Exploring Fiber Optic Strain Sensors for Testing Future Aerospace Structures

Air Force Research Laboratory

Air Vehicles Directorate-Structures Division

Wright Patterson AFB, OH

David.Banaszak@wpafb.af.mil

Larry.Kretz@wpafb.af.mil

Burton.Fisher@wpafb.af.mil

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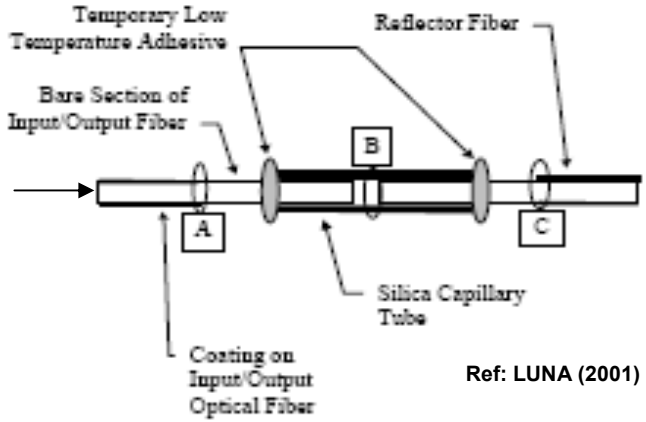
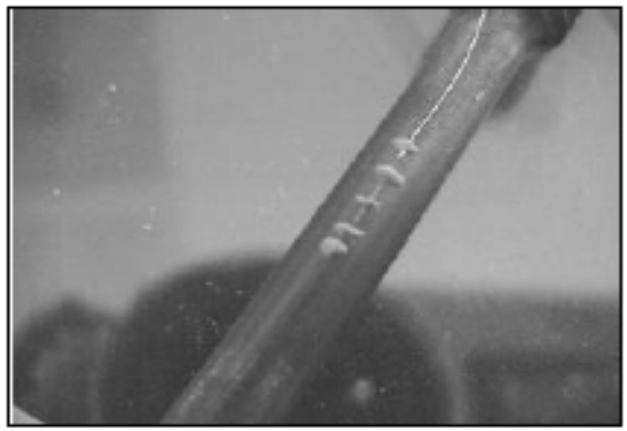
Exploring Fiber Optic Stain Sensors

- Current AFRL Fiber Sensor Evaluation Efforts
- Extrinsic Fabry-Perot Interferometer (EFPI) Sensors
  - Specimen test using Aluminum and C-C coupons subjected to high temperature using different adhesives.
  - To measure strain on structures experiencing temperatures up to 2000ºF (1093.3 ºC)
  - COTS sensors specified to 350 ºC.
- Fiber Bragg Grating (FBG) sensors
  - Supplement conventional strain gages.
  - Provide many strain measurements on a single fiber.
- Present Plans, Efforts, and Results to Date.

Introduction to EFPI Sensors



Ref: LUNA (2001)



- EFPIs consist of reflector and incoming fiber in quartz tube
- Bond to specimen with high temperature adhesive or flame spray
- Distance between attachments is gage length (GL)
- Nominal gap in tube is 50μm (1.97 mil)
- Multiple light waves reflect from the incoming and reflector fibers
- Interference pattern is used to measure the gap length (L)
  - Gap varies between 30-80 μm (1.18-3.15 mil)
- EFPI conditioner output is an analog voltage proportional to strain
- Strain =ΔL/GL, where ΔL is the change in gap length
- Strain unit-less- often expressed in microstrain(με) = (ΔL/GL) x 10^{-6}

Introduction To EFPI Studies

- **Extreme aerospace environments up to 3000˚F (1648.9ºC)**
- **Above 1800 ºF (i.e. gold's melting point) Bhatia, V, Green, J., et. al. (1996) experimented with sapphire fibers**
- **Bhatia, V., Greene, J., et. al. (2000) outline theory of an EFPI extensometer and describe equations to determine the gap**
- **EFPI sensor manufactures can provide technical details:**
  e.g. Luna, Blue Road, and Fiso
- **AFRL engineers examining EFPI sensors' potential to measure strain on aerospace at temperatures up to 2000 ºF (1093.3 º C).**

