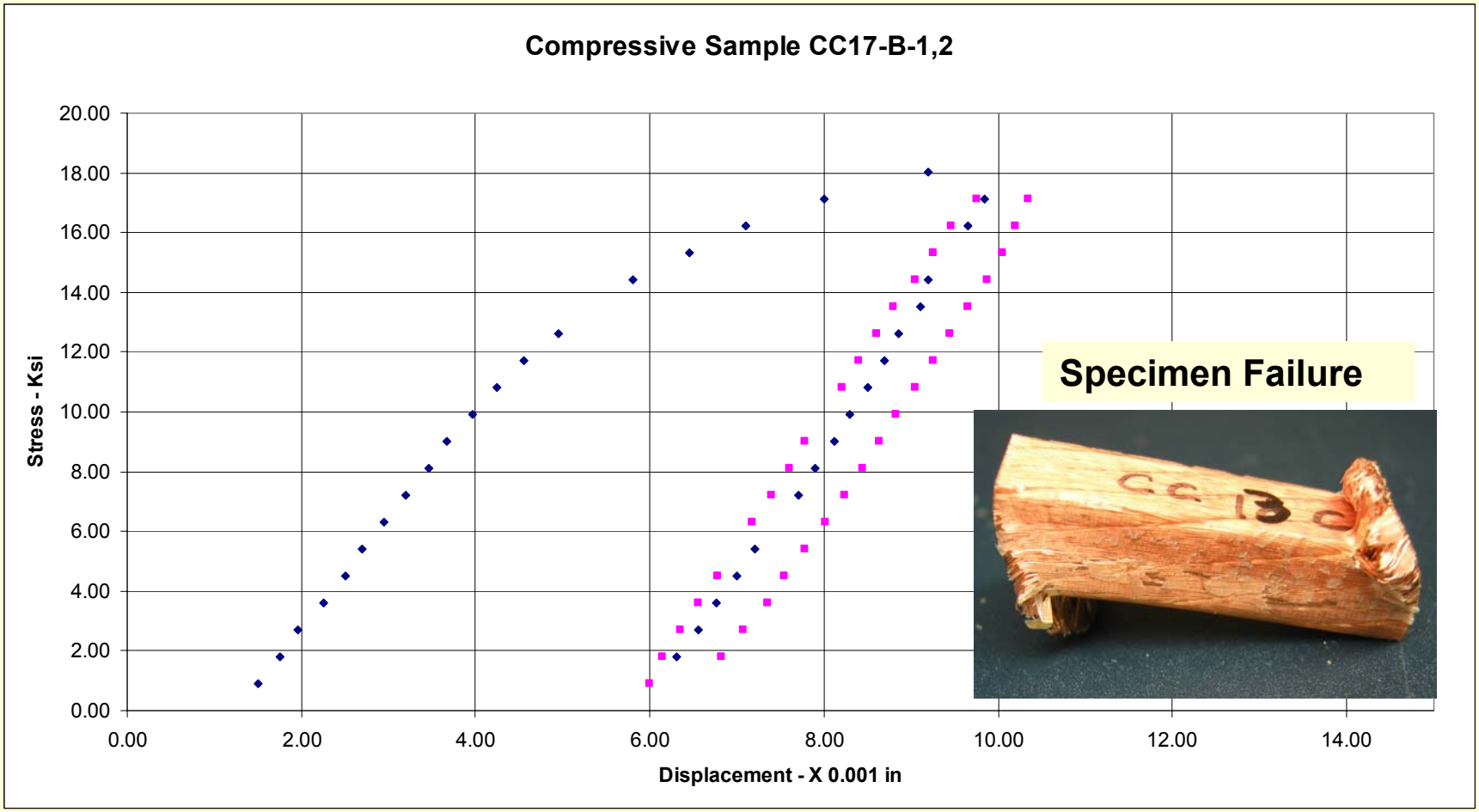
- **Calibration:**
  - Removing the frame compression from Copper Specimen Data provides a modulus of: **17.9 Msi**
  - These results are close to the expected copper modulus of about **17.0 Msi.**

- **Test Loads**
  - Specimens were found to yield between 1500 and 2000 lbf load
  - Test cycles were run between near 0 and 2000 lbf.
  - Several specimens failed near zero to 2000 lbf, so load range was reduced to **1800 lbf peak**.
  - Load rate was **7.5 lbf/sec**

