Modular Coil Material Properties Measurements

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and the NCSX Team

NCSX Final Design Review for Modular Coil Winding Form

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 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

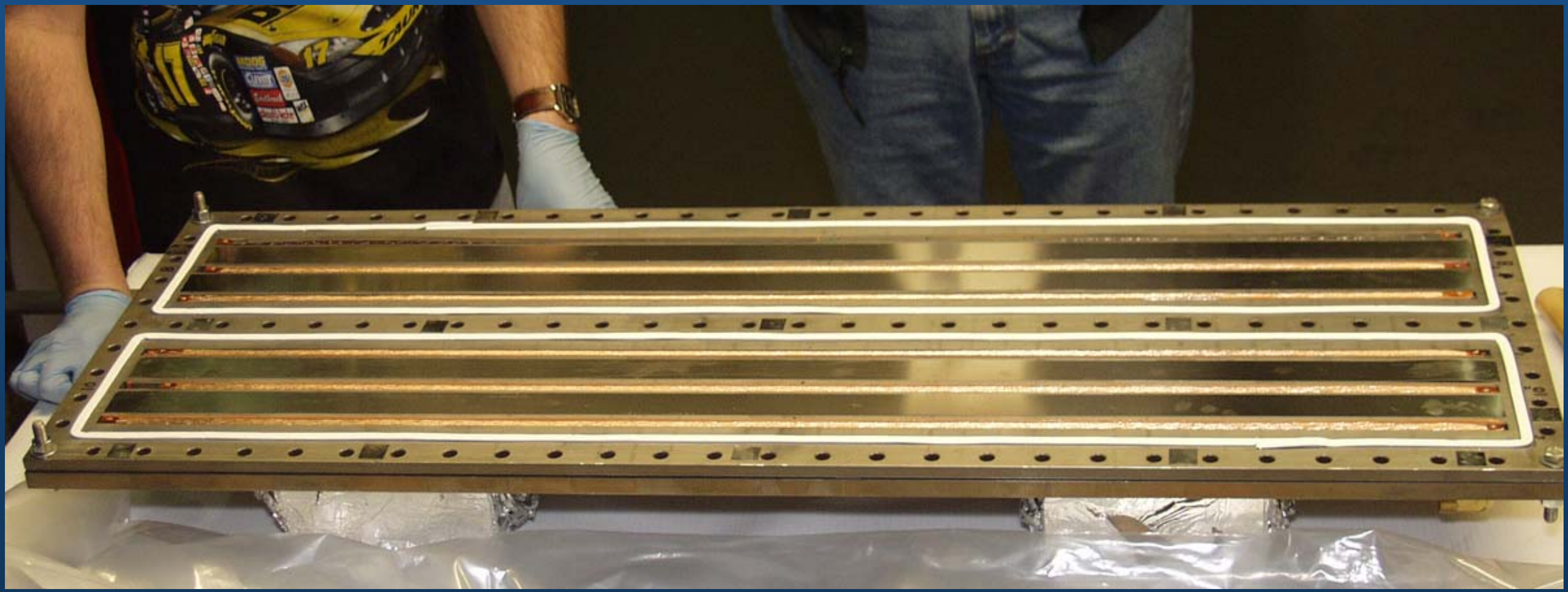
- **Properties of Wire:**
  - Tensile Strength (typical) - Soft **35,000 psi**
  - Yield Strength (typical, 1% offset)- Soft **10,000 psi**
  - Elongation (Typical,% in 10")- Soft **10-25%**
  - Percent Copper (Minimum, including silver)- **99.95%**
  - Electrical Conductivity (IACS-Minimum)- **100%**
  - 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- Materials

- **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

- **Single Conductor-** Transverse bend, longitudinal compression & shear
  - Conductors were bare with no insulation
  - VPI'd using CTD-101K in straight 40 inch lengths



Specimen Preparation- Tensile/Fatigue Tests

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- **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

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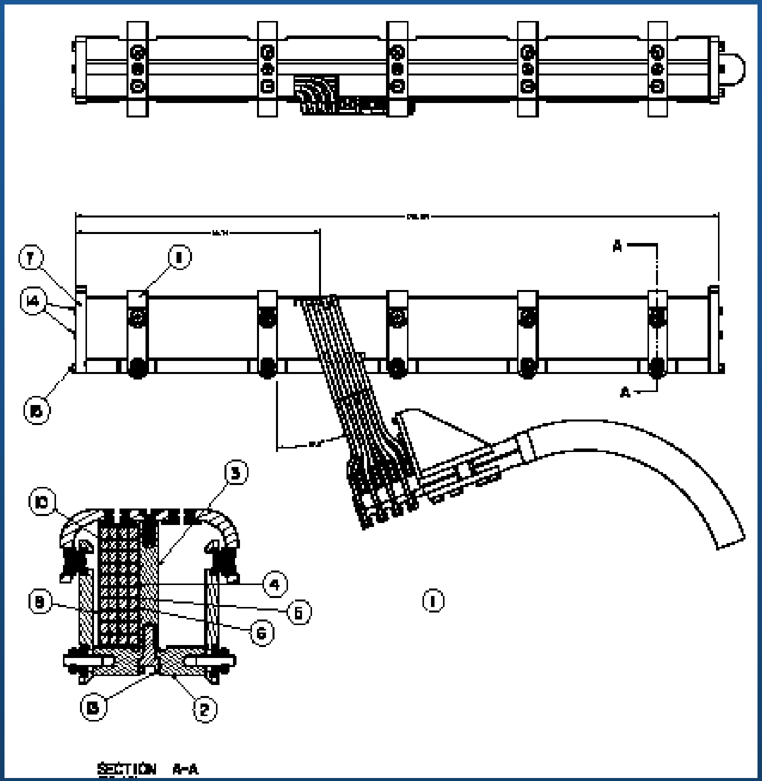
- **2 x 5 Bundle-** Transverse Compression
  - Conductors will be bare with no insulation
  - Conductors will be VPI'd as a 2 x 5 bundle using CTD-101K (in process)
- **Full Bundle-** 40 turn (Bending/flexural)
  - Using Tee mold- construct a full 40-turn bundle with turn and ground wrap insulation as being proposed for modular coils.
  - Coil lead arrangement will be included on one side of bundle



Material Testing

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- **Specimen Load Orientation:**
  - Transverse Bending/Shear
  - Transverse Compression
  - Longitudinal (Axial) Compression
  - Longitudinal Tensile
  - Longitudinal Shear
  - Fatigue cycling
- **Material Properties Measured:**
  - Modulus
  - Yield Strength
  - Ultimate Strength
  - Fatigue Strength

Material Testing Notes

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- **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 Specimens

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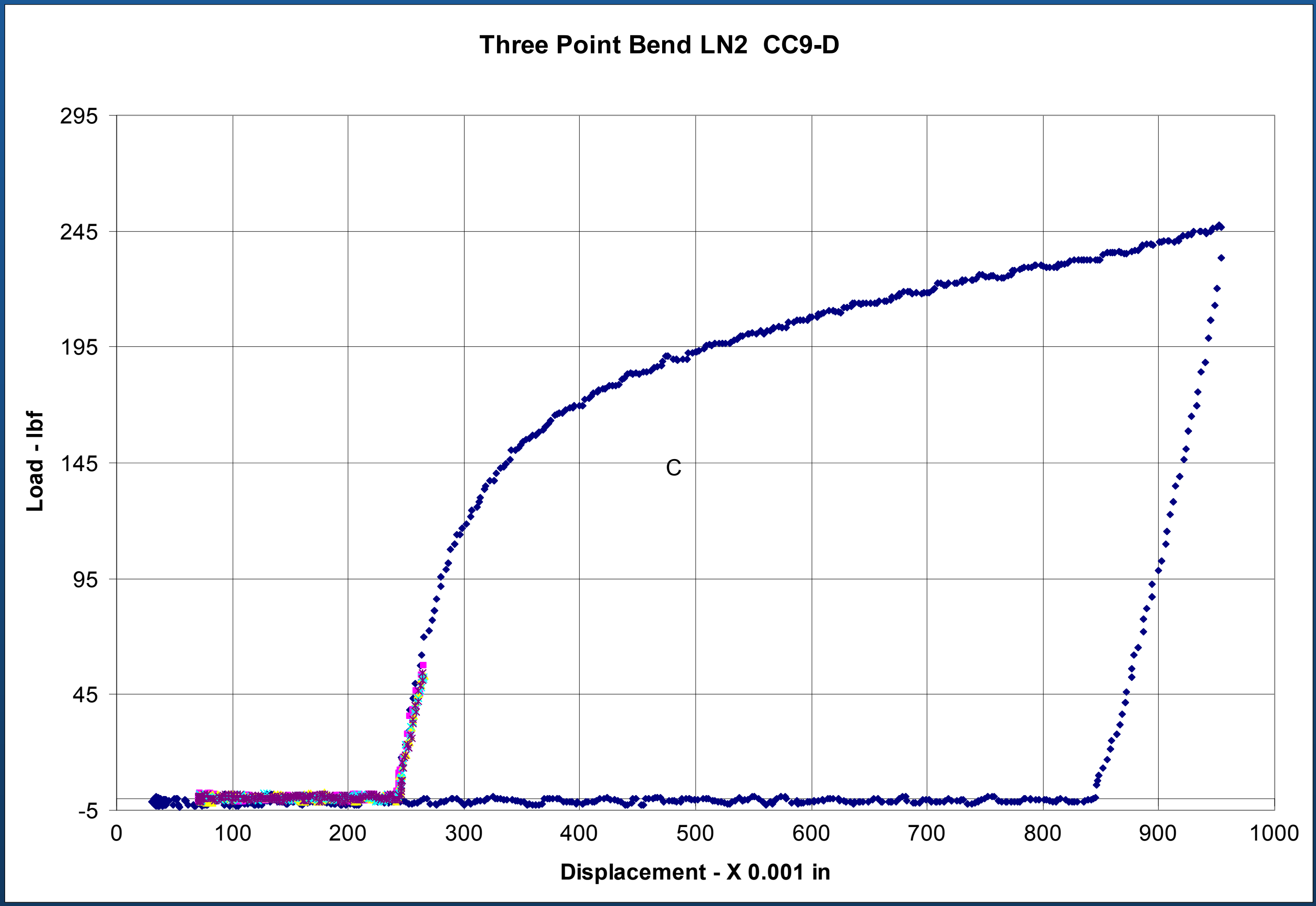
Room Temperature Specimens

3- Point Flexural Test
LN2 Sample Data- 5 Cycles



3- Point Flexural Test
Detail of Elastic Region

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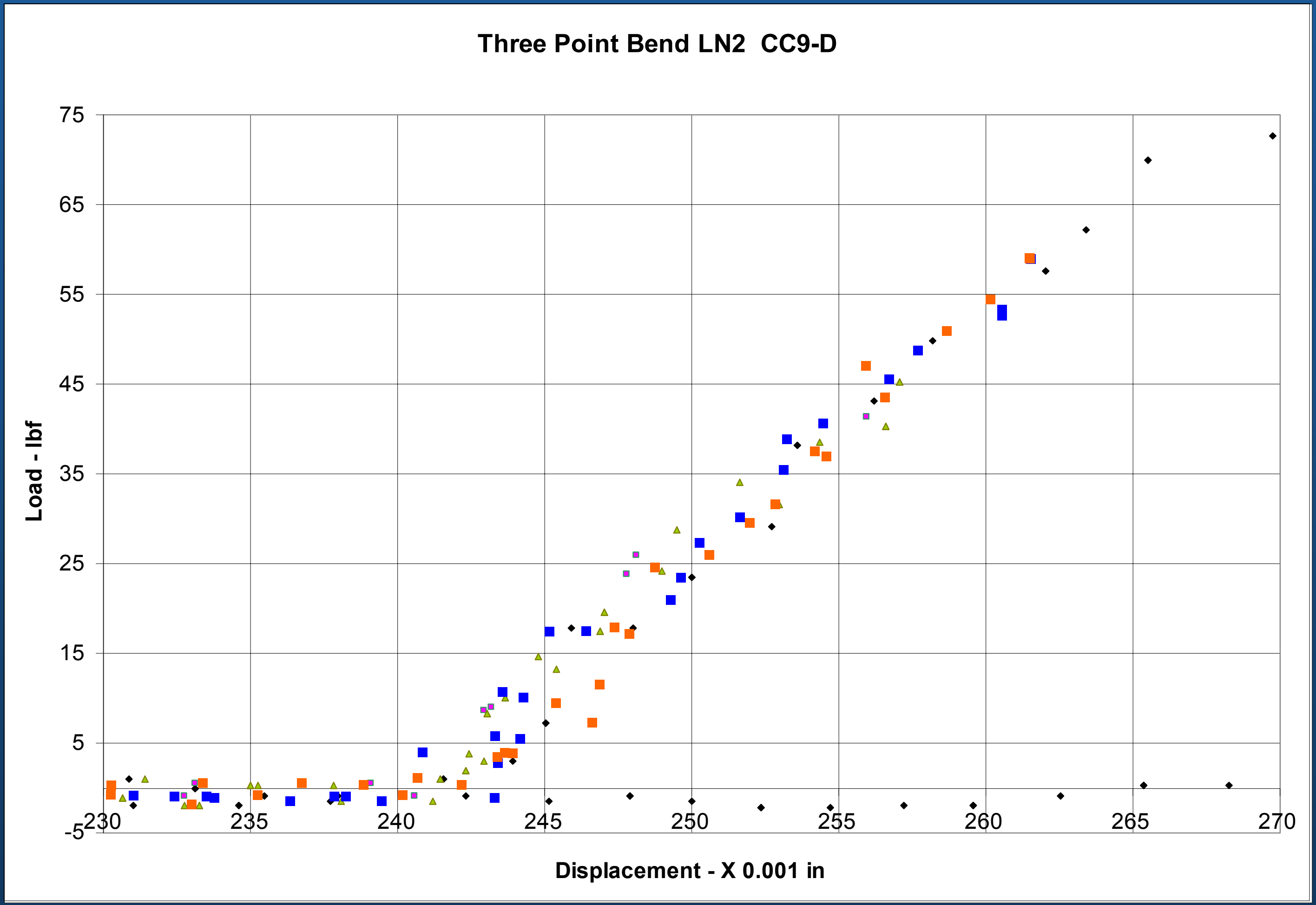

3- Point Flexural Test
Comparison of RT and LN2

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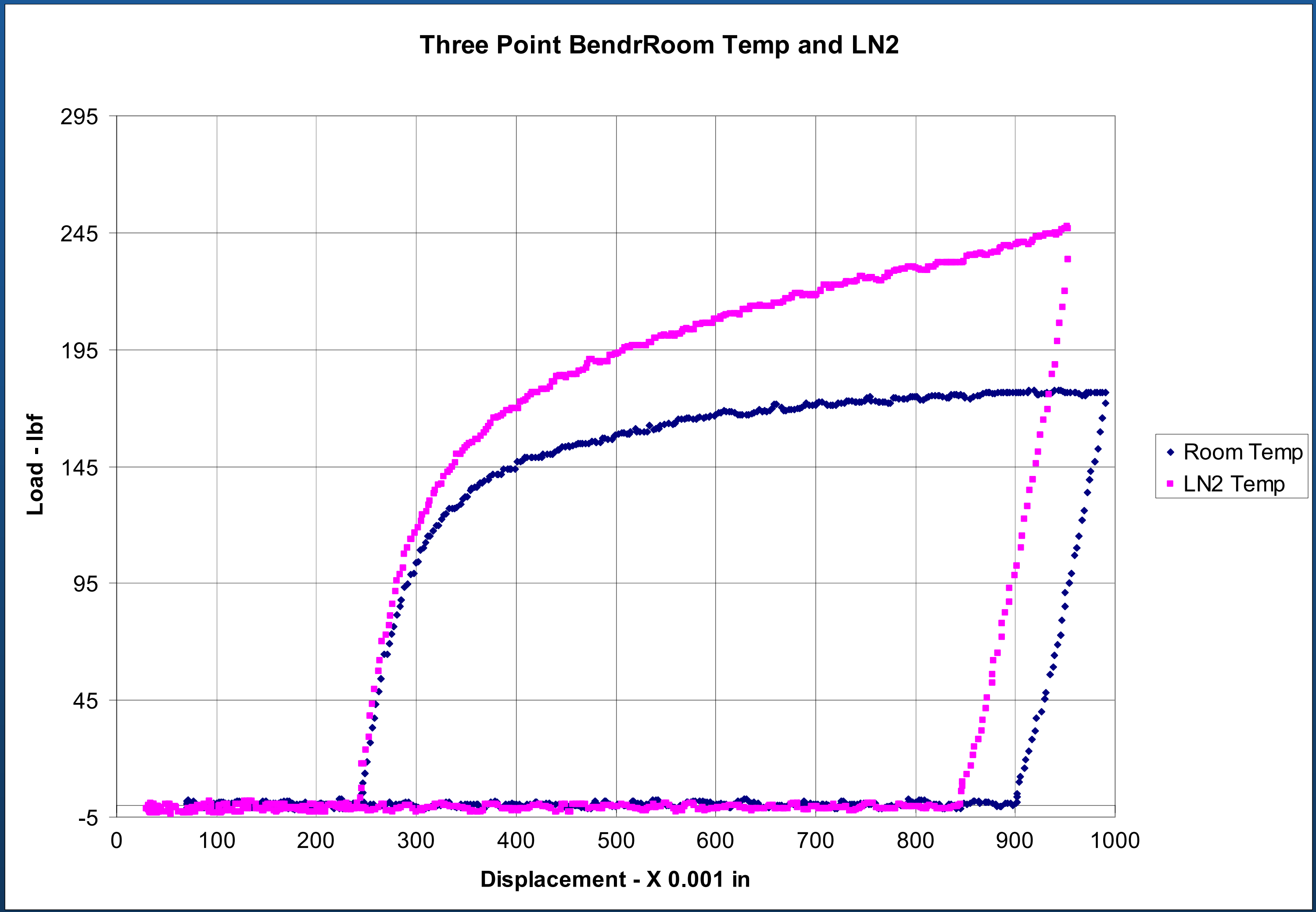

Tangent Modulus of Elasticity (ASTM D-790)

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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

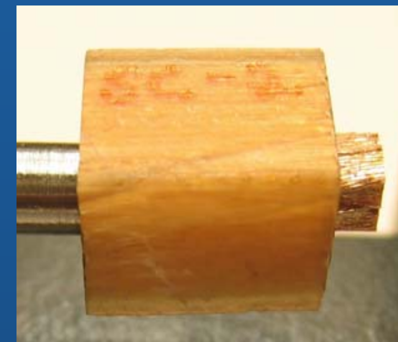
Three Point Bend- Flexural Offset Yield Strength (at 1% offset) [See ASTM D790]