Preliminary Thermocouple Tests

- **July 2004**
- **Used ceramic adhesive Zircon Potting Cement No. 13 to bond K-type thermocouples (TCs) to Carbon-Carbon (CC) flame sprayed with a base coat**
- **Subjected TC attachments to 2000ºF (1093.3ºC) in approximately 40,000 seconds (about 11.1 hours)**

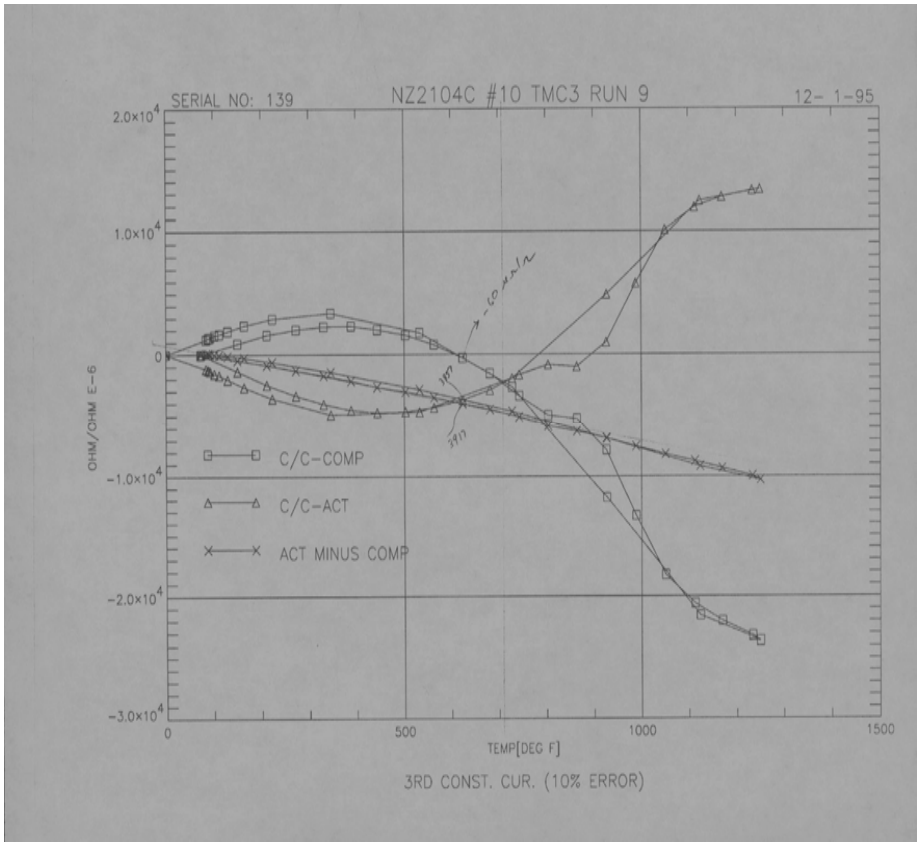
- **August 2004**
- **Sauereisen 13 successfully bonded about 40 thermocouples simultaneously to a CC test Article**

Overview

- 2 methods of bonding EFPI Sensors
  - flame spray
  - high temperature adhesives
- Estimate GL by formula:
  - GL= (2*inner+outer)/3,
  - “inner” and “outer” are distances in millimeters (mm) of the end attachment bonds
- e.g. Adhesive Mount on Item 4 (C-C)

  GL = (2*6.056+9.294)/3 = 21.406/3 = 7.135 mm (.281 inches)