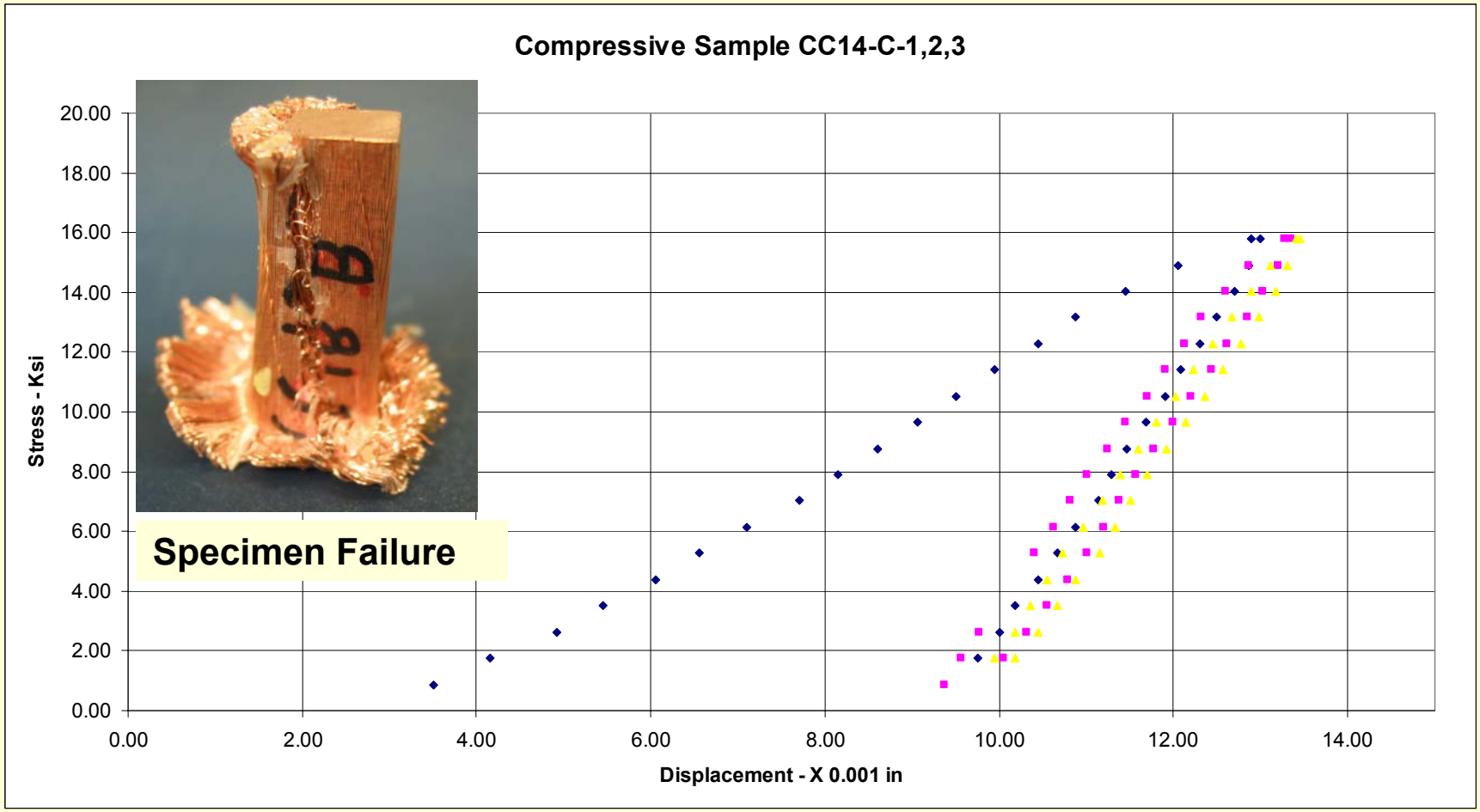
Test Data Results

- Specimens were usually cycled several times, unless failure occurred
- Some specimens had failures.
- Initial curves were of two types
  - Expected straight then yield
  - Very soft with out definite yield point

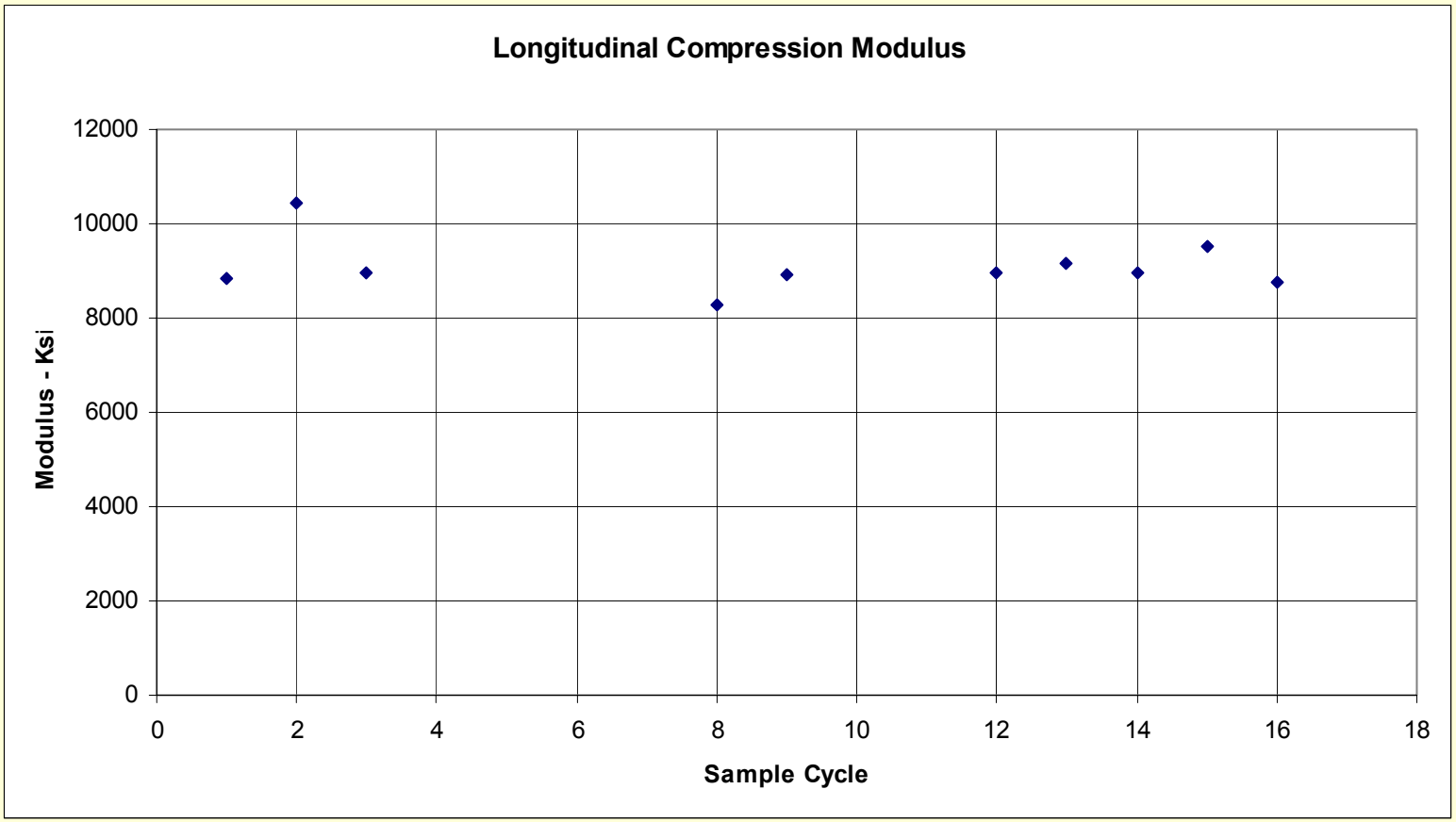
Longitudinal Compressive Test
Type 1 Curve