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

Longitudinal Shear Strength Tests

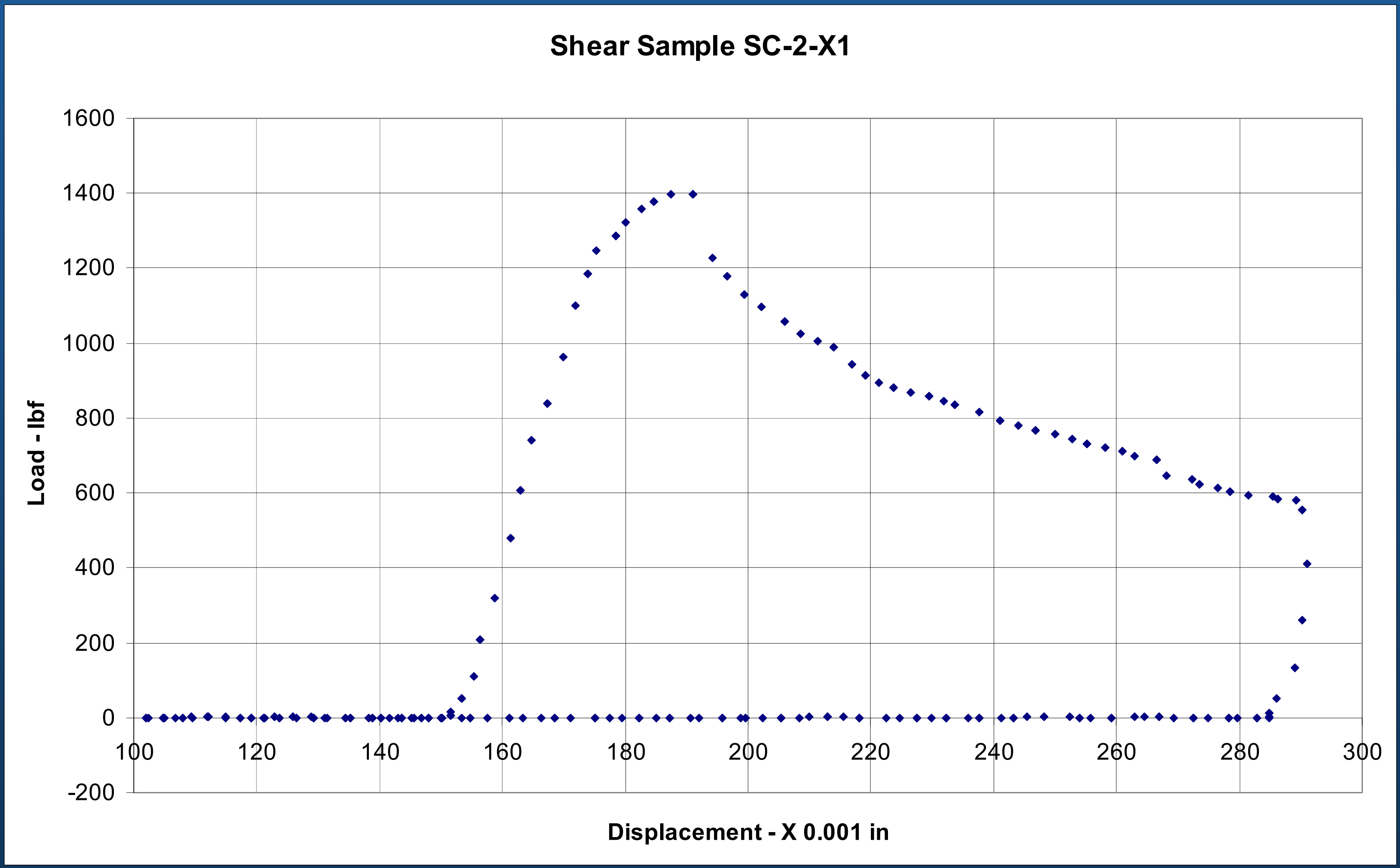
- Test were performed only at room temperature.
- Tested several length samples: 0.5”, 0.25”, 0.15”
- Tested several diameter punches: 0.187”,0.125”
- Various aspect ratios tested:
  - If the specimen length is to long with respect to the punch diameter – the material crushes before it shears and ultimately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



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

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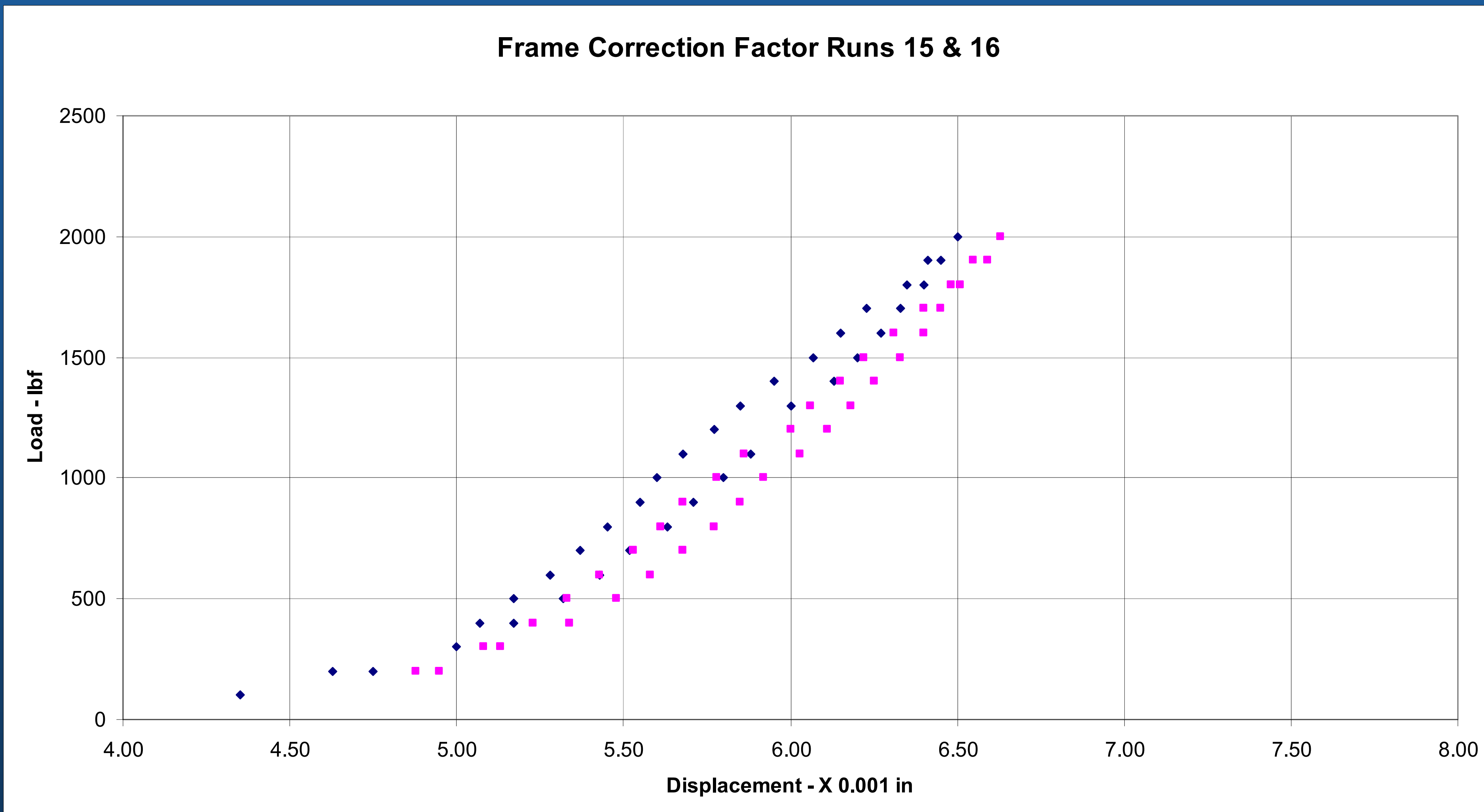
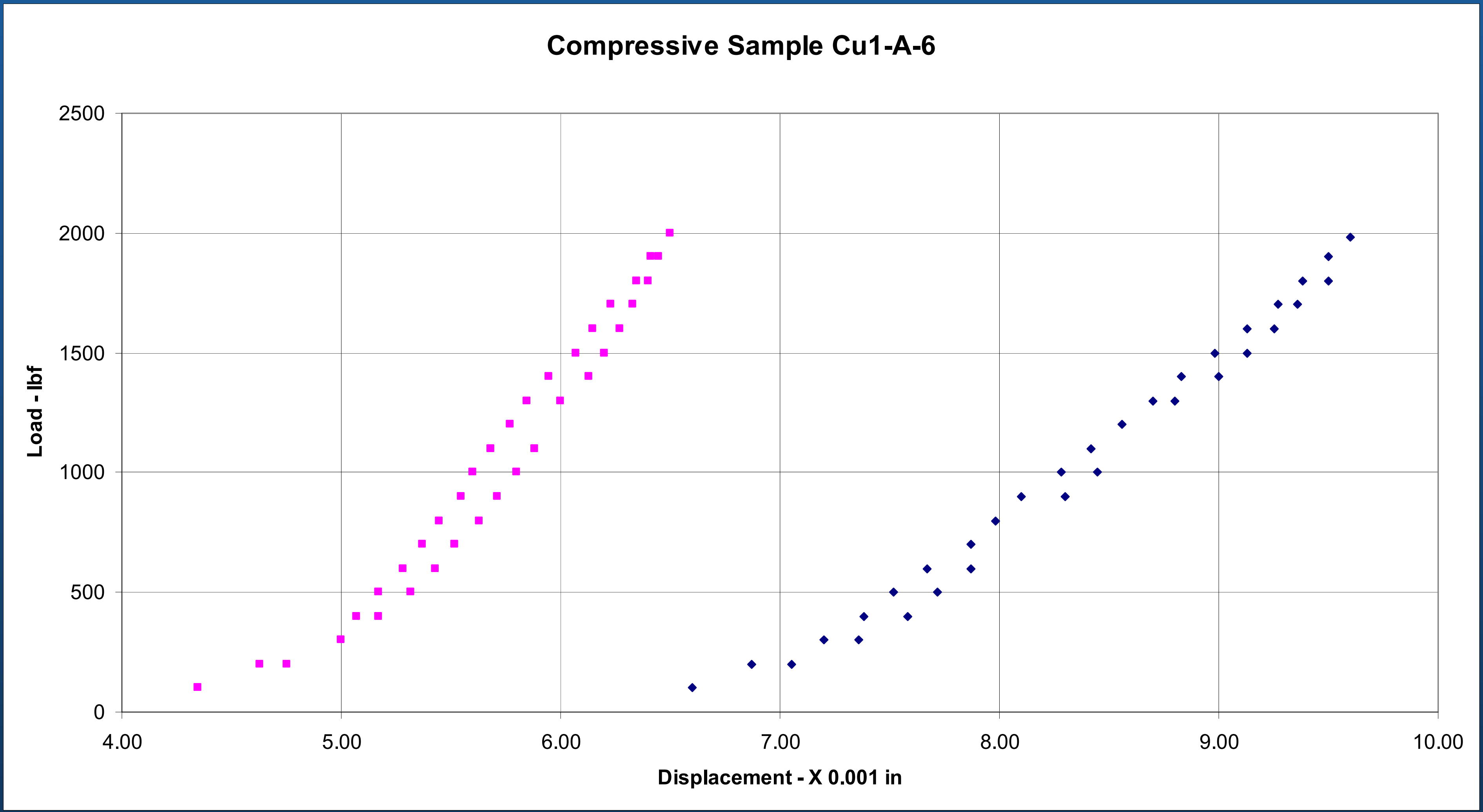
- **Test Specimen:**
  - Resin impregnated bare conductor
  - Specimen length approximately 1.34”
  - Ends ground smooth and parallel
- **Test Resolution:**
  - Load: 1 lbf
  - Displacement: <0.0001”
- Tests were performed at **room temperature**

Longitudinal Compressive Test
Frame Deflection Corrections



Longitudinal Compressive Test
Copper Specimen Calibration



Longitudinal Compressive Test

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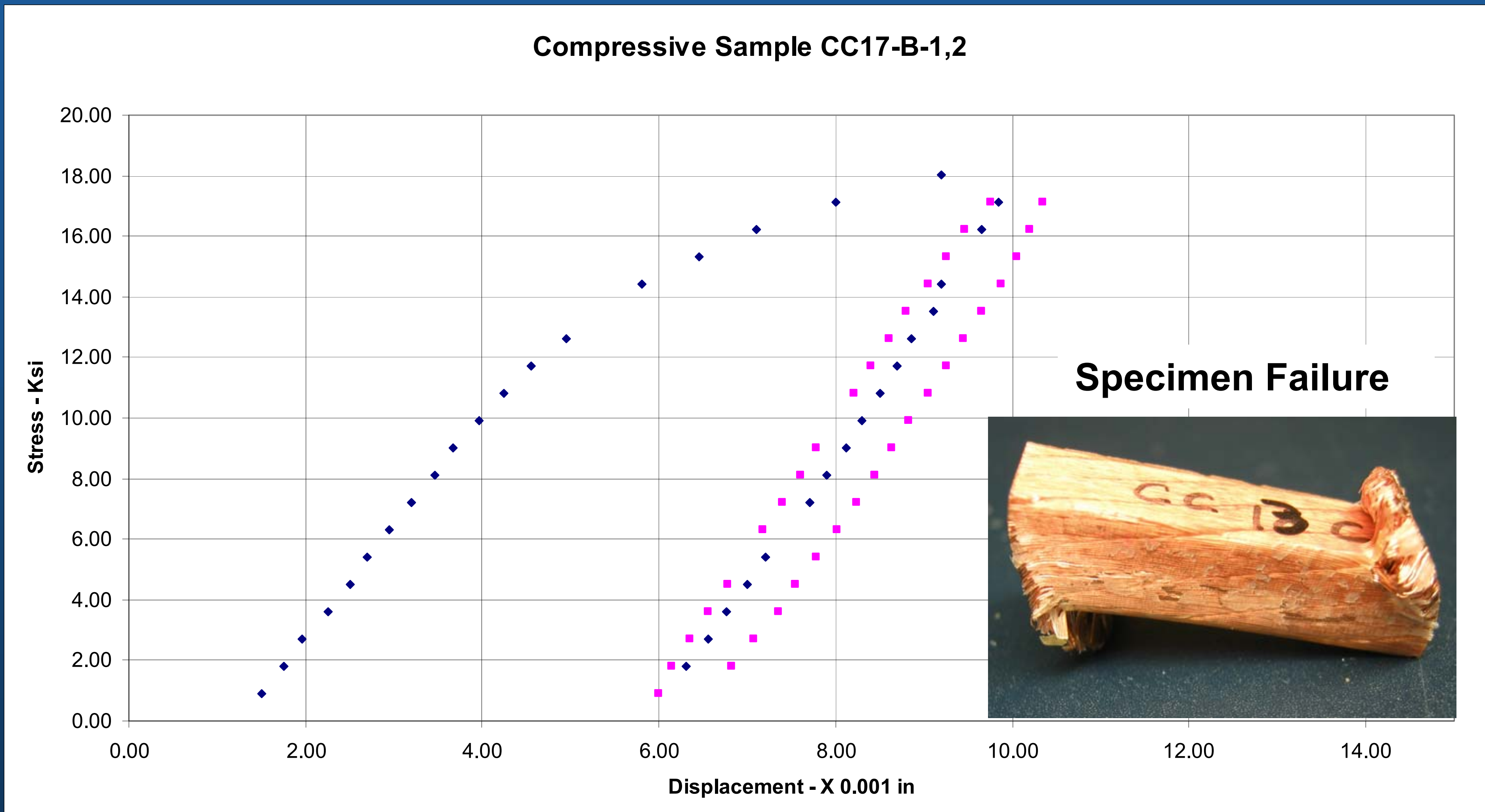
- **Calibration:**
  - Removing the frame compression from Copper Specimen Data provides a modulus of: **17.9 Msi**
  - These results are close to the expected copper modulus of about **17.0 Msi.**