AFRL Requirements and Past Results

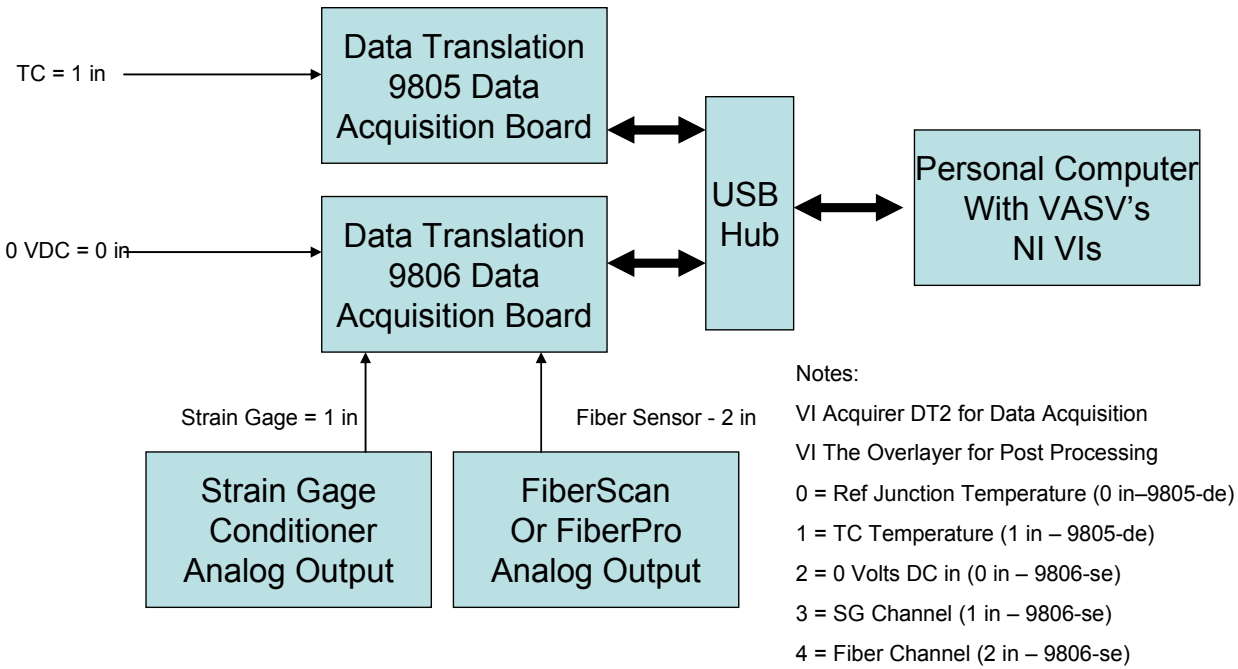


- **Engineers expect temperatures exceeding 1832ºF (1000ºC) in extreme thermal environments and high vibratory strain loads**
- **High apparent strain curves obtained using valid strain measurements at temperatures up to 1250 ºF (667.7 ºC)**
- **Convert ΔR/R to strain by using the strain gage factor (GF) for conventional resistance gages**

Apparent Strain-Conventional Gages (1 Dec 95)

Lab Test Measurement System

- Acquired data using a read data virtual instrument (VI)
- Sampled each channel 10 times per second.
- VI “overlayer” creates Microsoft® Excel readable file.
- Import data to Excel-generate time history and apparent strain plots



Preliminary Design of Experiments (DOE)

Experimental Outputs

1-Correlation between EFPI and Strain Gages at room temperature using bending and axial loading

2-Apparent Strain Curves up to 1600ºF (871.1ºC)

3-Combined Strain Correlation & Apparent Strain at high Temperature

Test Items

1 - rectangular Aluminum 2024 (1.5 x 8.25 “(38.1mm x 209.6mm))

2 - rectangular CC-1 (1.25 inches x 4 inches (31.8mm x 101.4mm))

4 - round CC (69.8mm in diameter)