Longitudinal Compressive Test
Type 2 Curve



Modulus Data

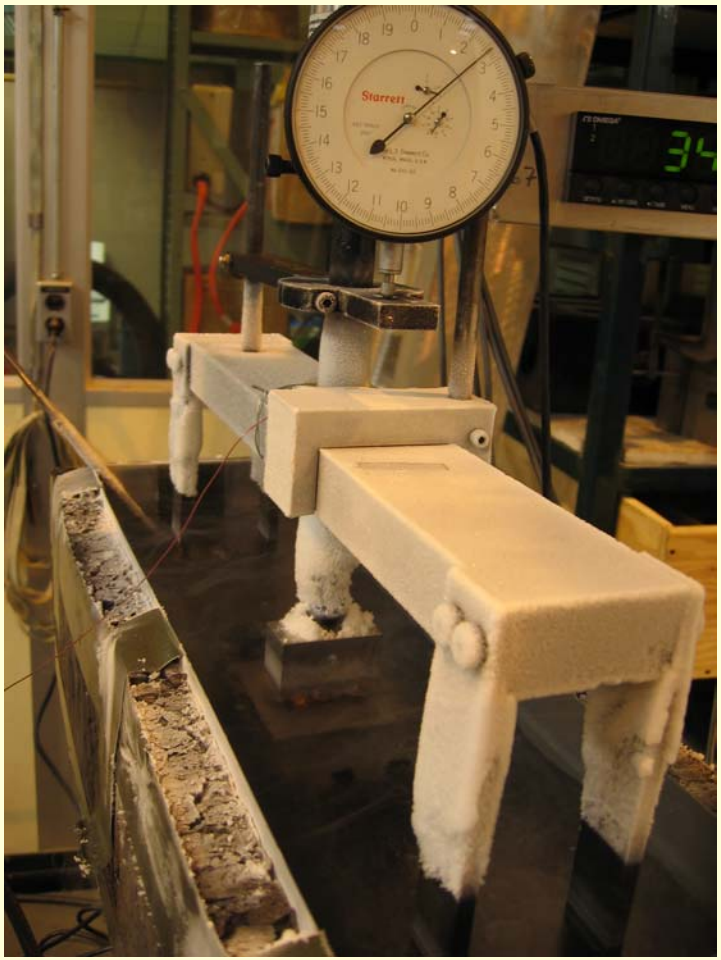


Transverse Compressive Tests

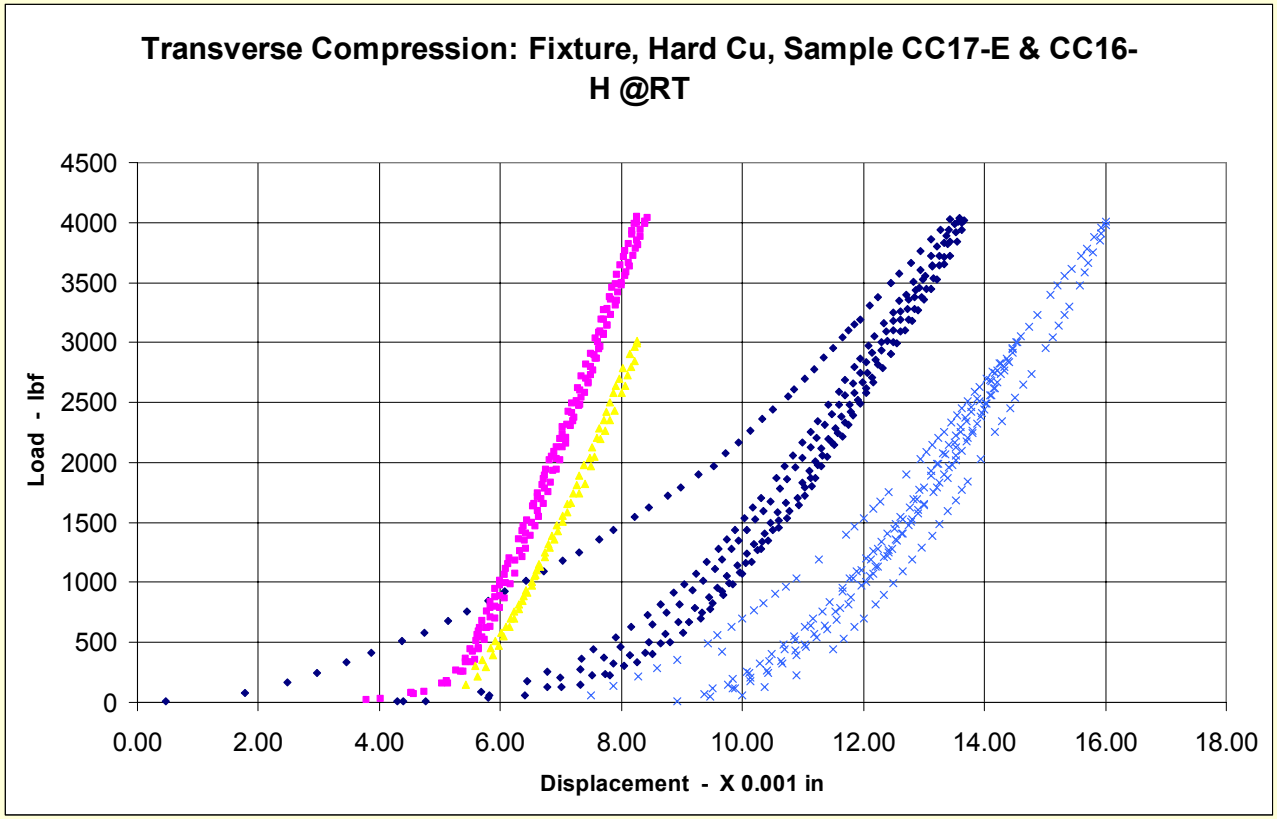
Transverse Compressive Test Description

- Test Specimens
  - Resin impregnated bare conductor
  - Specimen area 0.406 to 0.426 sq in
  - Specimen depth about 0.350 in
- Test Resolution:
  - Load: 1 lbf
  - Displacement: 0.0001 in
  - Tests performed at Room and LN2 temperature
- Ran fixture and hard Copper calibrations at both room and LN2 temperature
- Initial load range from 0 to 3000 lbf, increased to 4000 lbf, still only 10 Ksi max.
- No specimens were loaded to failure.