- **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

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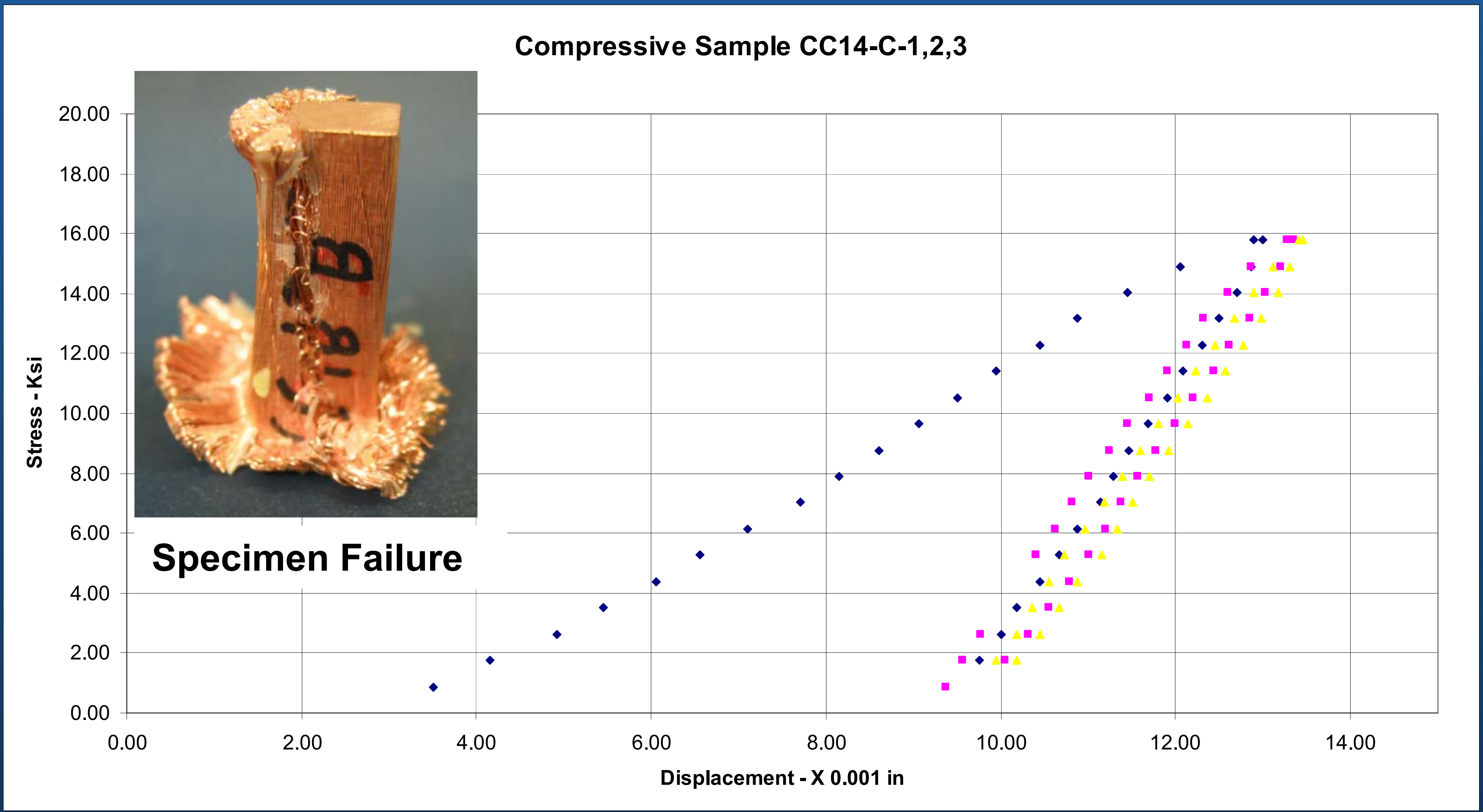
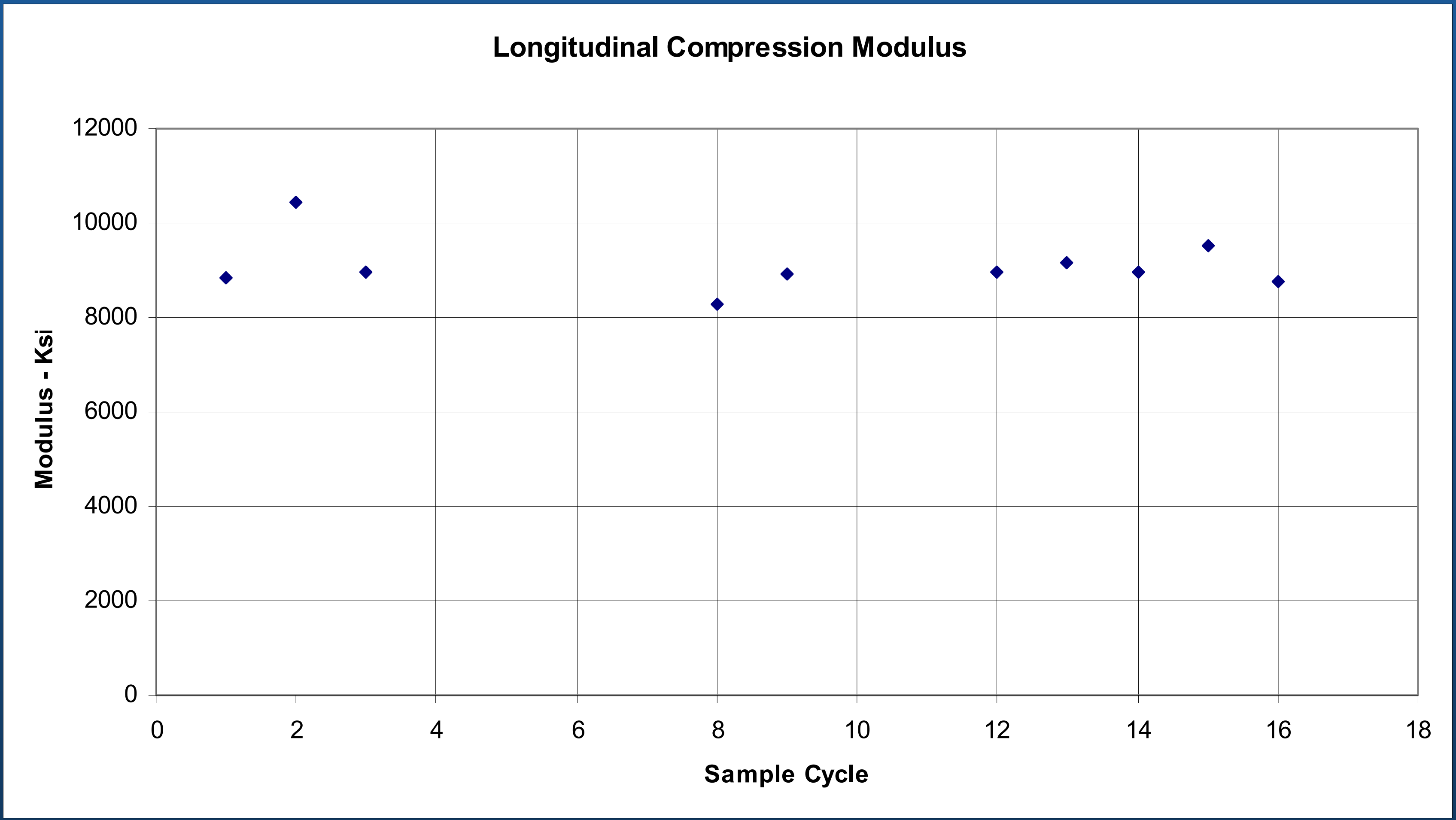


Longitudinal Compressive Test -Modulus Data

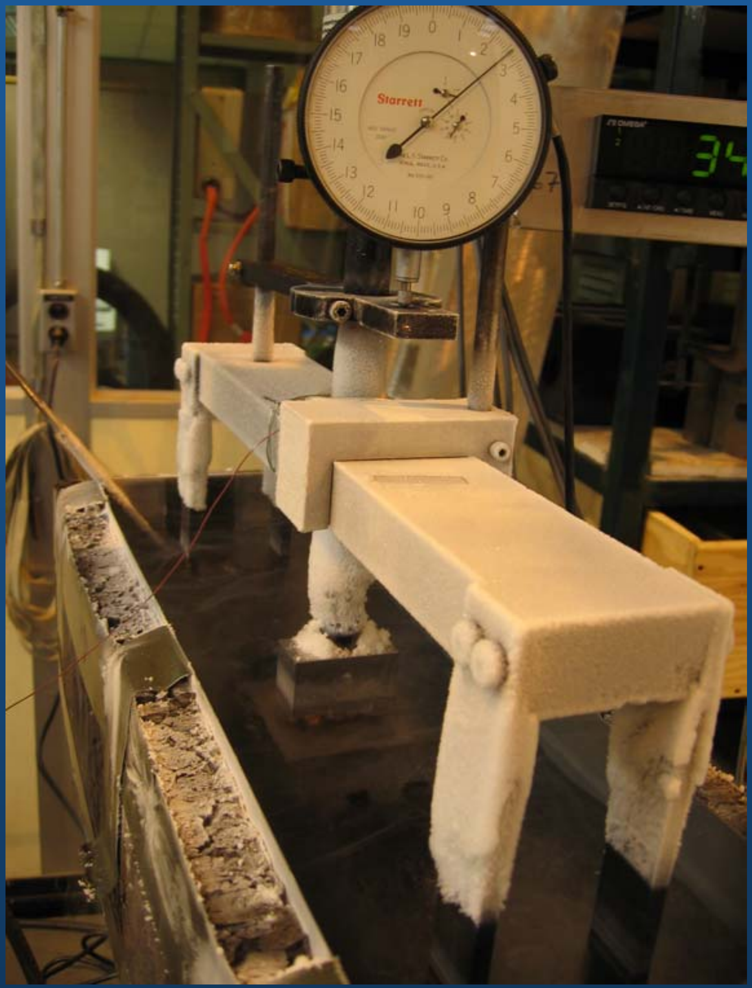


Transverse Compressive Tests

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

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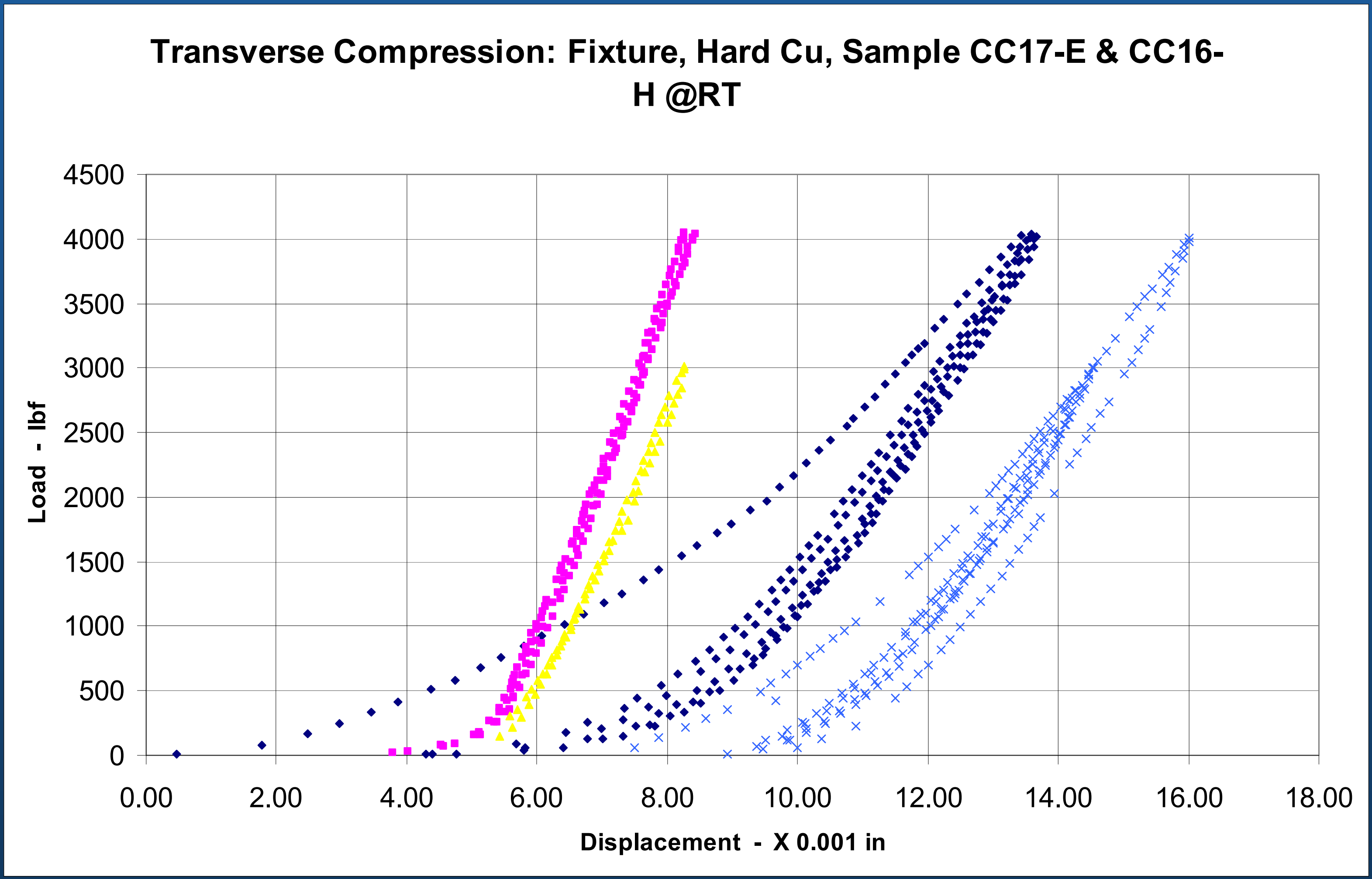

Transverse Compressive Curves

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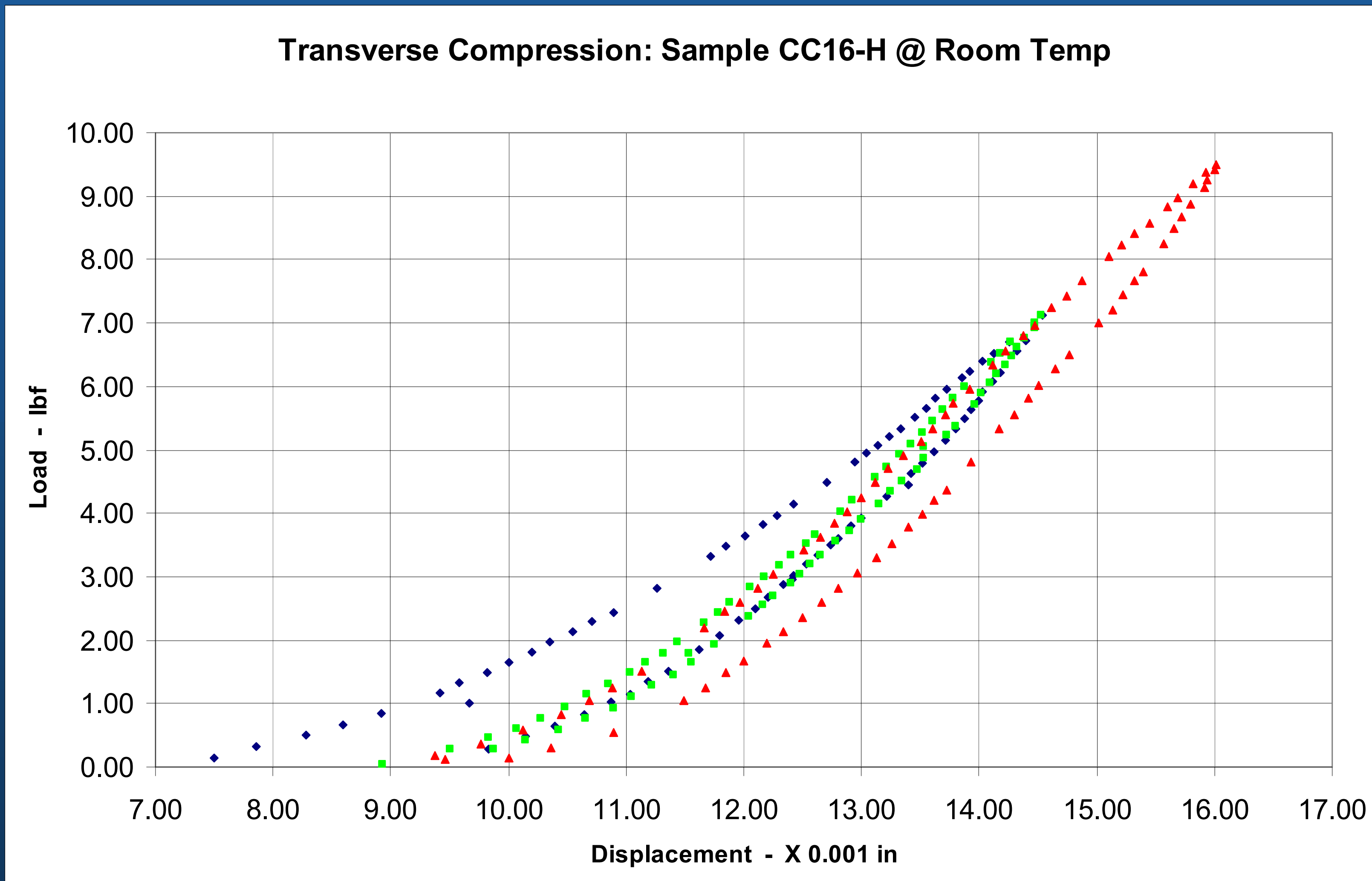

Analysis of Transverse Compressive

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- 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

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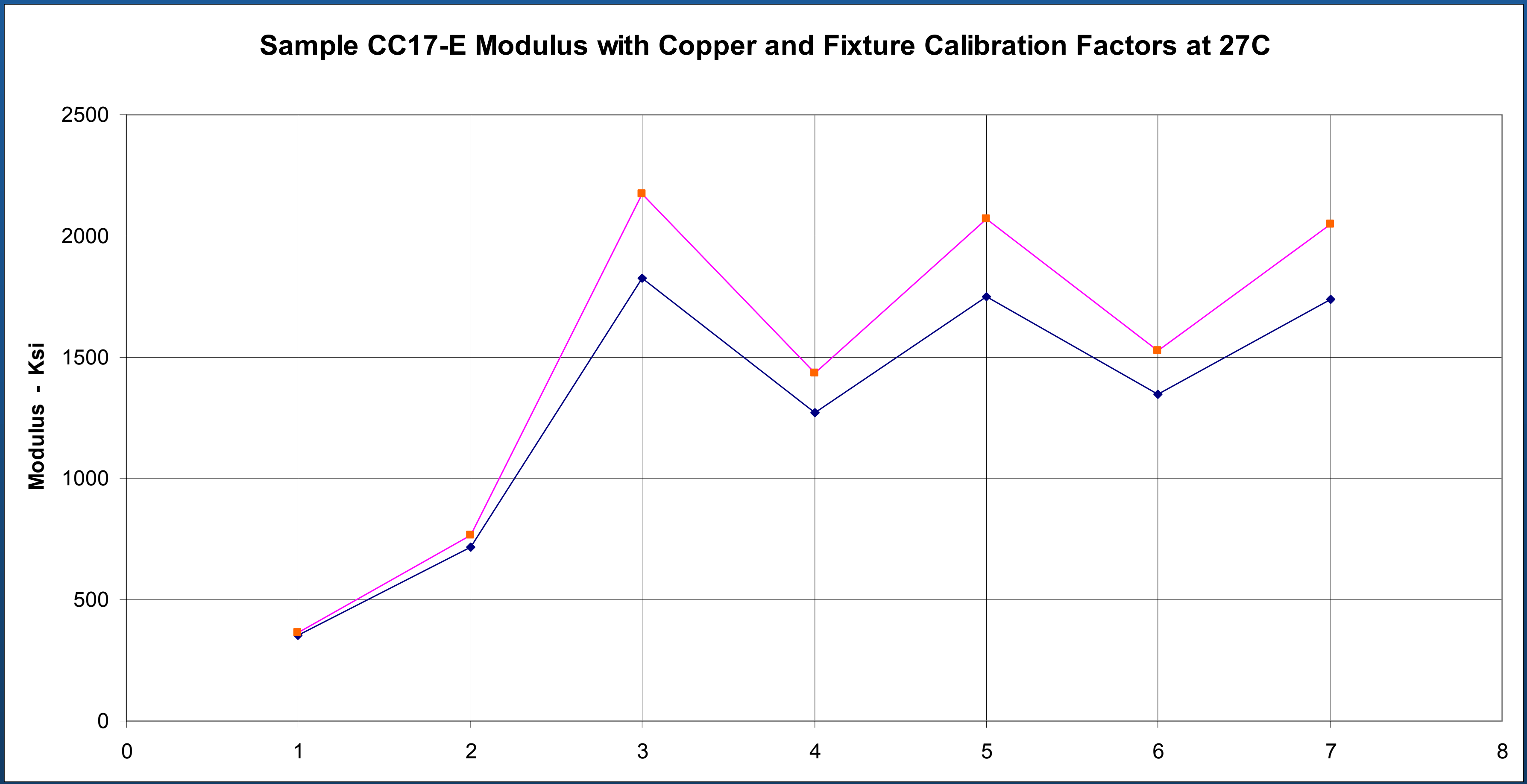