Preliminary Design of Experiments (DOE) Control Factors

Test Type	Specimen Material	Specimen Shape/Size	Attachment Techniques	Fiber & SG Location	Specimen Side	Test Temperature	Max Test Strain	Atmosphere
Room Temperature Load	C-C Samples With Flame Spray	Round Diameter 2.75 “inches	LaRC Flame Spray	Center For In-Plane	Top	Room Temperature	0με	Normal Air
Apparent Strain	2024-T3 AL	Rectangular 1.5x8x.125 ”	Ceramic Cements (e.g. Sauereisen 13)	Near End For Bending	Bottom	Low 550 F	500με	Nitrogen Purged
Combined	Inconel 718	Rectangular 1x12x.125	M Bond 610		Both	Medium 1100 F	2000με	
	Rene 41		AE 10			High (1945F=1063C)		
	Ti64							
	ScrapC-C							

Preliminary Design of Experiments (DOE) Partial Test Matrix

No.	Test Type	Material	Size	Attachments	Location	Gages	Atm	Oven	Temp.	Strain
1	Bending	AL2024	1.5x8.25	Sauereisen 13 or Ceramic Cements	Center	Fiber Optic & Foil & TC	None	None	Room Low	1000 με
2	Apparent Strain	X-37 #1	1-1/4x4	Flame Spray & Sauereisen 13	Center	Fiber Optic & Foil & TC	N2	L & L	500F 2000F	None
4	Apparent Strain	Round	2.75	Flame Spray – Then Cements	Center	Fiber Optic & Foil & TC	N2	Lamp Bank (L&L)	2000F	None
11	Apparent Strain	Round C-C	2.75	Flame Spray	Center	Fiber Optic & Foil & TC	N2	Lamp Bank (L&L)	2000F	None

Preliminary Design of Experiments (DOE)

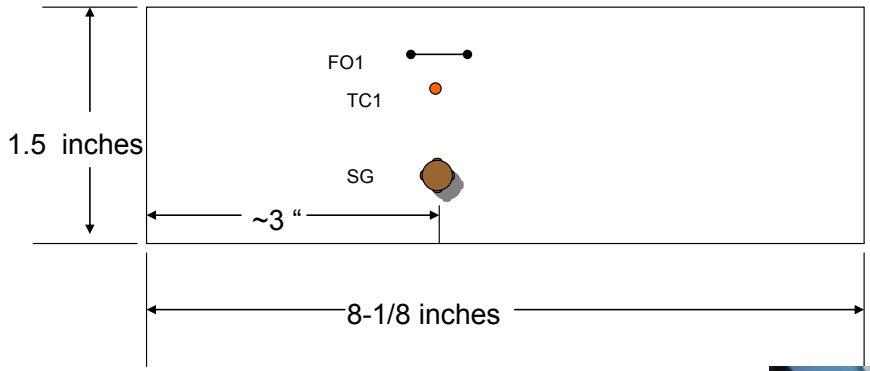
- Correlation between EFPI and Strain Gages at room temperature using bending loads.
  - **Technician opportunity to practice mounting EFPI sensors on known materials i.e. Aluminum and CC with flame sprayed base coat**
  - **Measure outputs to determine correlation between EFPI sensors & strain gages**

- *Apparent Strain Curves*
  - **Measure apparent strain curves up to 1600°F (871.1°C) on Test Item 2**
    - **EFPI sensors attached to CC with a flamed sprayed base coat**
    - **TC and 2 EFPI sensors mounted with Sauereisen 13**
    - **Convention strain gage mounted using M-Bond 600 adhesive**
  - **Heat specimens but not strain in 2 types of heat tests**
    - **Clamp specimen to lab bench-heat it to about 500 ºF (260 ºC) using a heat gun**
    - **Placed specimen in oven for apparent strain up to 2000°F (1093.3 ºC)**