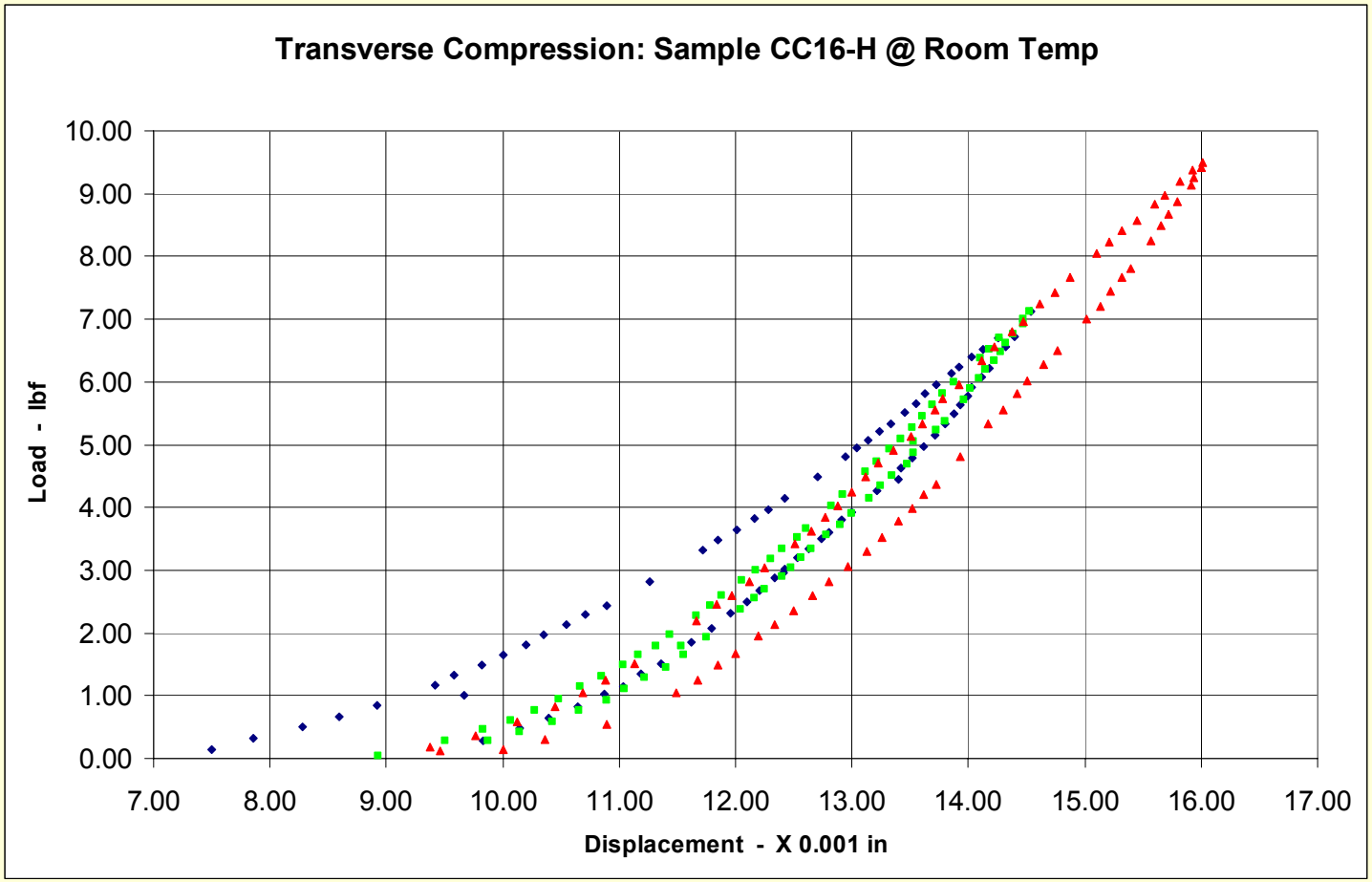
Transverse Compression Test Fixture



Transverse Compressive Curves



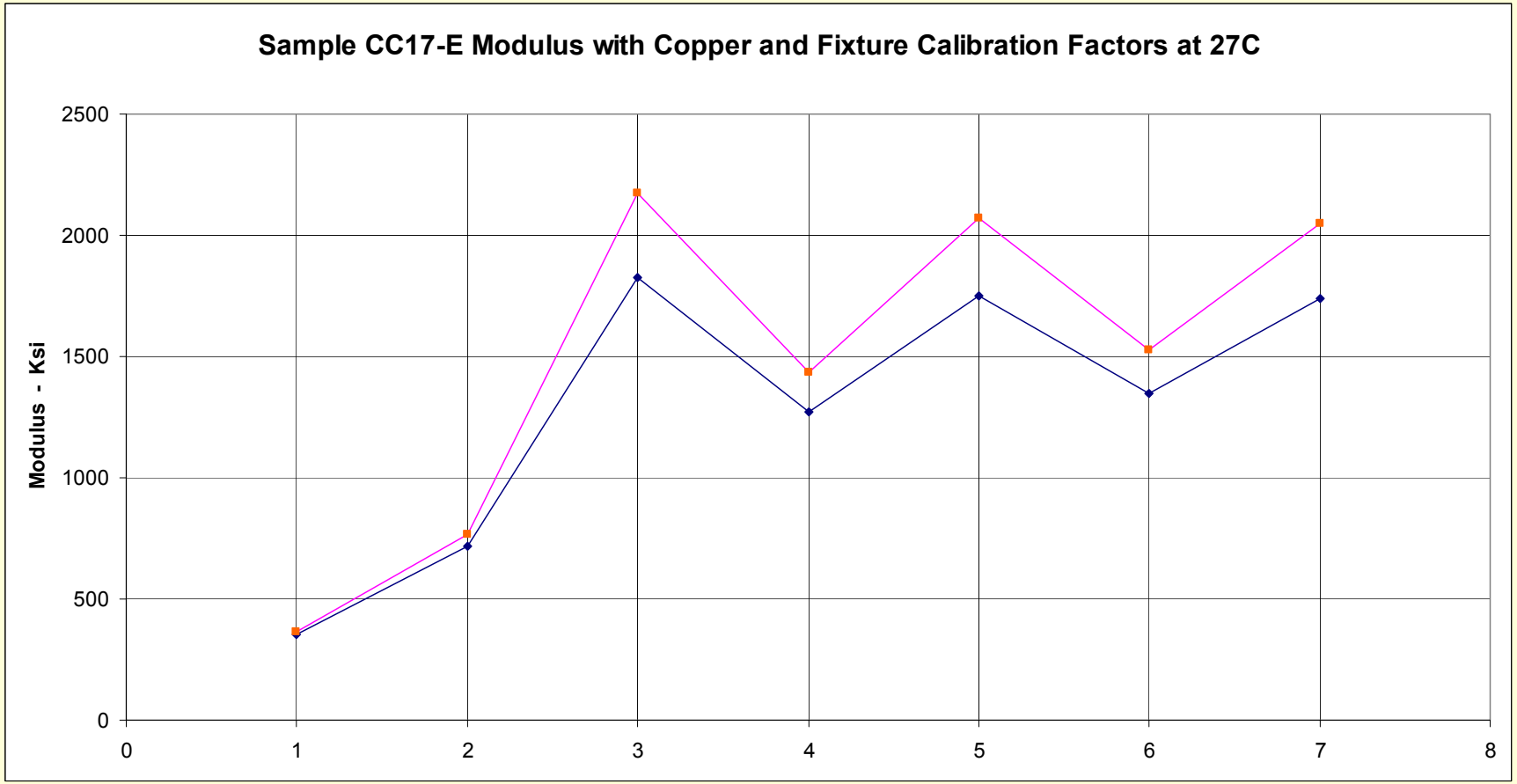
Transverse Compressive Curves



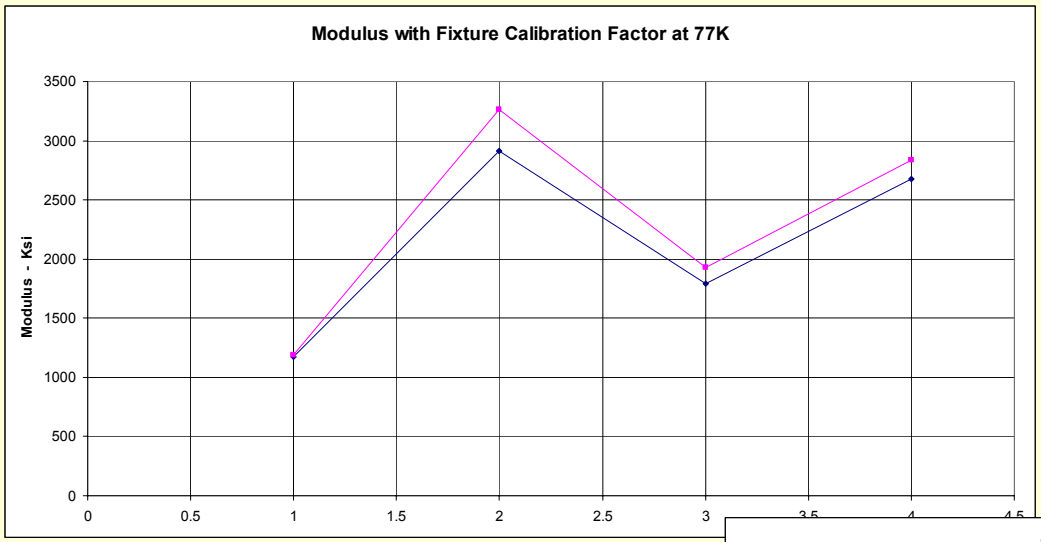
Analysis of Transverse Compressive

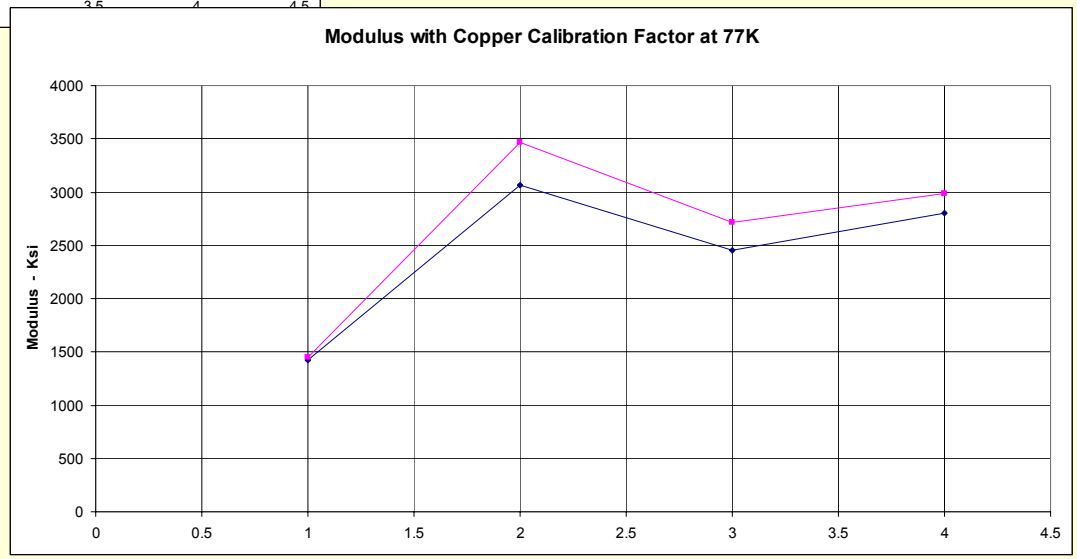
- Using fixture correction factor with Copper gives an incorrect modulus of:
  - 6419 and 6289 Ksi at 27 C
  - 4323 and 12650 Ksi at 77 K
- Possible reasons for large error:
  - Copper deflection is less than the test fixture with this geometry
  - Limited load range