Transverse Compressive-Results at 77 K

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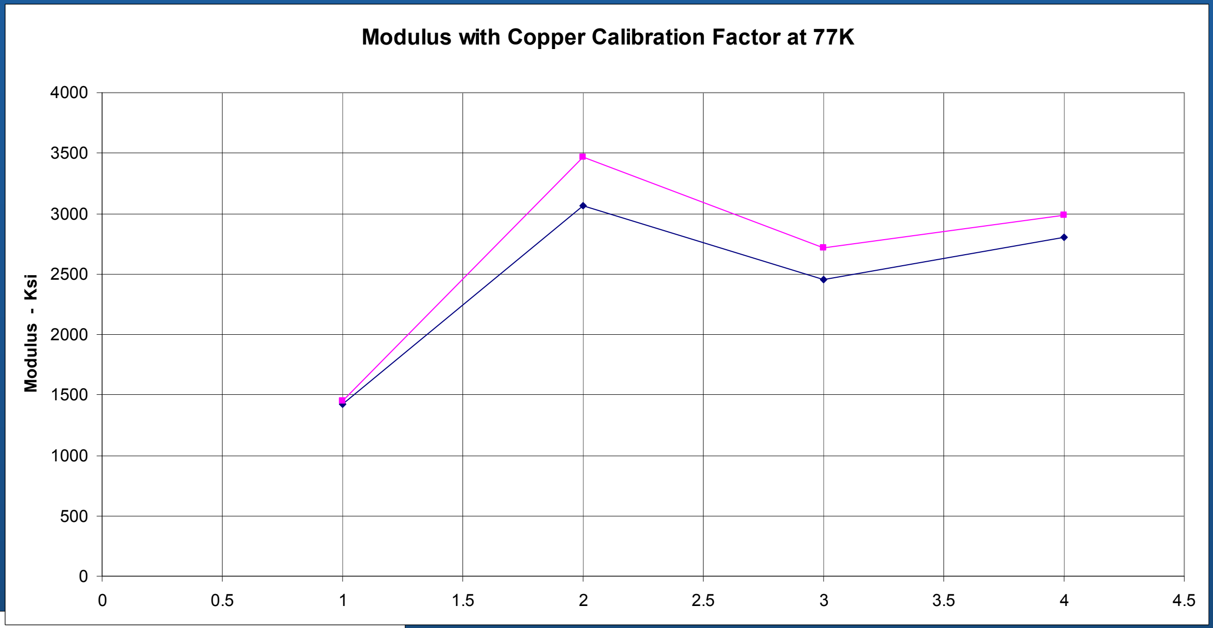
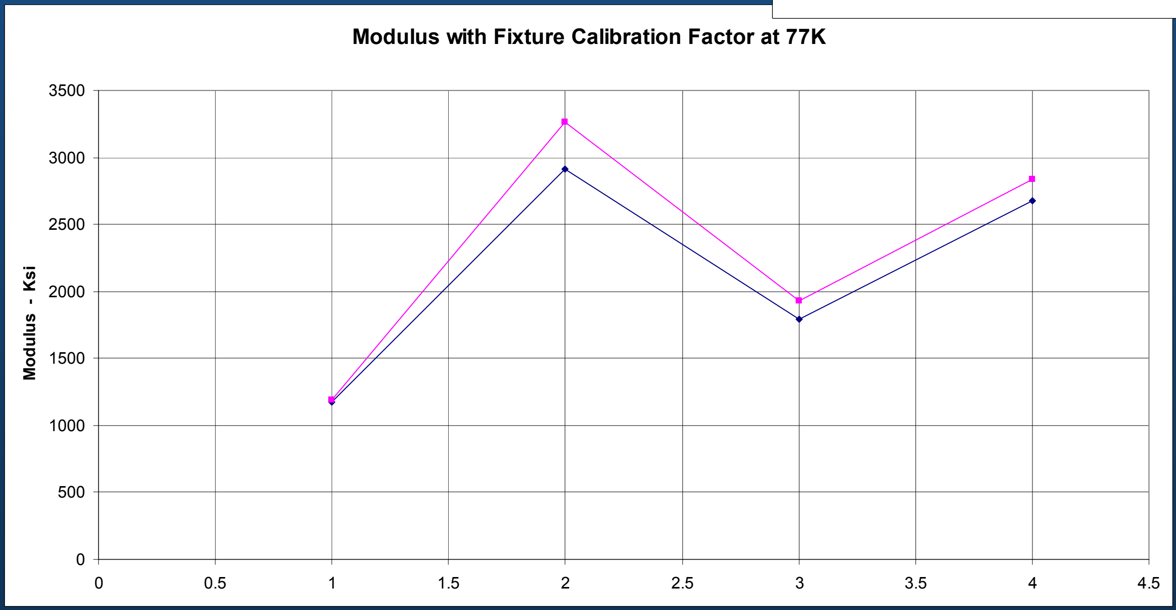
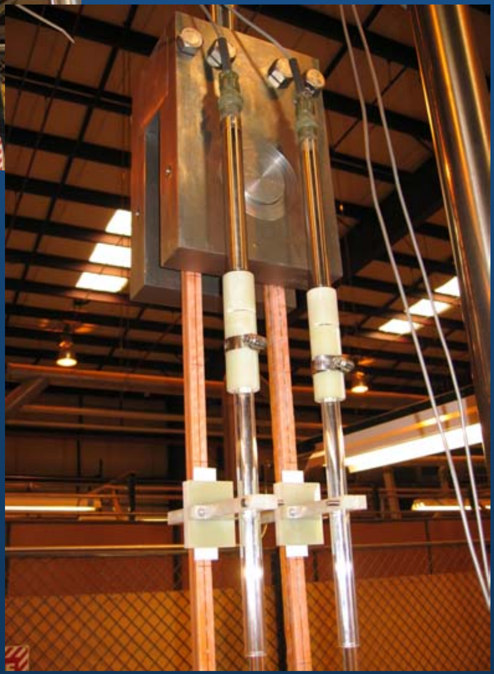




Tensile Test of Long Race Track Coil at Room Temp

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 Procedure

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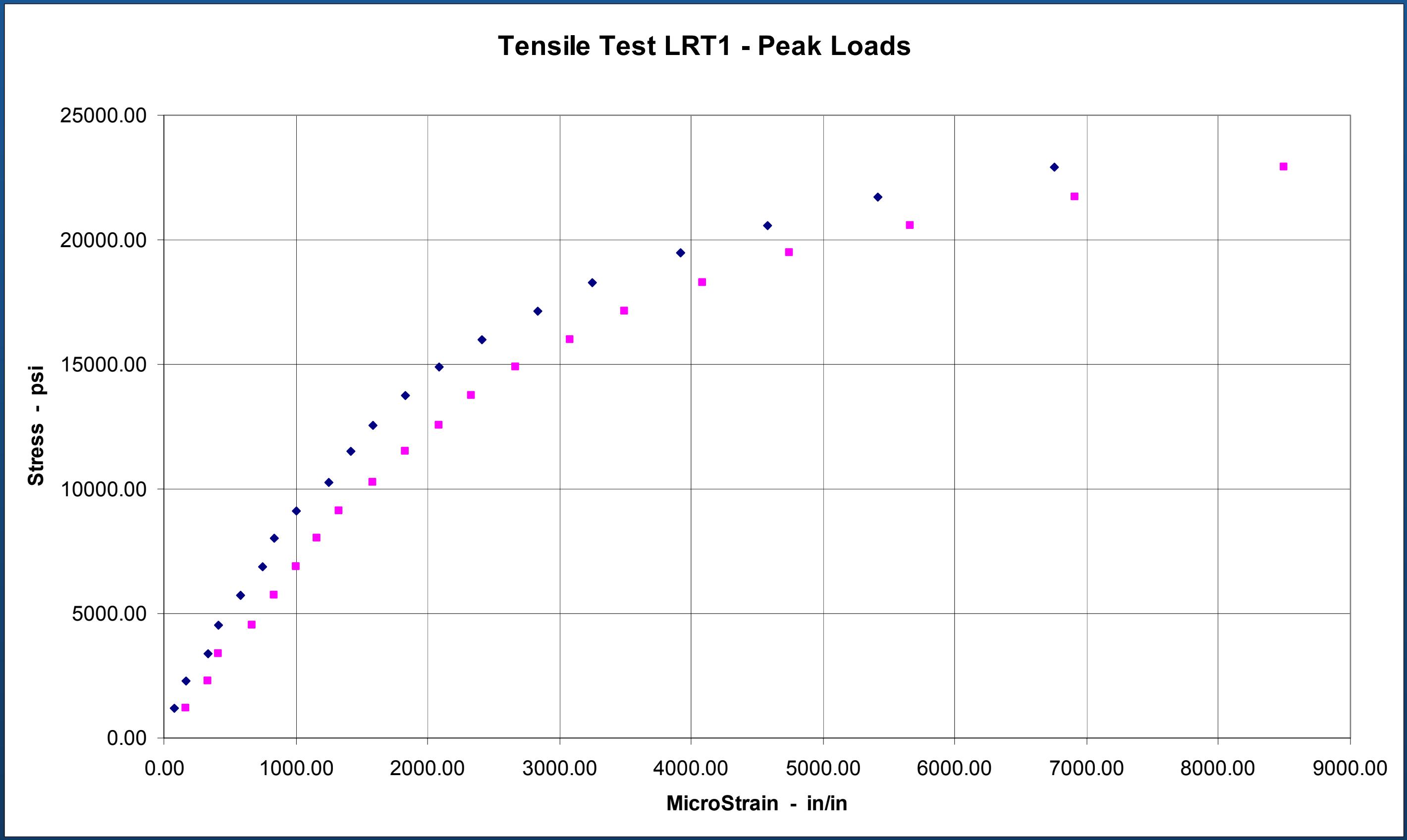

- **Test Procedure**
  - Operated under load control
  - Maintained minimum load of about 100 lb
  - Ramped load from minimum to peak and back starting with 1000 lb
  - Incremented peak load by 1000 lb up to 20000 lb

Stress-Strain Curve for 20000 lb Cycle

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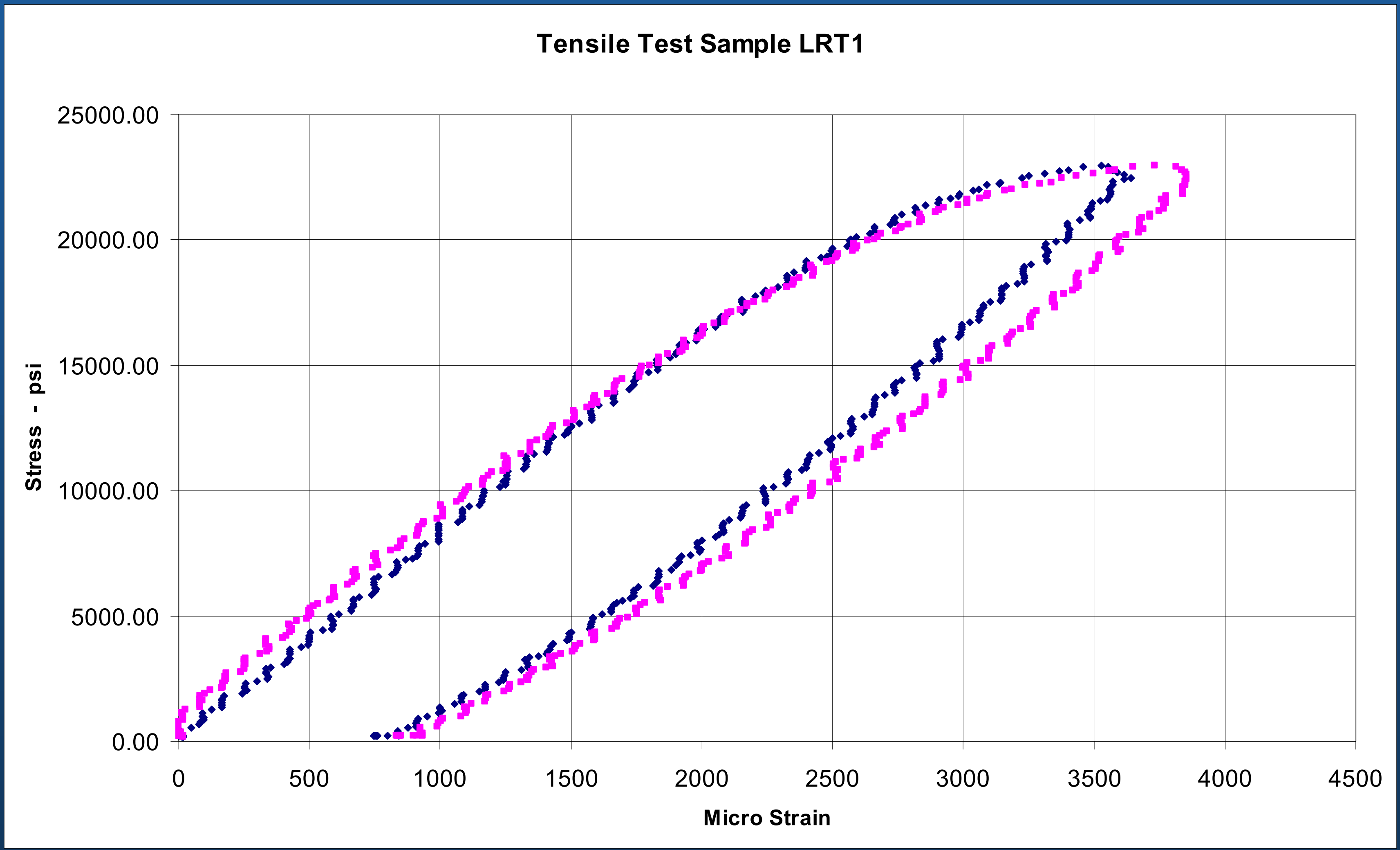

Test Notes

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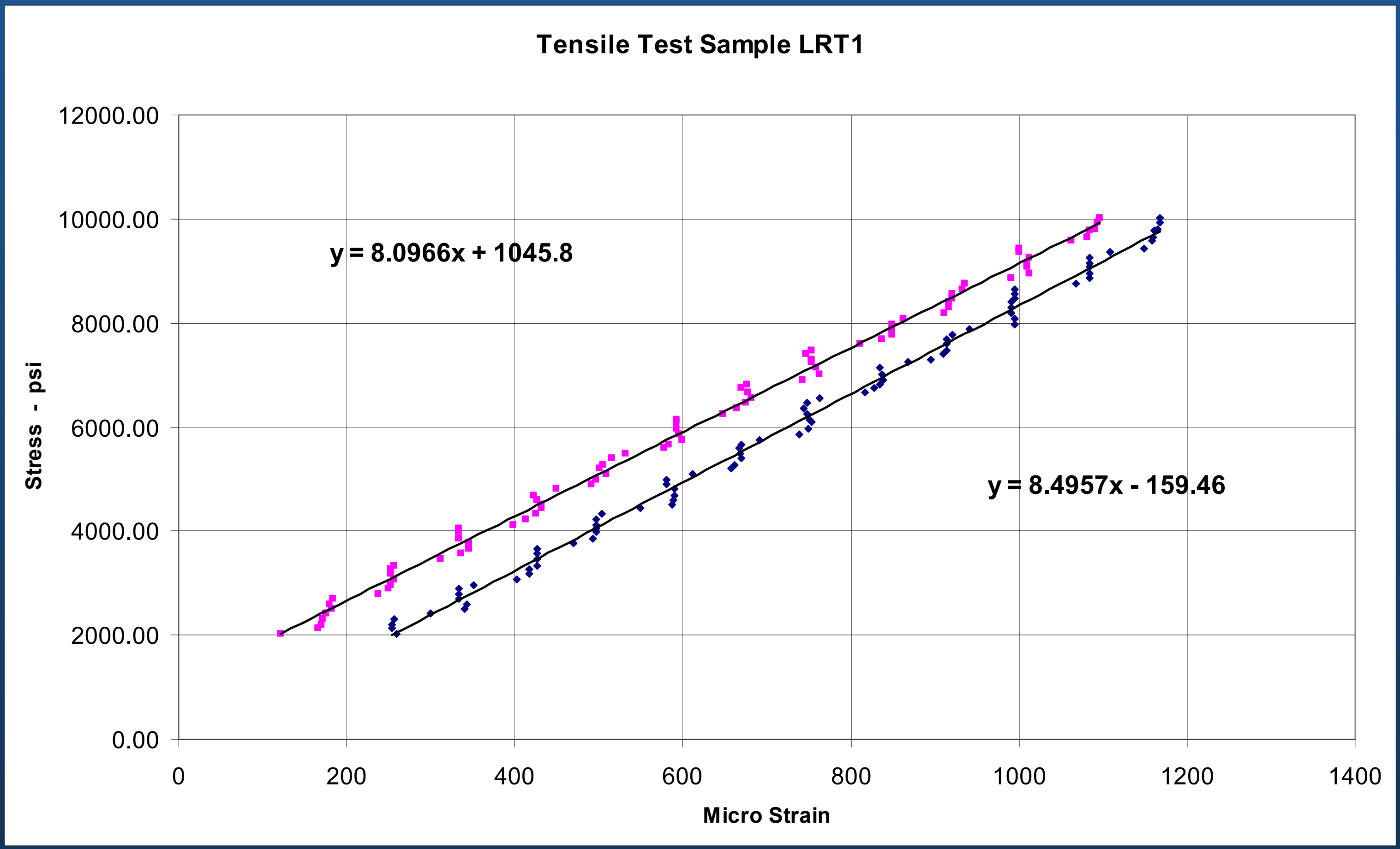
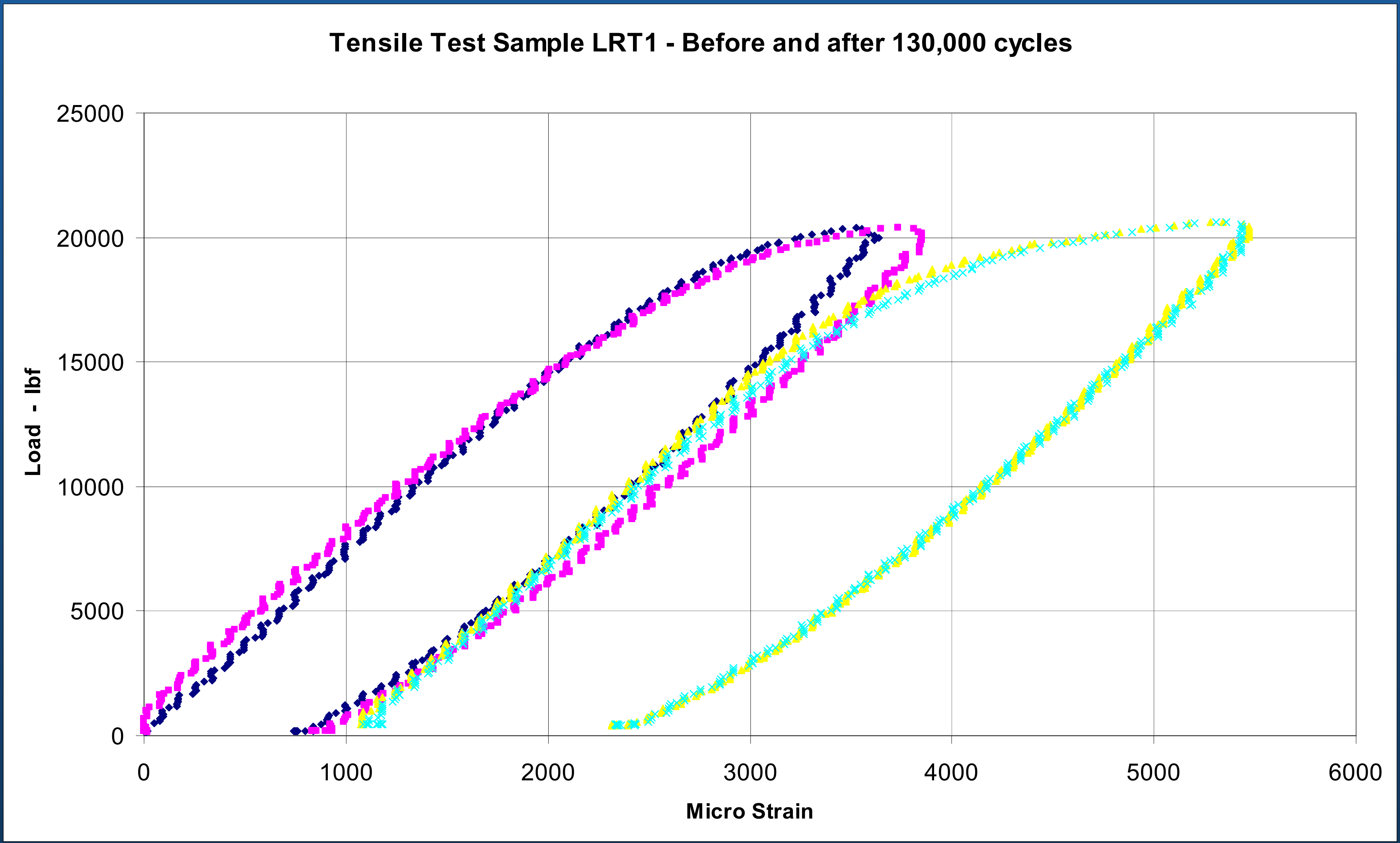
- Modulus depends on the section area selected for the composite structure.
- After 19000 lb cycle, resistance changed from 0.00344 to 0.00345 ohms