- *Combined Strain Correlation and Apparent Strain at High Temperatures*
  - **Building a combined temperature and mechanical loading test chamber**
  - **Correlation between the EFPI sensor and strain gages at low, medium and high temperatures**
  - **Subject specimens to 2100°F (1148.9 ºC) and 1000 με of in-plane or out-of-plane loads**
  - **Chamber will have nitrogen purge capabilities**
  - **Attain set temperature in less than 1 hour- simulate thermal transient**

Test Item 1 Laboratory Bending and Heat Tests (2024-T3 Al)

- **Room temperature tests**
- **Approximately equal bending strain on strain gage and EFPI sensors by clamping Al beam to a lab bench**
- **Bent to stimulate tension and compression then compare the strain gage and EFPI sensor outputs**
- **Outputs slightly different**
- **After corrections for GL, the EPFI sensor and strain gage outputs correlated well**



F1- EFPI fiber sensor Attached using Saureiensen #13.

TC- ThermoCouple Attached using Saureiensen #13

Route TC wires & fibers toward Right Hand Side of Plate

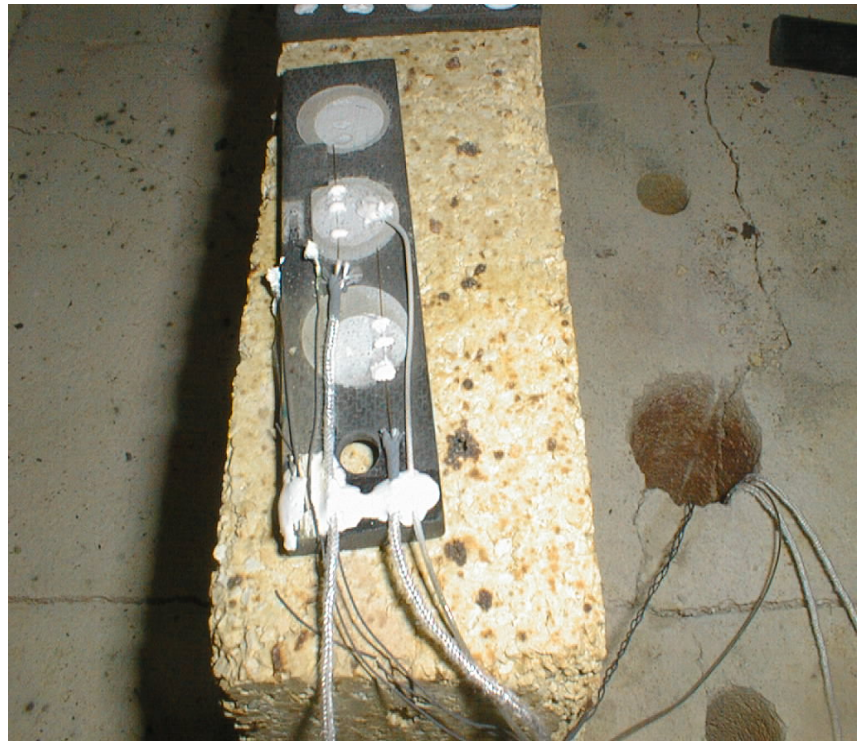
SG – Document SG Type and Bonding