Transverse Compressive-Results at Room Temperature



Transverse Compressive-Results at 77 K





Tensile Test of Long Race Track Coil at Room Temp

Tensile Test Parameters

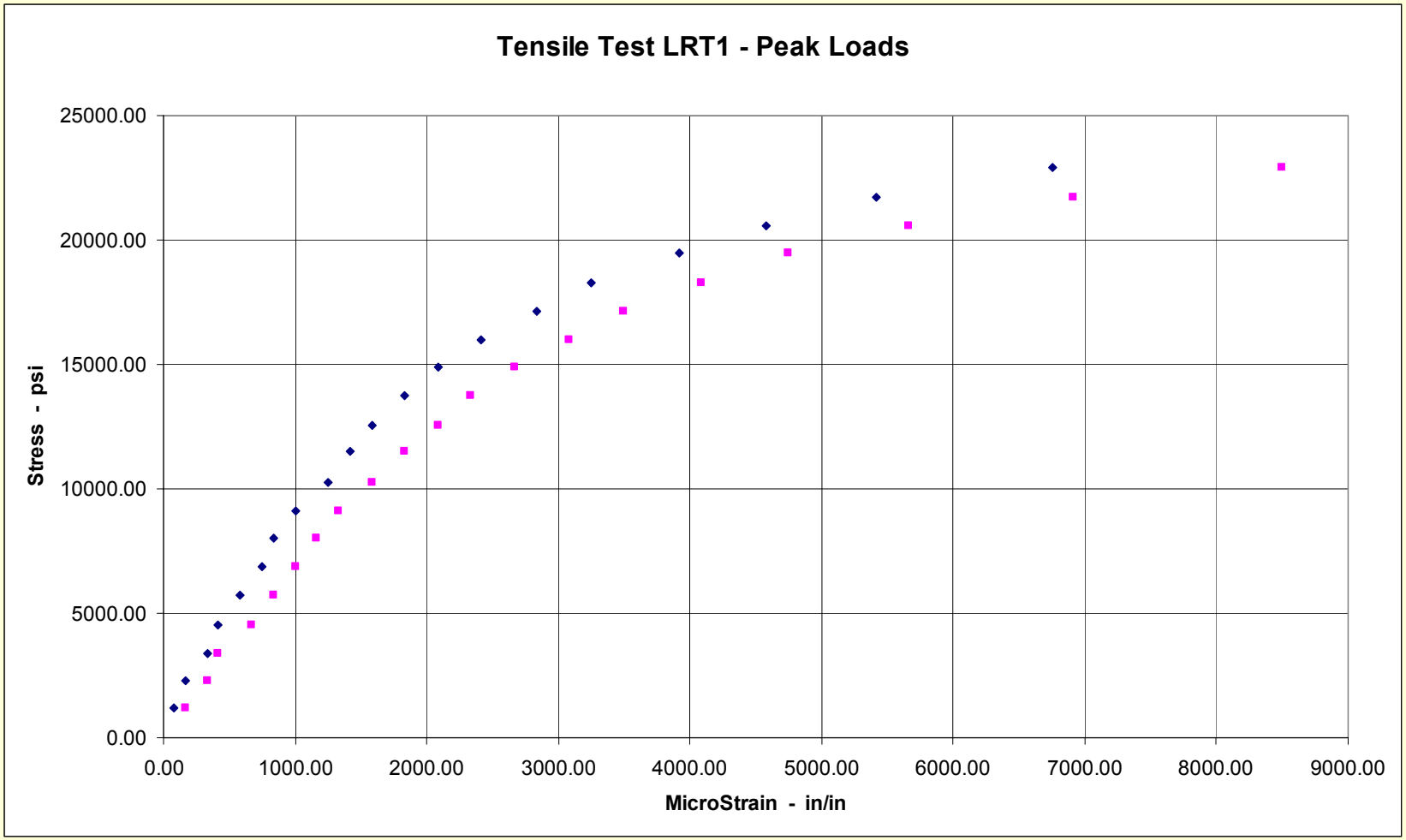
- 100 Kip MTS System
- Specimen LRT1
- Extensometers:
  - One on each leg
  - Measurement range: 0 to 1.000 in
  - Measurement resolution: 0.001 in
  - Gauge length: 12.00 in
- Section area: *estimated* at 0.444 sq in for each leg

Tensile Test Configuration

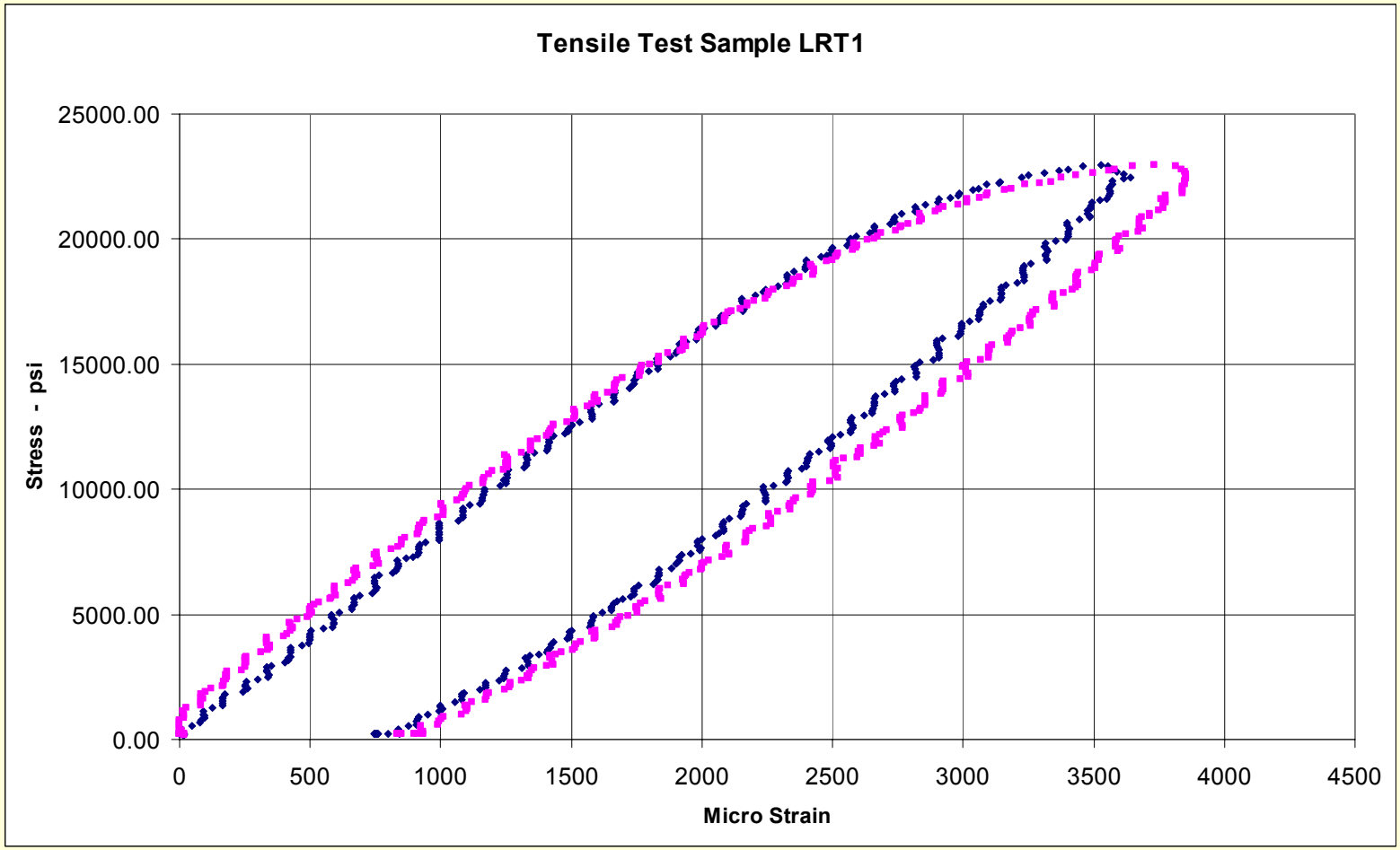
Tensile Test Procedure

- Operated under load control
- Maintained minimum load of about 100 lb
- Ramped load from minimum to peak and back starting with 1000 lb
- Incremented peak load by 1000 lb up to 20000 lb