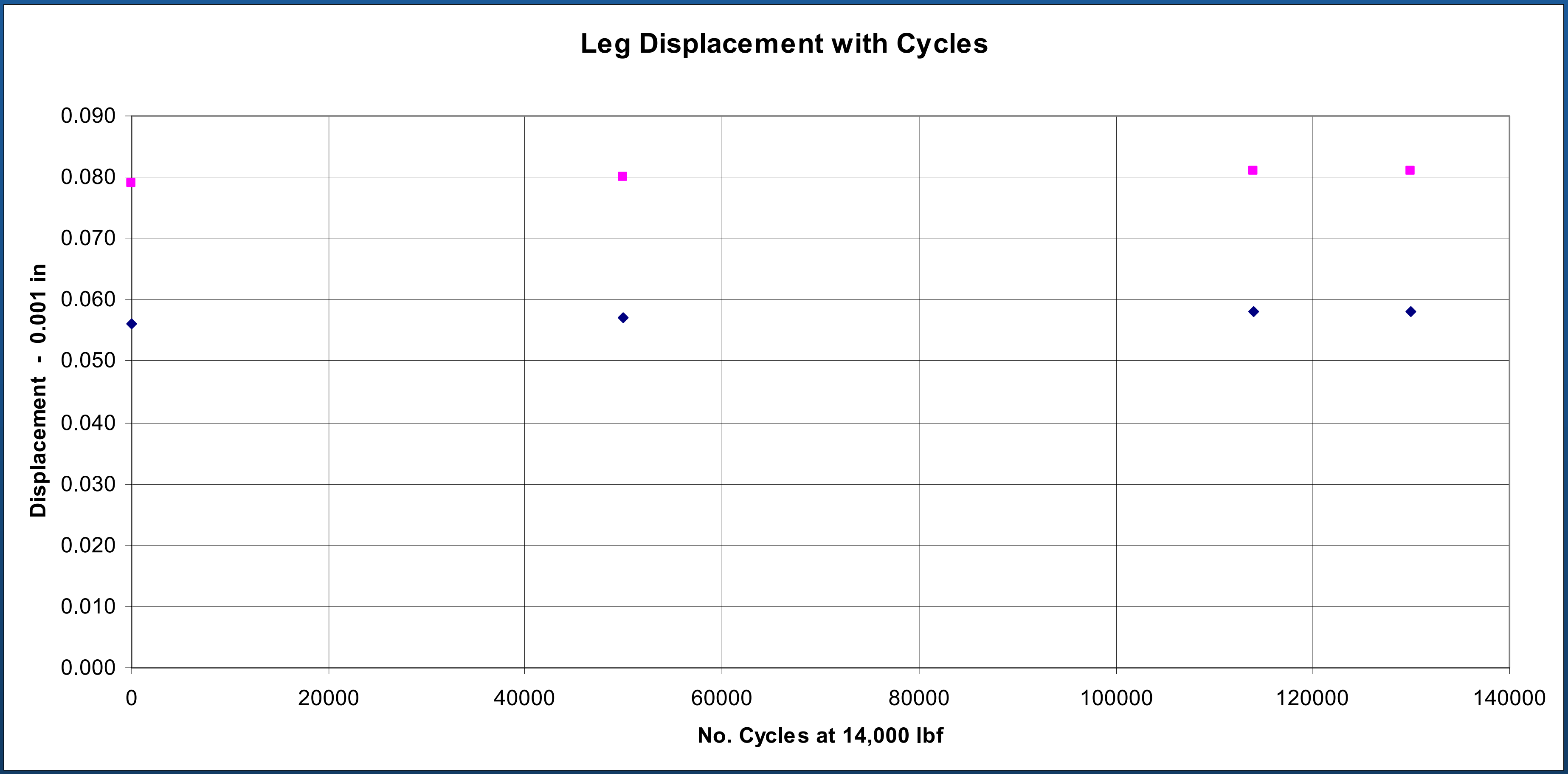
Test Procedure-
Cycle Tested Specimen LRT1

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

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

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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

Fatigue Test
of
Short Race Track Coil
at
Liquid Nitrogen Temp

Cyclic Fatigue Tests

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- **Test Objective:** Perform cyclic fatigue test of short racetrack coil (SRT3) at liquid nitrogen temperature
- **Goal:**
  - 130,000 fatigue cycles at 2 x expected strain
  - Maintain specimen at liquid nitrogen temperature
  - Measure specimen parameters before, during and after fatigue cycles.
- **Test Procedure:**
  - Cool down specimen and fixture to liquid nitrogen temperature
  - Characterize specimen coil with several slow pulls before, after and at several points during cycling.
  - Fatigue cycle at high cycle rate (3.8 Hz max.) and 15,000 lbf peak load

Cyclic Fatigue Test Sequence

- Cool down coil and fixture
- 1st. Slow cycle at 20,000 lbf
- 2nd. Slow cycle at 20,000 lbf
- 65,000 rapid cycles to 15,000 lbf
- Slow cycle to 15,000 lbf
- 35,000 rapid cycles to 15,000 lbf [100,000 cycles total]
- Slow cycle to 15,000 lbf
- 30,000 rapid cycles to 15,000 lbf [130,000 cycles total]
- Slow cycle to 15,000 lbf
- 1st. Slow cycle at 20,000 lbf
- 2nd. Slow cycle at 20,000 lbf
- 20,000 rapid cycles to 15,000 lbf [150,000 cycles total]
- Warm up coil and fixture

Cyclic Fatigue Test

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- For stress and modulus calculations used area equal to copper core area plus two layers of 0.007” glass on all sides of core.
- Single conductor area = 0.130 sq in
- Total sample coil area = 1.040 sq in

Sample Cool Down-Extensometers

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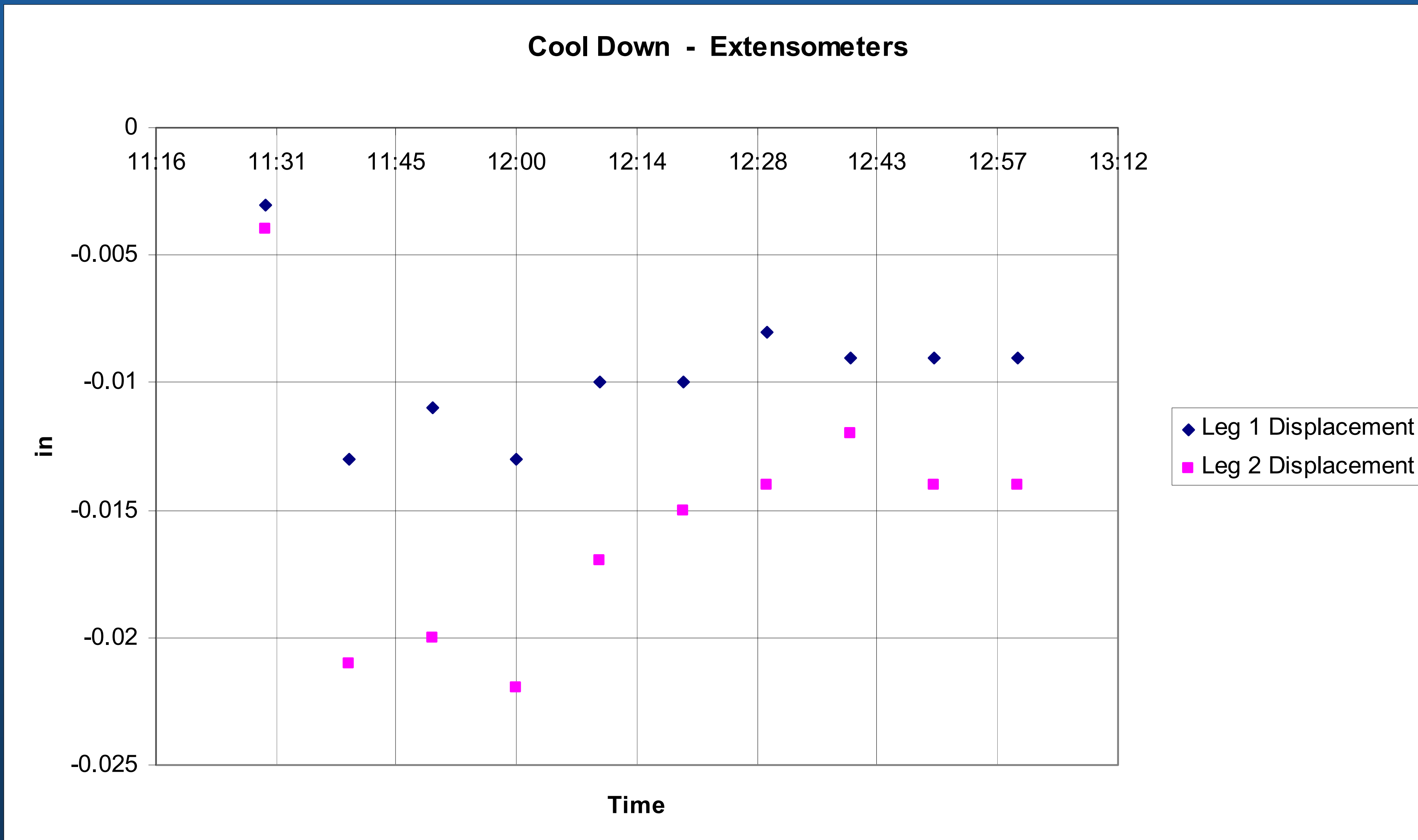
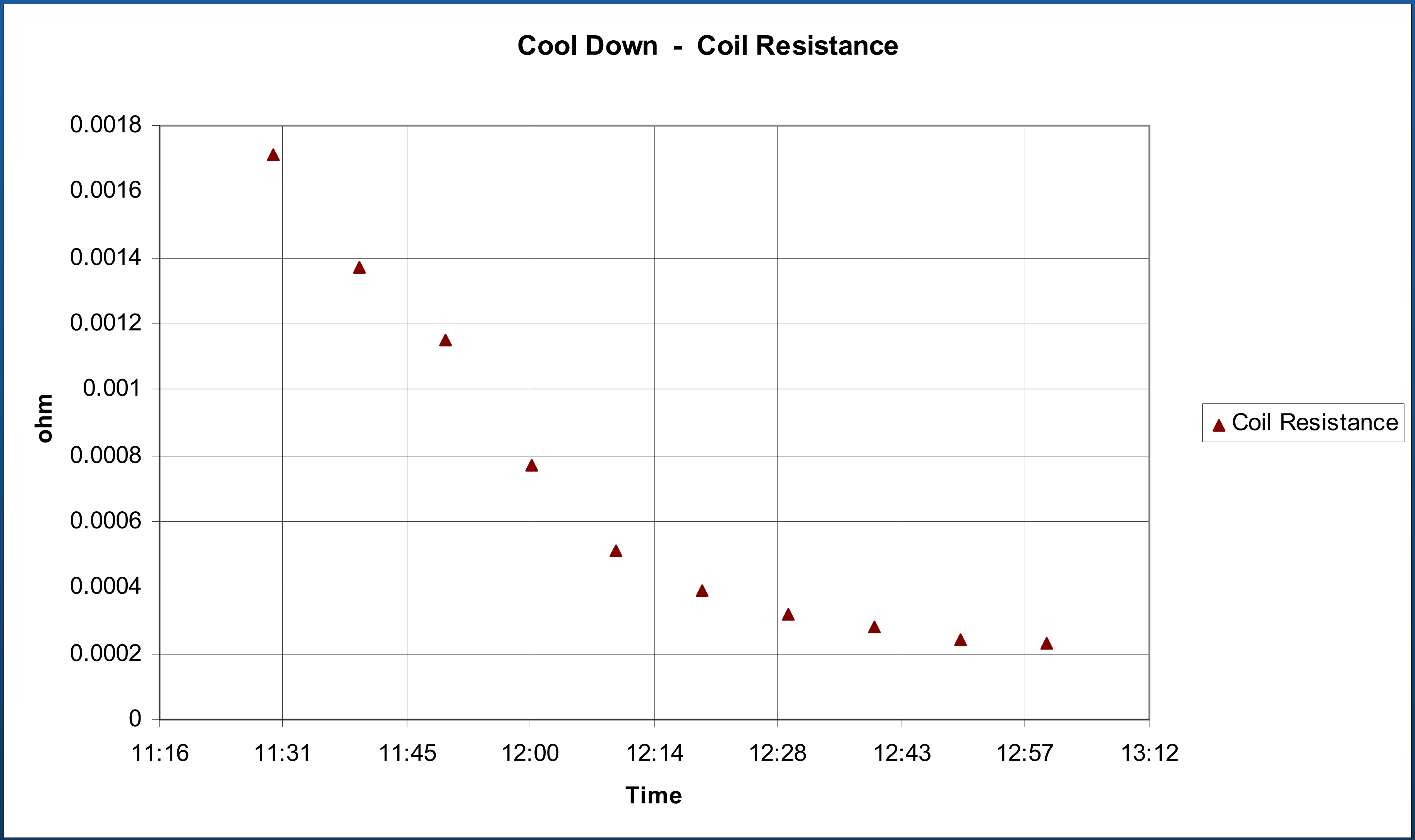
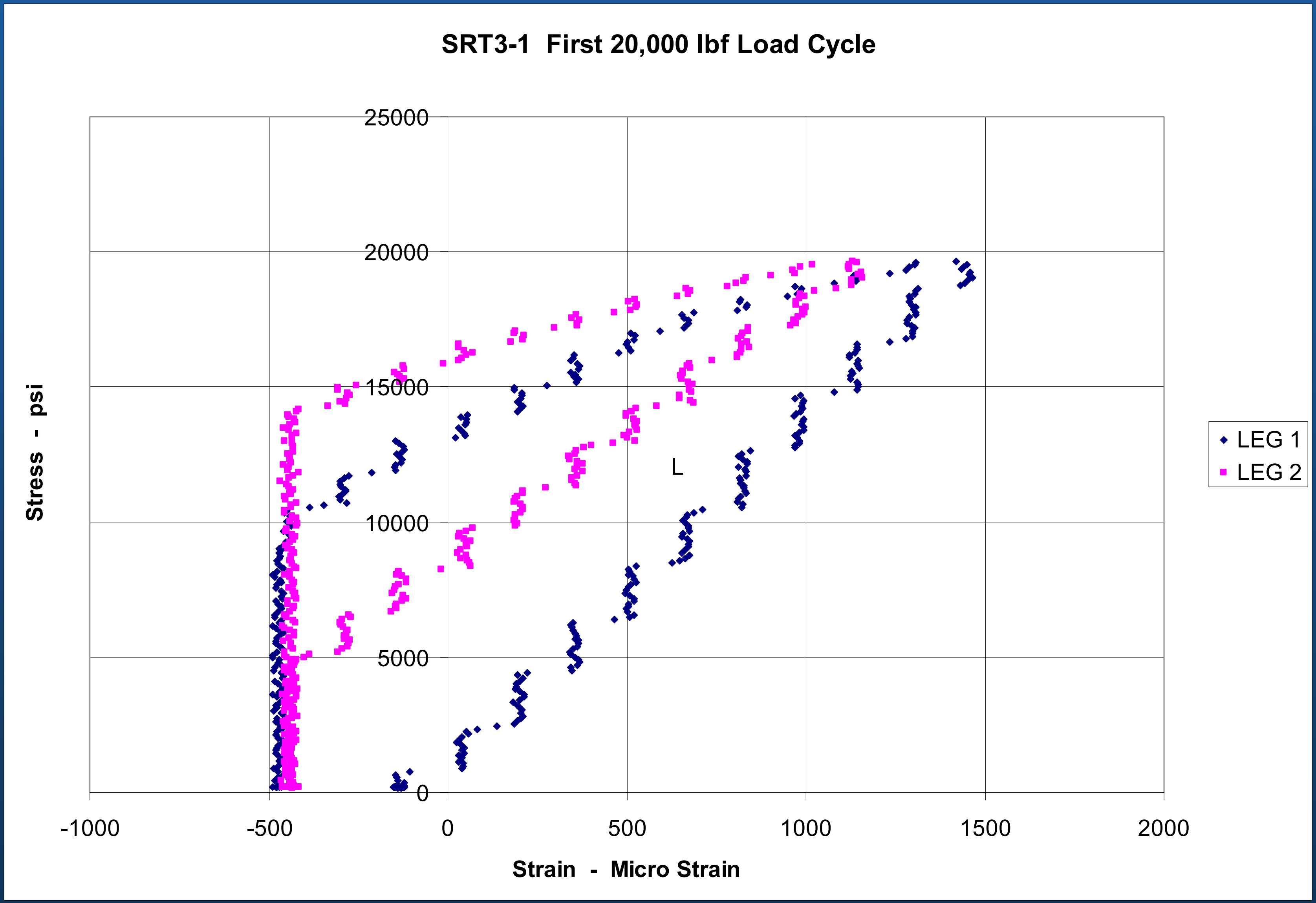