Low Heat Setup

Test Item 1(2024-T3 Al) Layout

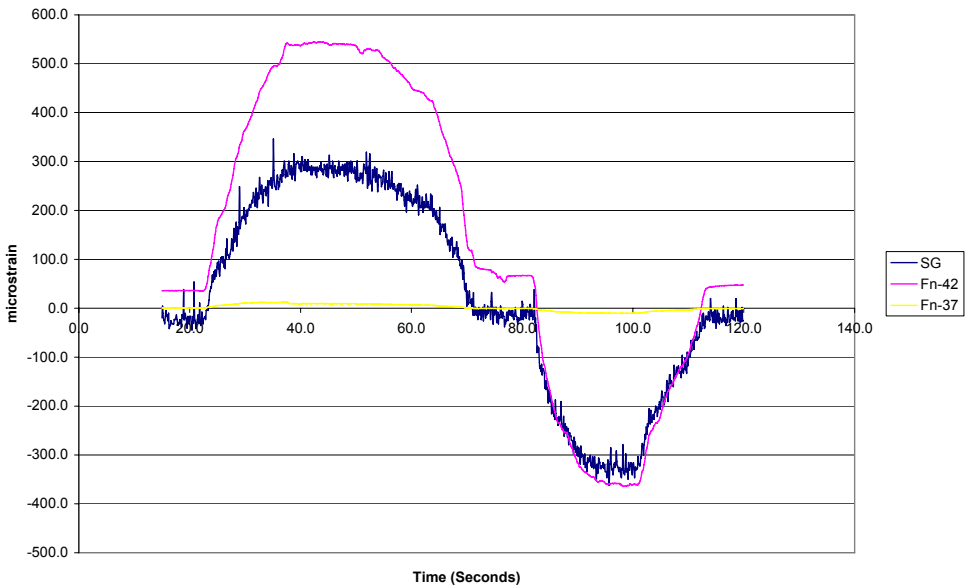
Test Item 2(CC) Laboratory Bending, Heat Gun and Oven Heat Tests

- **Rectangular piece of CC**
- **Designed for 2000ºF (1093.3ºC)**
- **4 sensors on Test Item**
- **Circular spots flame sprayed by Roth (2004) so that ceramic adhesives would bond to item at high temperatures**
- **Sauereisen 13 to bond EFPI sensors and thermocouple (TC) on the flame spray spots**
- **Mounted strain gage (SG) using M-Bond 610 adhesive**
- **Comparisons to 500ºF (260ºC)**



Test Item 2 (CC2) After 1600ºF Hest Test (F-42, TC, SG-Center & F-37-Hole)

Test Results on Test Item 2 (CC)

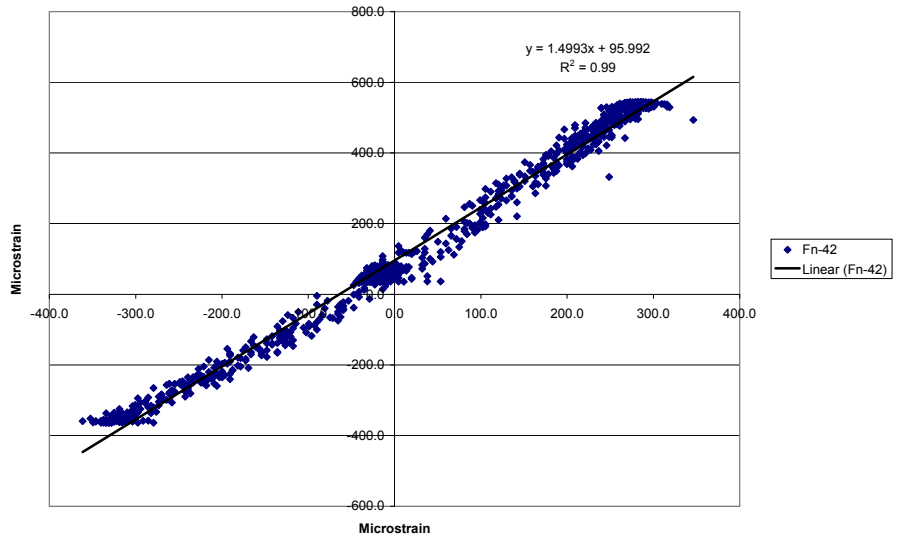


Lab Bending F-42 (Red) and Strain Gage (Blue) – F-37 (Yellow)-no Correction

- Clamped beam to lab bench to form a cantilever beam
- Bent manually to induce tension and compression of roughly equal magnitudes into each of the sensors.
- Outputs for fiber F-42 and the strain gage in the center of the beam and fiber ID F-37 located at the end of the beam
- F-42 and strain gage output correlated, but have significant different readings