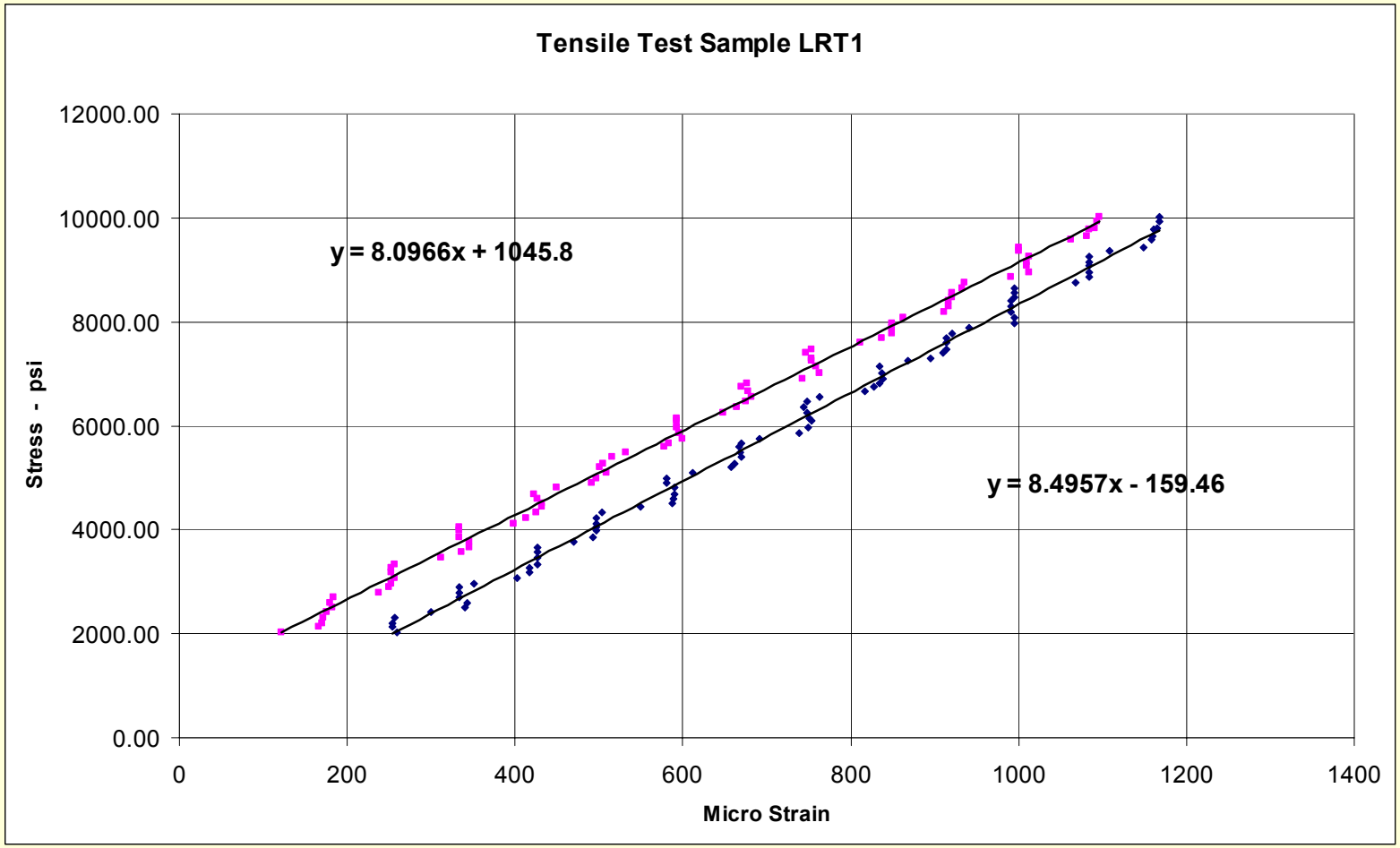
Plot of Peak Values



Stress-Strain Curve for 20000 lb Cycle



Modulus


Tensile Test Sample LRT1
y = 8.0966x + 1045.8
y = 8.4957x - 159.46
Stress - psi
Micro Strain
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
0
200
400
600
800
1000
1200
1400

Test Notes

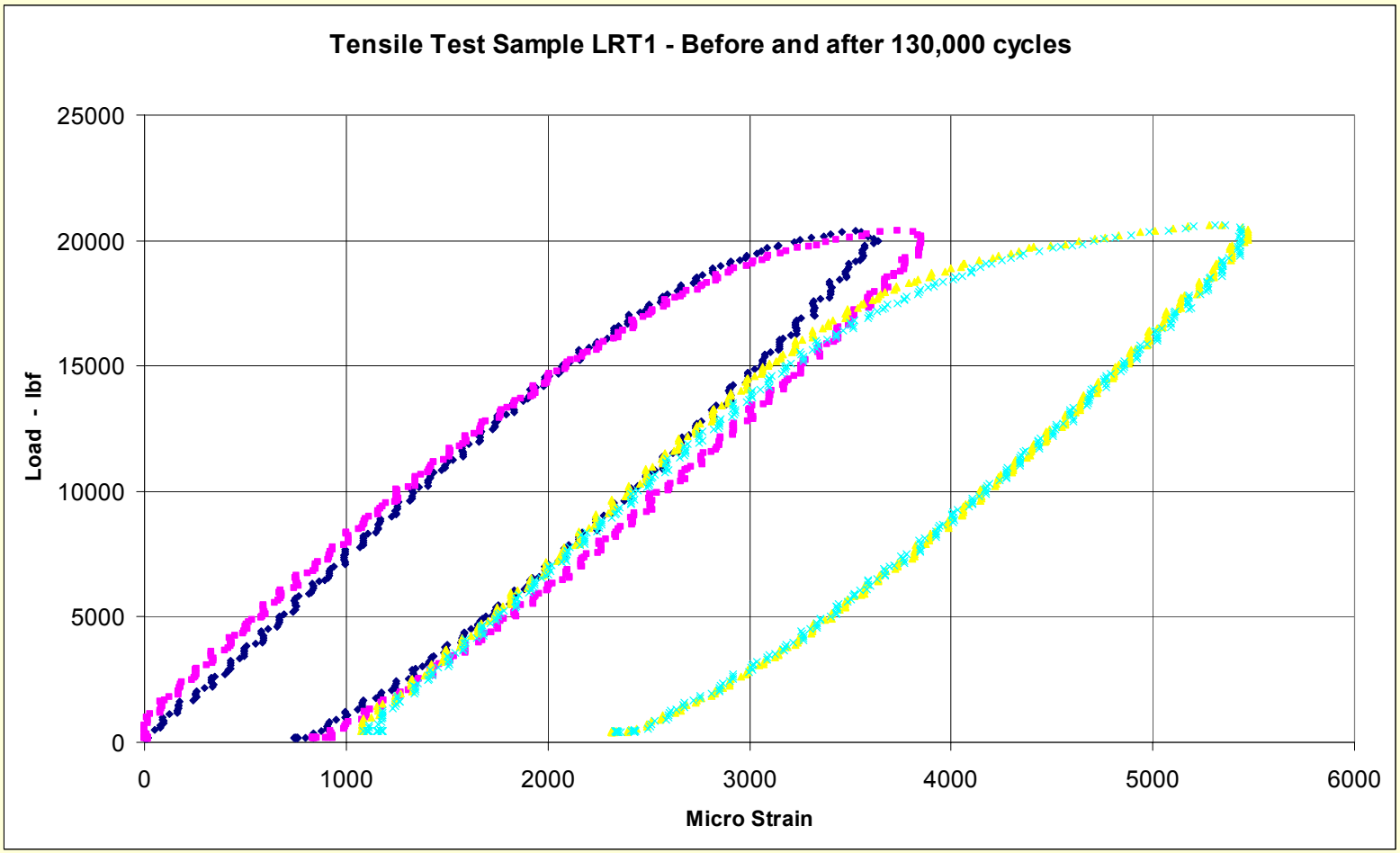
- Modulus depends on the section area selected for the composite structure.
- After 19000 lb cycle, resistance changed from 0.00344 to 0.00345 ohms