Sample Cool Down-Resistance



SRT3-1 First 20,000 lbf Load Cycle

NCSX



SRT3-1 First 20,000 lbf Load Cycle

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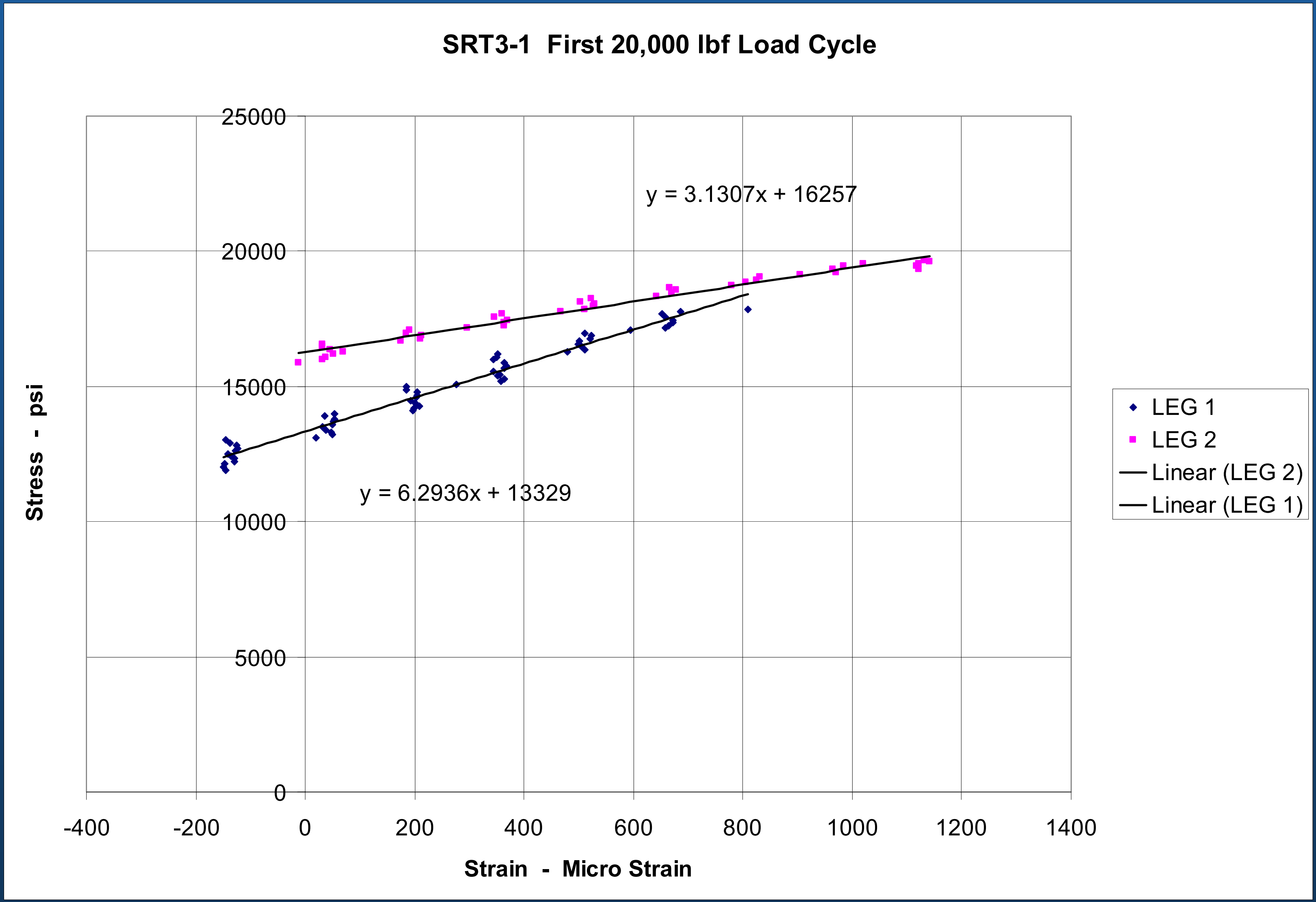

SRT3-2 Second 20,000 lbf Load Cycle

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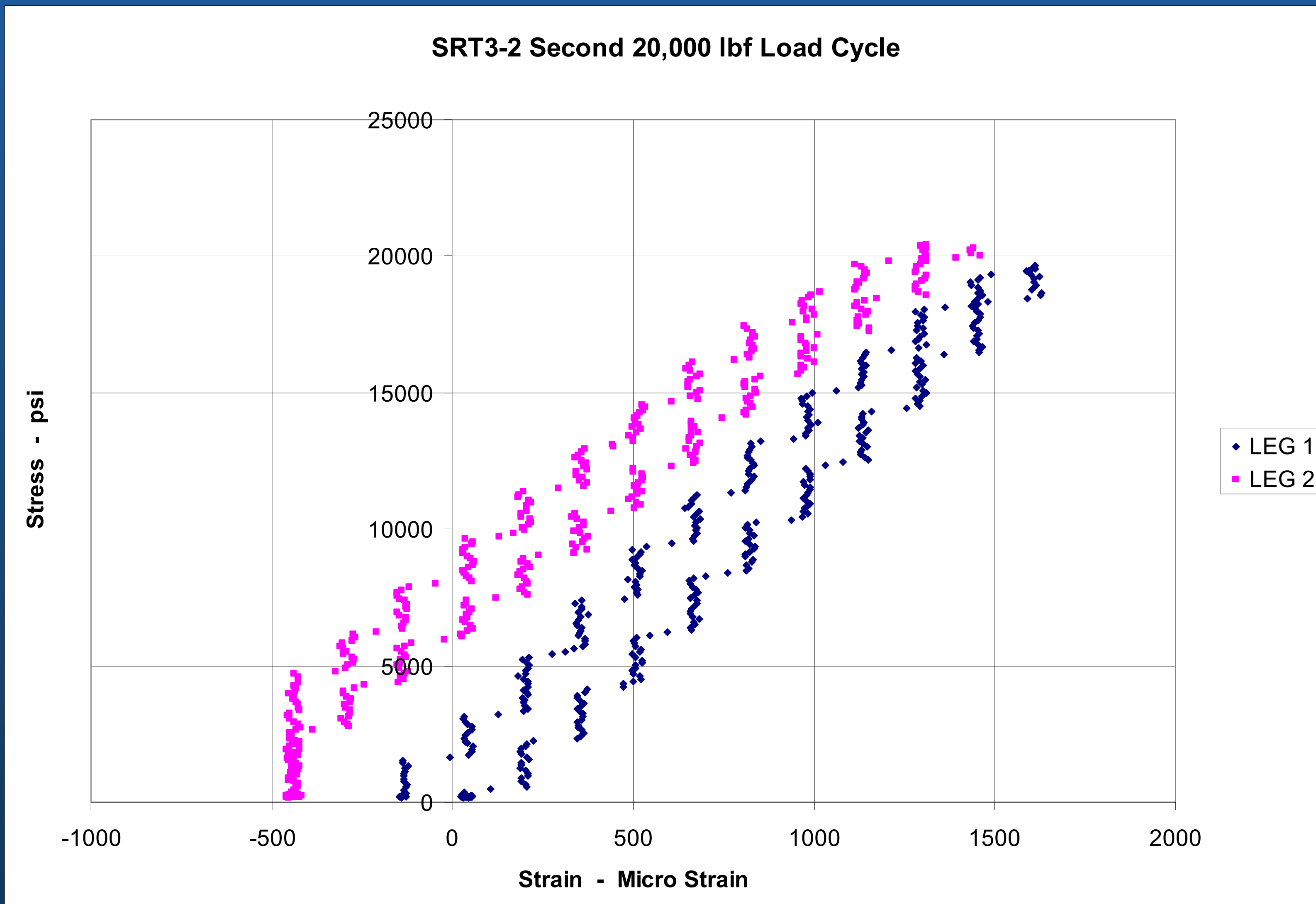

SRT3-2 Second 20,000 lbf Load Cycle

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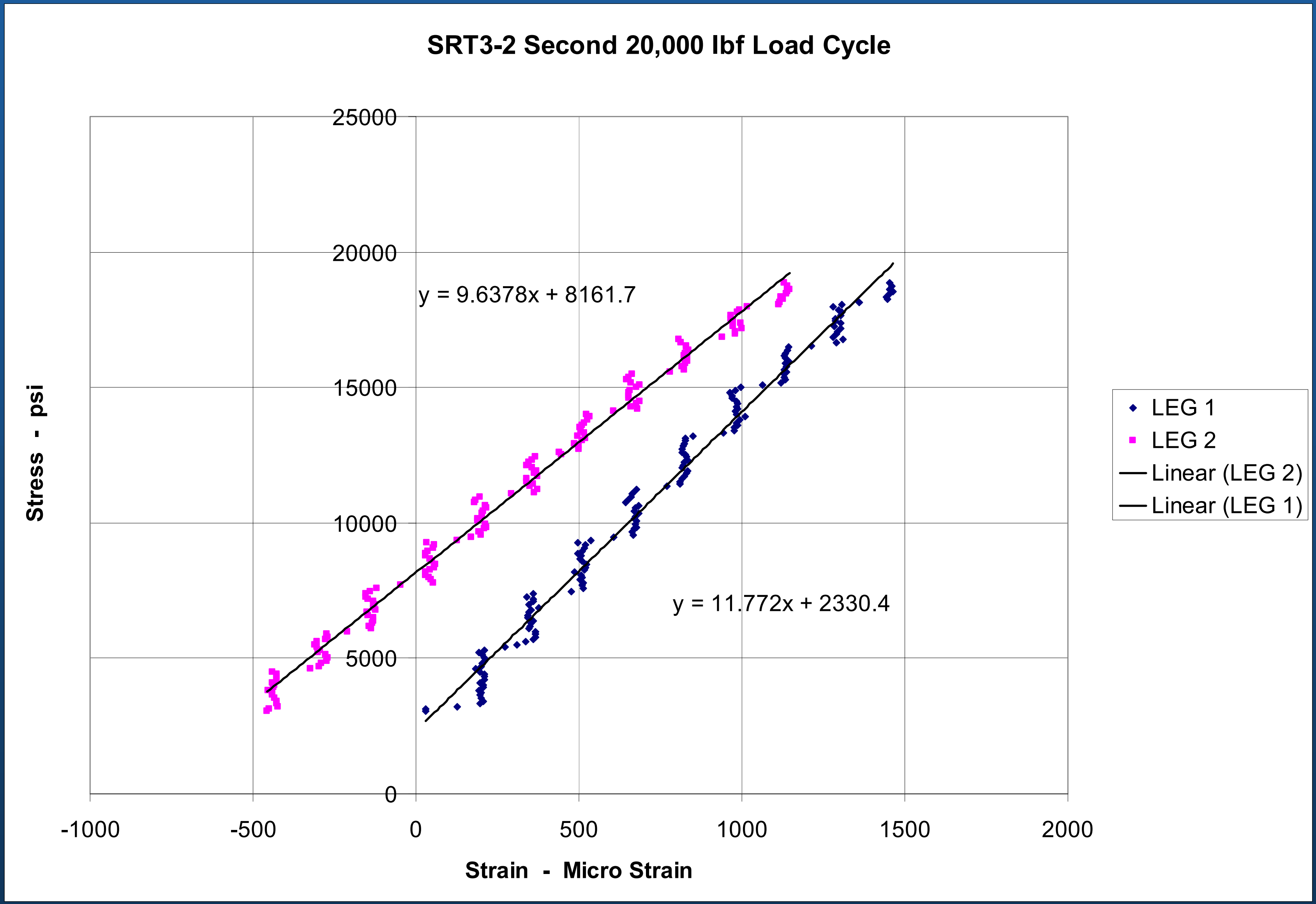

SRT3-3 15,000 lbf Load Cycle after 65,000 cycles

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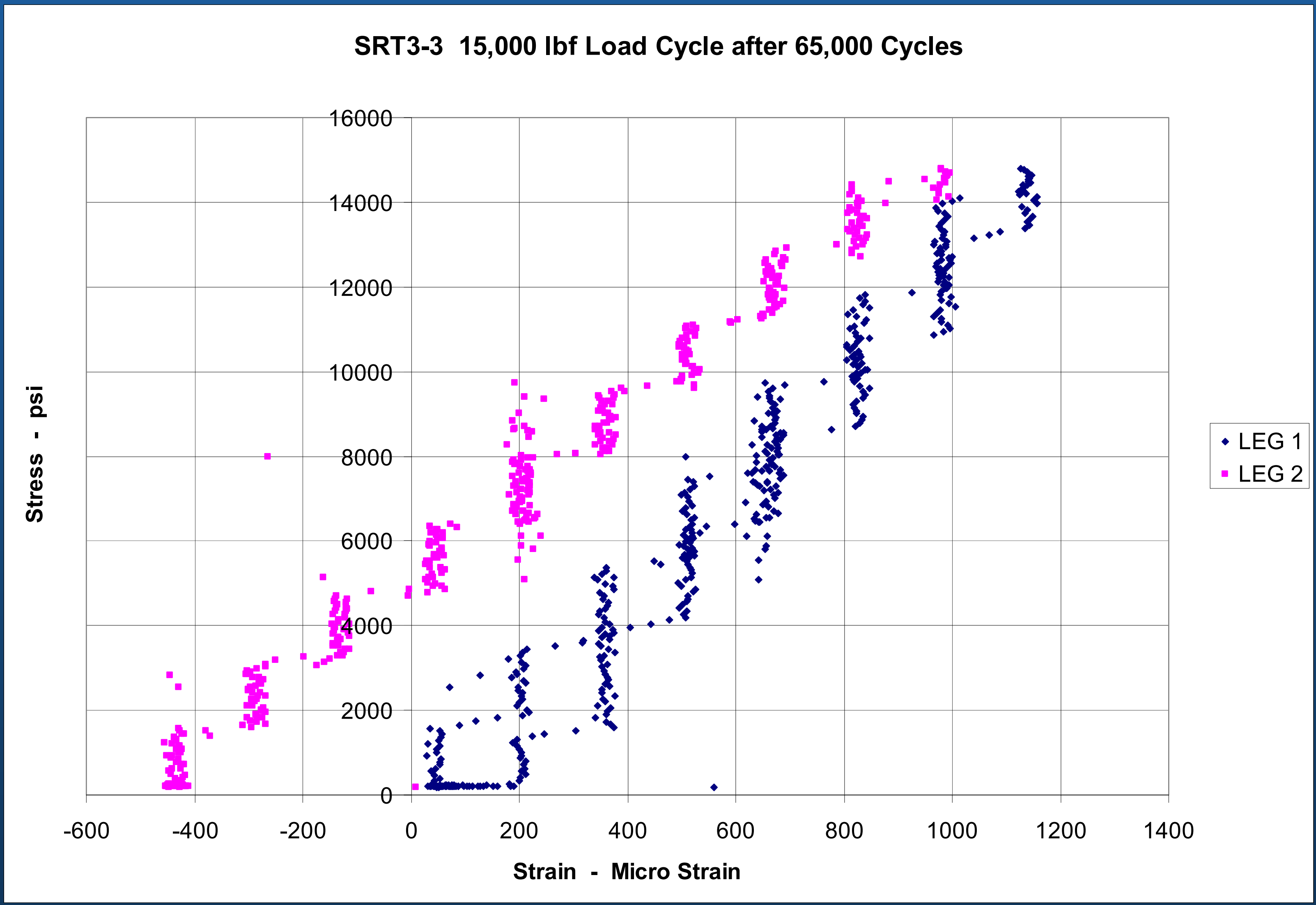

SRT3-3 15,000 lbf Load Cycle after 65,000 cycles

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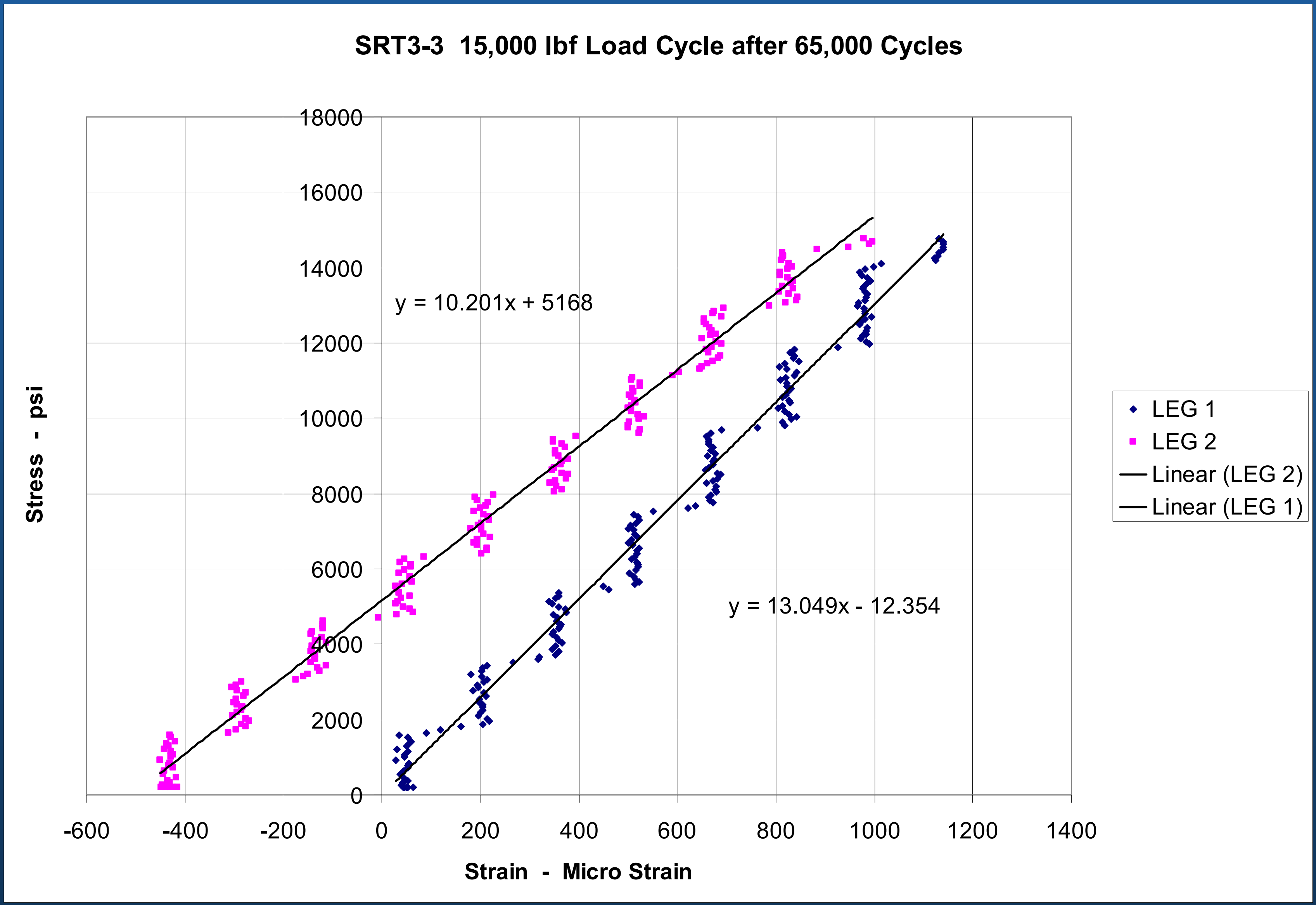
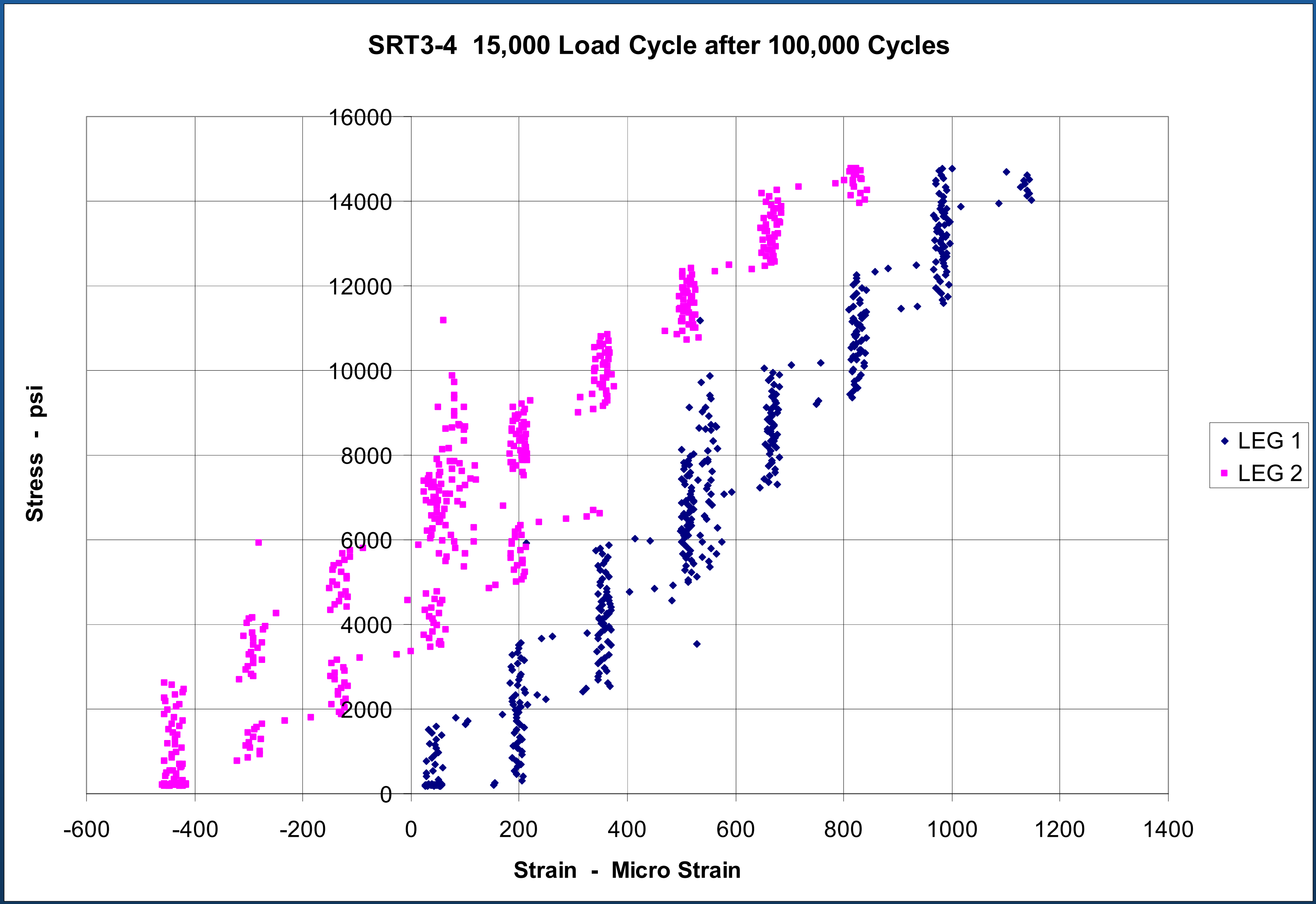


SRT3-4 15,000 lbf Load Cycle after 100,000 cycles

NCSX



SRT3-4 15,000 lbf Load Cycle after 100,000 cycles

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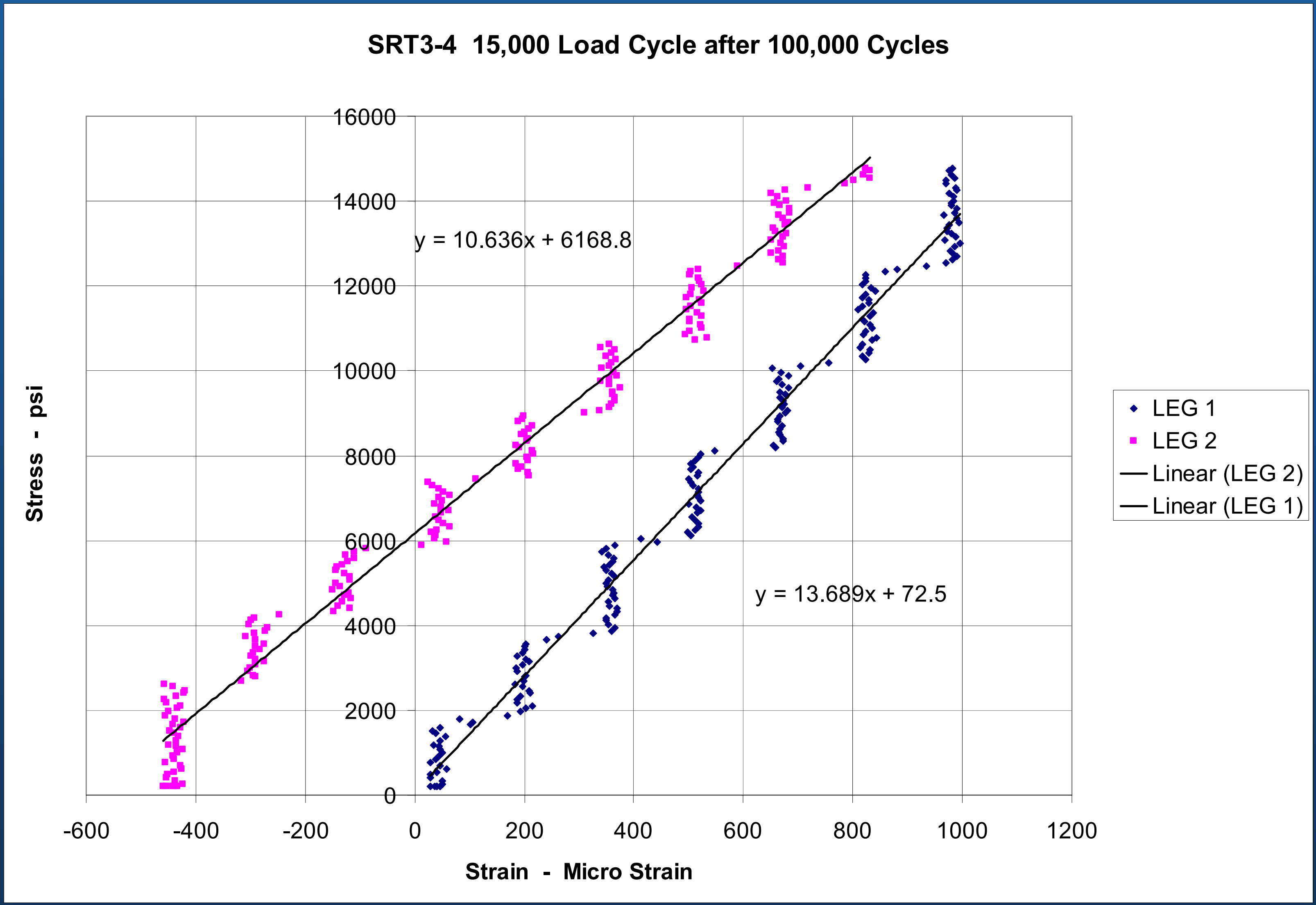
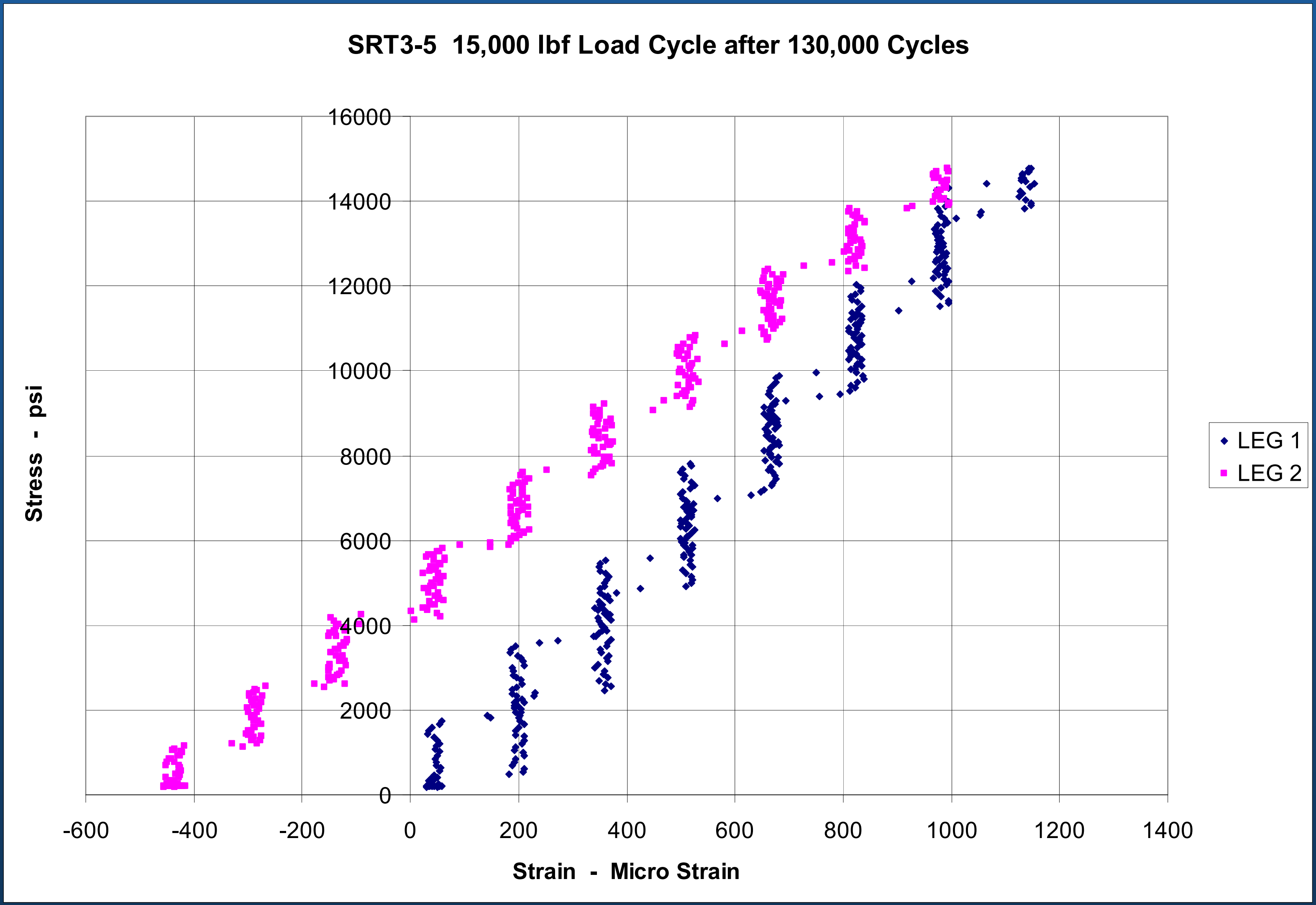
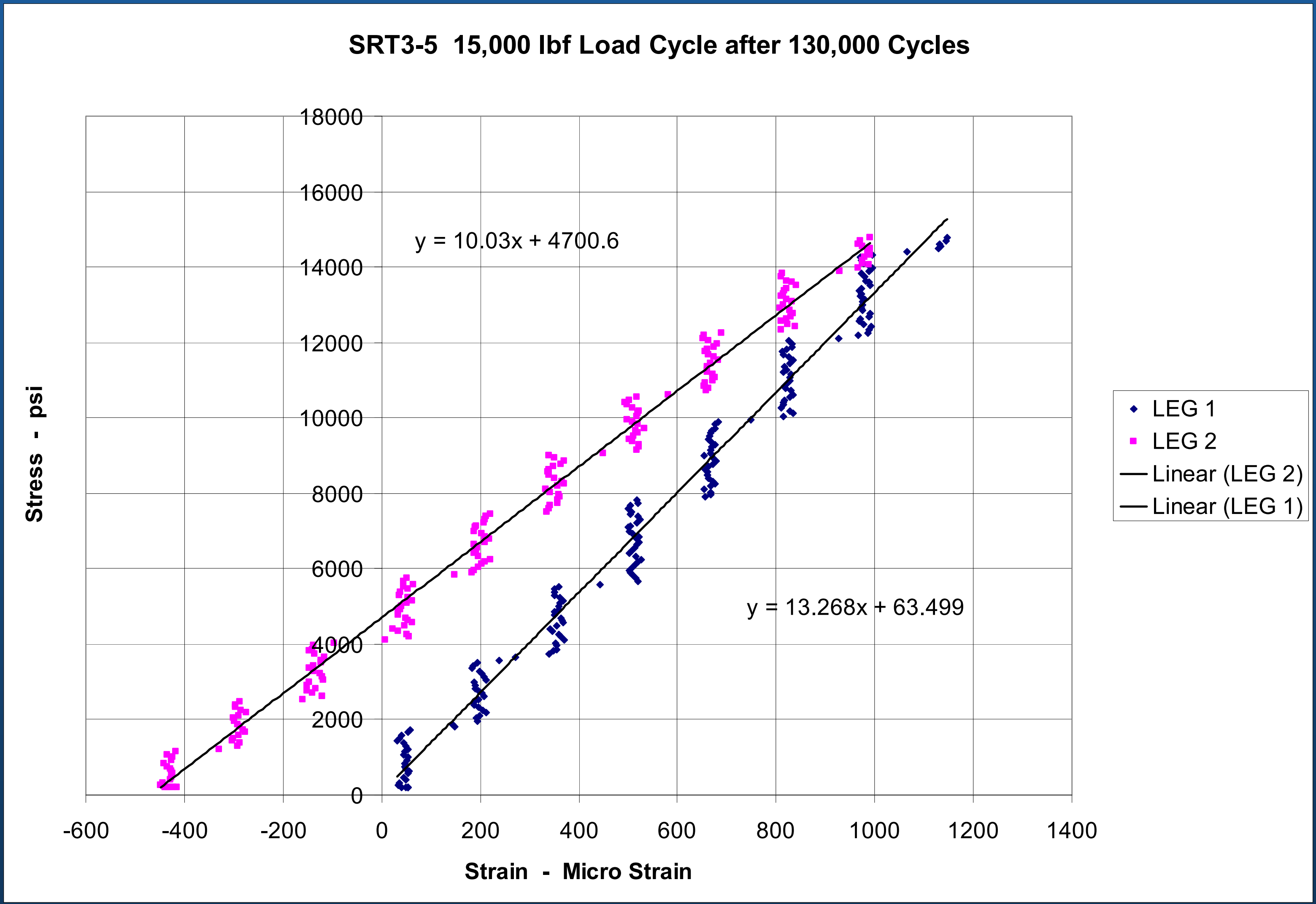