Test Procedure-
Cycle Tested Specimen LRT1

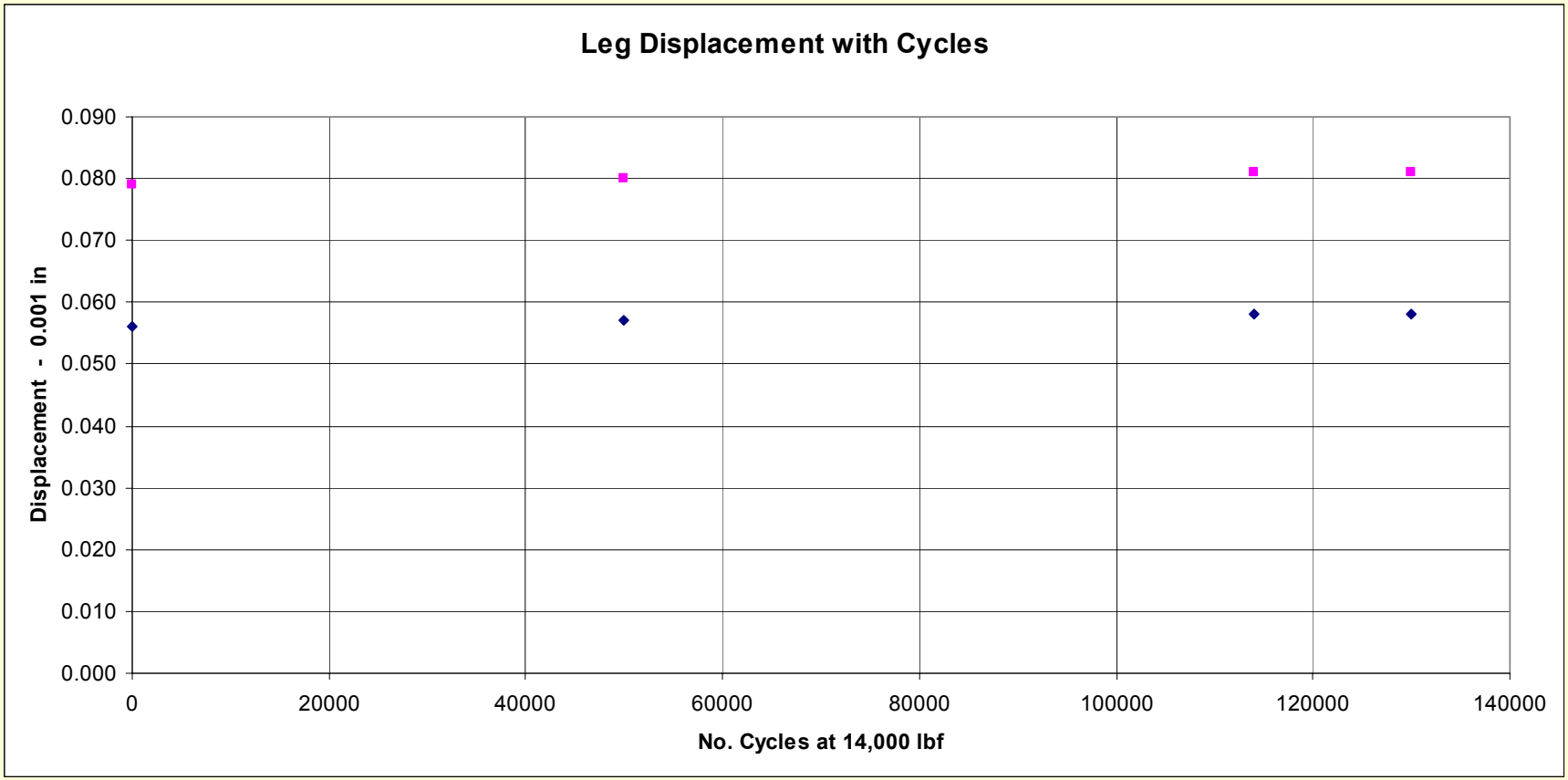
- Load: 400 to 14000 lbf
- Rate: 1 Hz
- Starting values:
  - Leg 1 = 0.056 in
  - Leg 2 = 0.079 in
  - Resistance = 0.00347 ohm

Resin Rich Area Cracks are Observed on Coil Surface

20,000 lb Tensile Cycle –
Before and After 130,000 14,000 lb cycles



Minimum Load Displacement of Legs with 14,000 lbf Cycles



Test Results Summary

Test Performed	Result - Ksi
Flexural modulus, bare conductor, at room temp	9700
Flexural modulus, bare conductor, at LN2 temp	11300
Flexural offset yield strength (at 1% offset) at room temp	36
Flexural offset yield strength (at 1% offset) at LN2 temp	45
Longitudinal shear yield strength at room temp	3.7
Longitudinal shear ultimate strength at room temp	4.6
Longitudinal compressive modulus at room temp	9100
Transverse compressive modulus (rough estimate)	**TBD**
Longitudinal tensile modulus at room temp	8300

Remaining Testing Activities

- Cyclic fatigue testing and Modulus of race-track coil at liquid N2 temperature.
- Transverse compression using a 2X5 bare sample to improve the modulus resolution.
- Short 3-point bend tests to determine shear properties.
- Compression testing for yield and ultimate strength
- Single conductor tensile testing for modulus, yield and ultimate strength