SRT3-5 15,000 lbf Load Cycle after 130,000 cycles

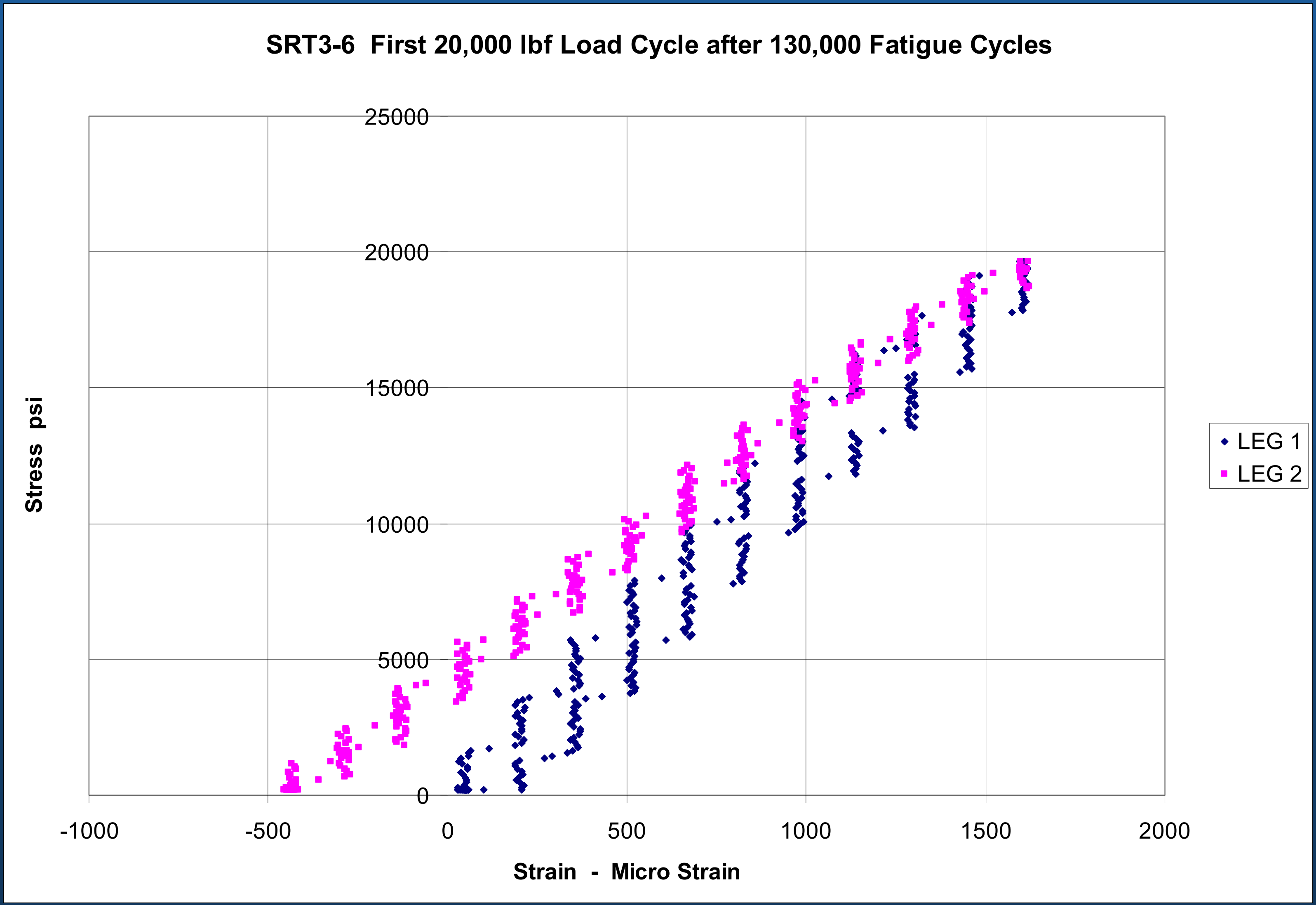


SRT3-5 15,000 lbf Load Cycle after 130,000 cycles



SRT3-6 First 20,000 lbf Load Cycle after 130,000 cycles

NCSX



SRT3-6 First 20,000 lbf Load Cycle after 130,000 cycles

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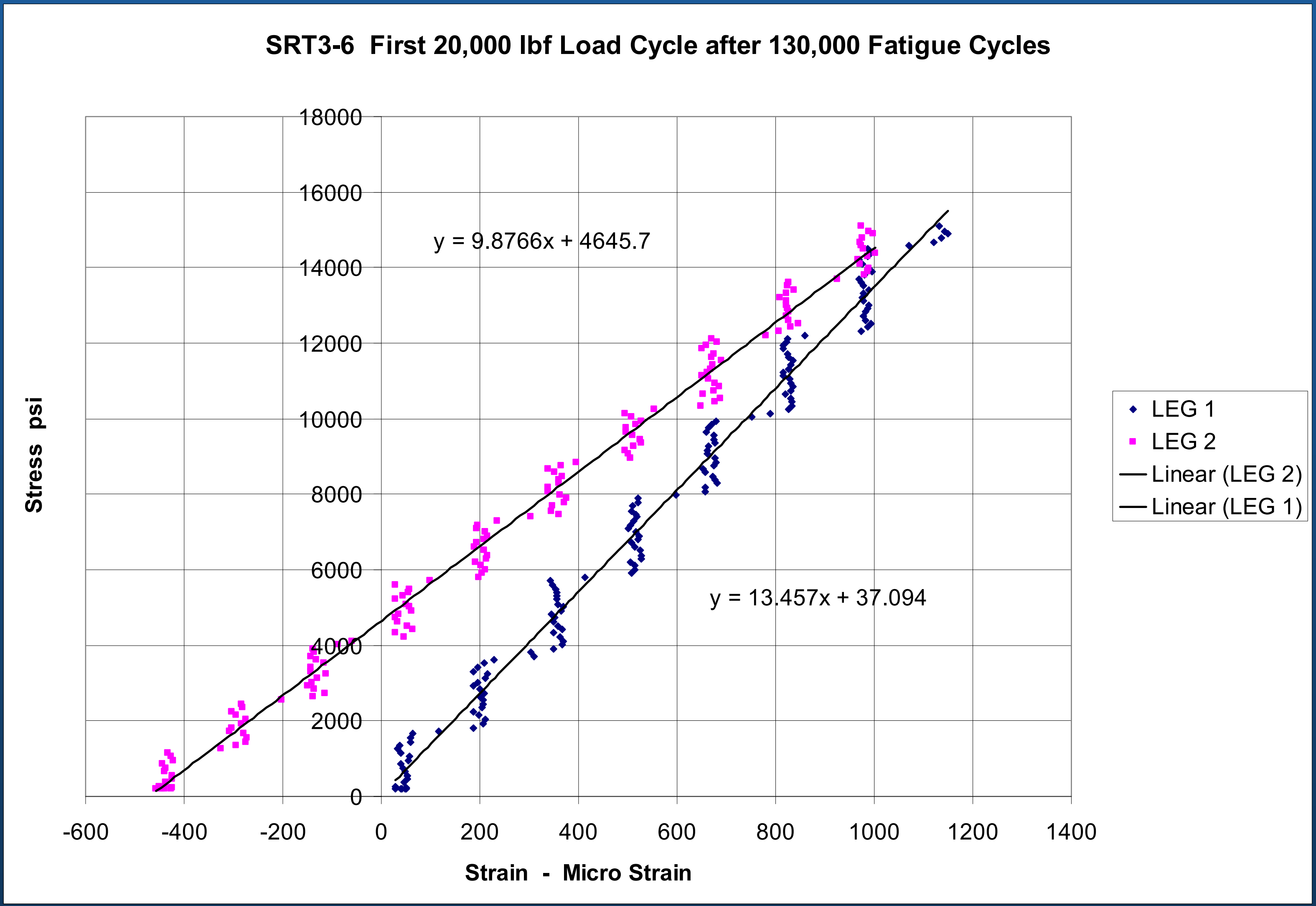
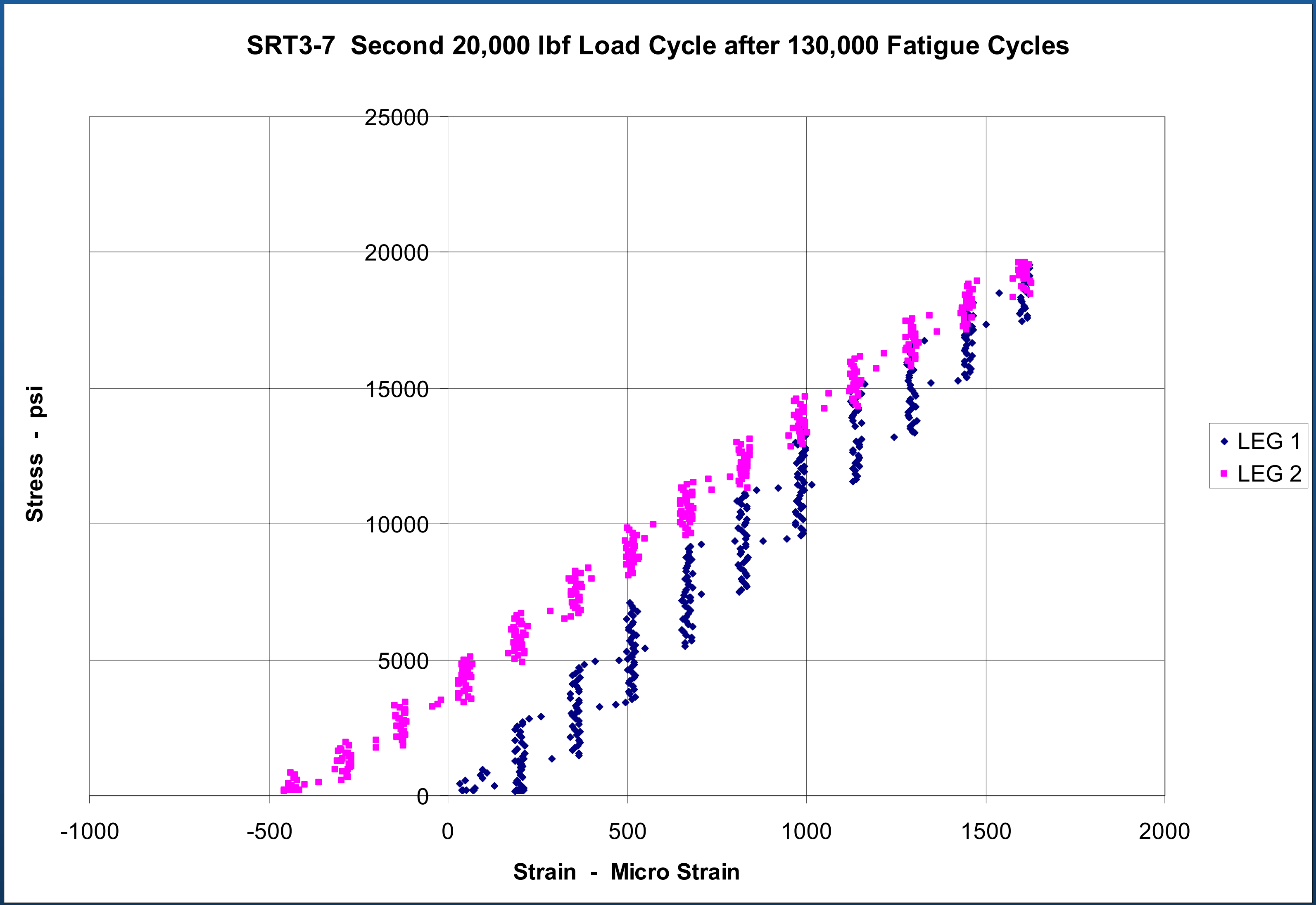
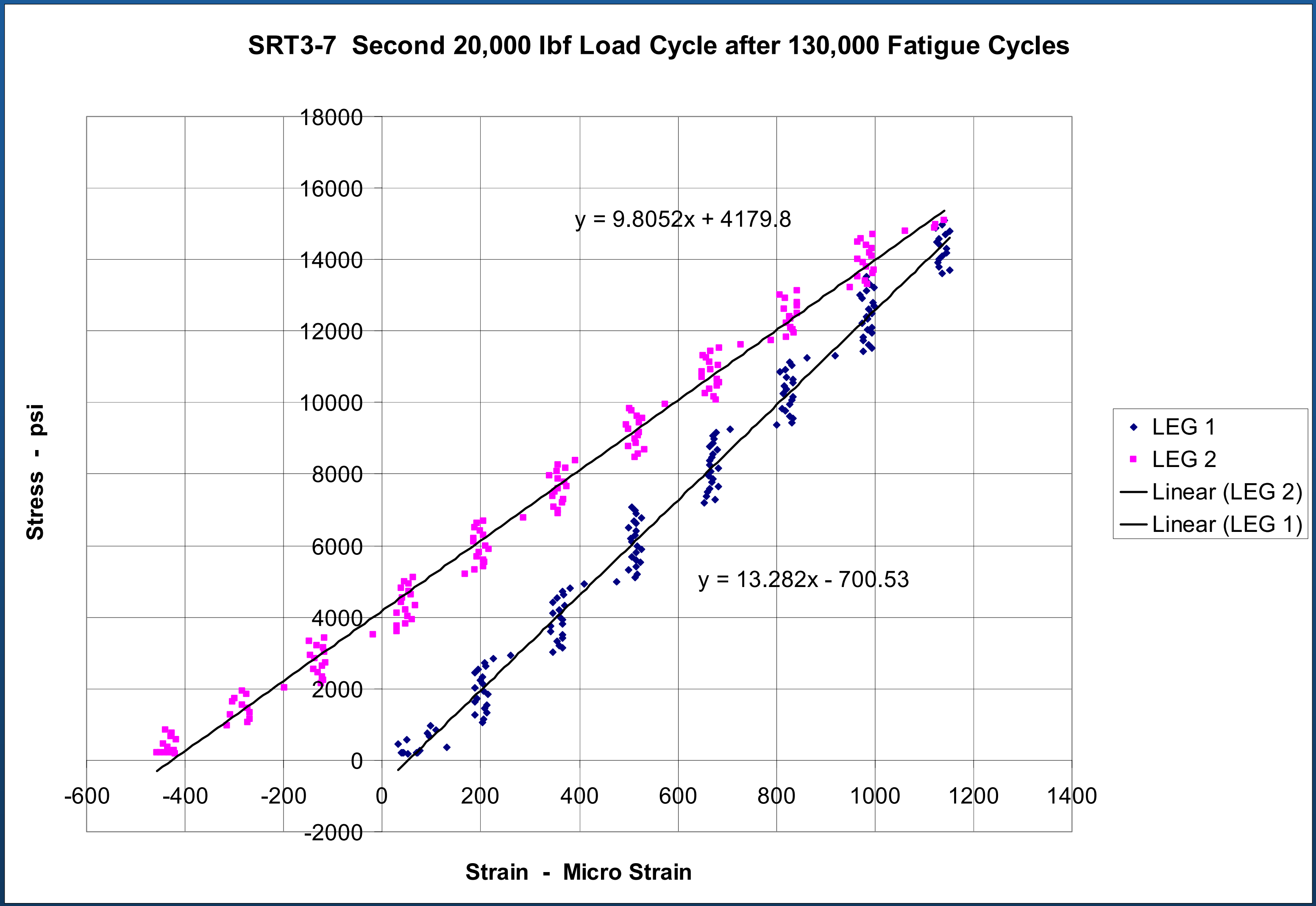


SRT3-7 Second 20,000 lbf Load Cycle after 130,000 cycles



SRT3-7 Second 20,000 lbf Load Cycle after 130,000 cycles

NCSX



Modulus Summary

Test Cycle File	Test Cycle Peak Load lbf	Cumulative Fatigue Cycles	Leg 1 Modulus Msi	Leg 2 Modulus Msi	Average Modulus Msi
SRT3-1	20,000	0	6.3	3.1	4.7
SRT3-2	20,000	0	11.8	9.6	10.7
SRT3-3	15,000	65,000	13.0	10.2	11.6
SRT3-4	15,000	100,000	13.7	10.6	12.2
SRT3-5	15,000	130,000	13.3	10.0	11.7
SRT3-6	20,000	130,000	13.5	9.9	11.7
SRT3-7	20,000	130,000	13.2	9.8	11.5
Average (excluding first cycle)			13.1	10.0	11.6

Modulus Results

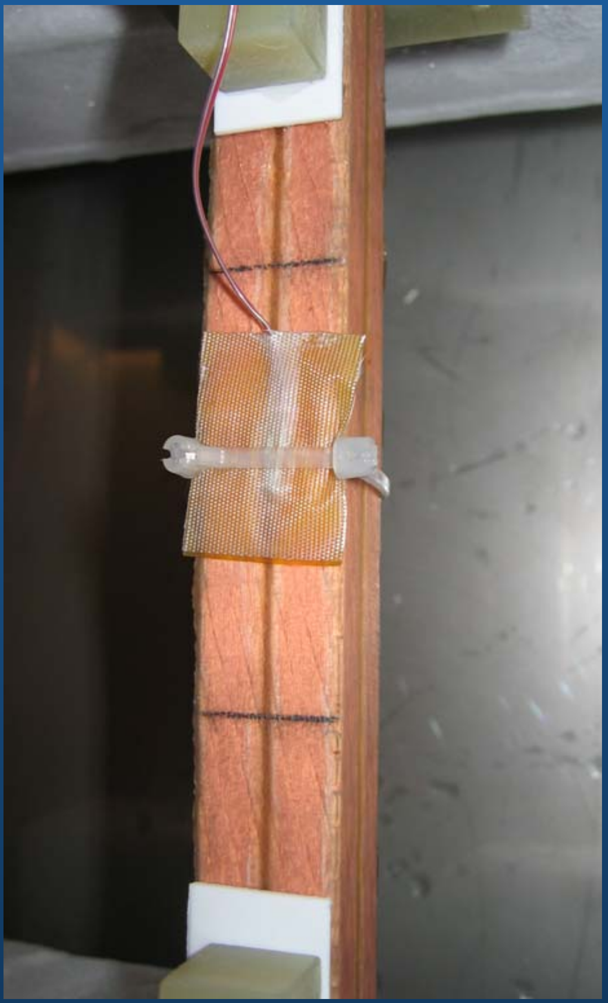
NCSX

- The variation in the tensile modulus between the two legs is probably the result of unequal load sharing.
- The average modulus is representative for the strain resulting from a uniform stress over the total cross-section.

Coil Condition After Fatigue Cycles

NCSX

- The race-track coil legs are in excellent condition after the 150,000 load cycles.
- Leg 1 (left picture) has a casting mark in the center from the manufacturing process, not the cycle testing.
- Leg 2 (right picture)has a thermocouple attached to its front face.
- No change in coil resistance from fatigue cycling.



Next Cyclic Fatigue Test Series

- The next specimen, SRT3, will be slow cycled at room temperature to provide comparative modulus values.
- Two more short race-track coils will be cycle tested at LN2 temperature.
- One sample will have a variation in the attachment of the pin block in an attempt to improve the leg-to-leg load equalization.

Remaining Testing Activities

NCSX

- **Cyclic fatigue** testing and Modulus of race-track coil at liquid N2 temperature. (In progress)
- **Transverse compression** using a 2X5 bare sample to improve the modulus resolution. (Sample ready for VPI)
- **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