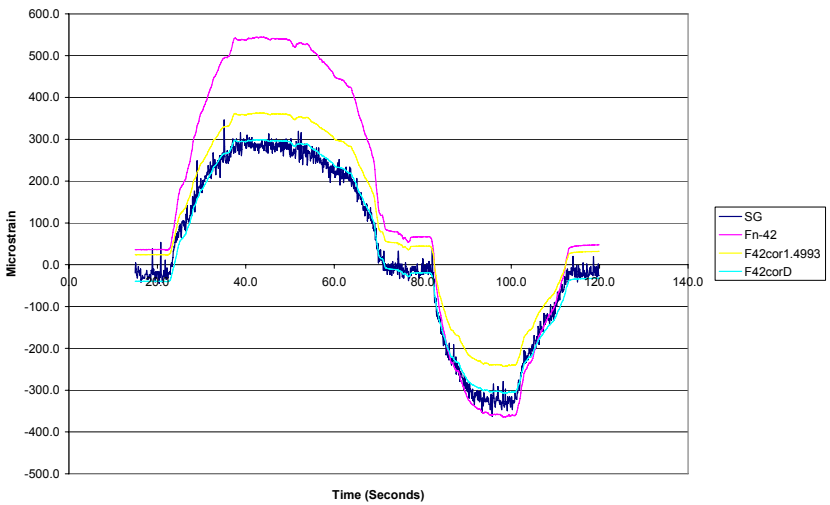
Test Results on Test Item 2 (CC)

- Plot of output of fiber Fn-42 versus strain gage confirms high correlation
- Best fit straight line (BFSL), (y=1.4993x+95.962 with correlation R^2 = .99) relates the fiber output to the strain gage output
- BFSL should have slope=1
- Correct fiber out by dividing GL by slope (1.4993)



Lab Bending - F42 versus Strain Gage

Test Results on Test Item 2 (CC)

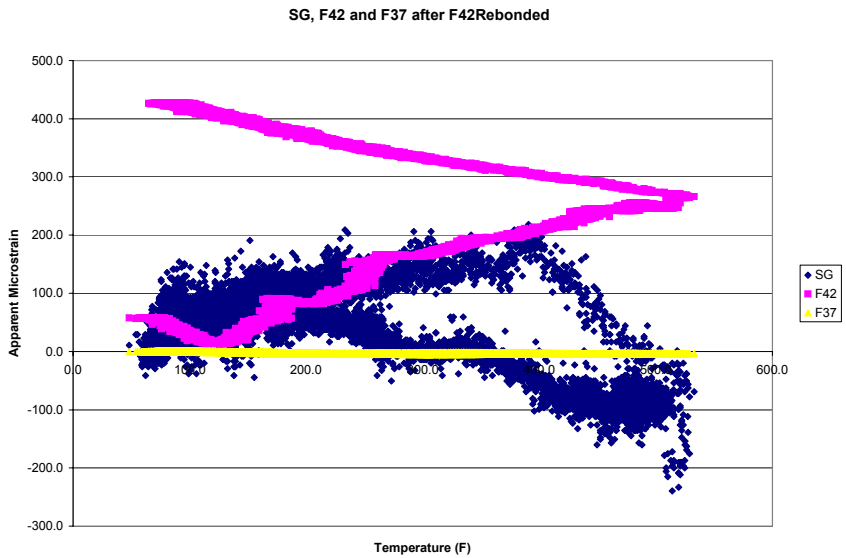


Lab Bending F-42 (Corrected) and Strain Gage

- **Figure shows the original fiber F-42 output, strain gage output, and corrected F-42**
- **Correction results much closer agreement, even without applying the offset term**
- **Same technique worked for bending tests on Item 1**
- **Note: Output of F-37 was much lower as expected since it's further from the clamped edge of the beam**

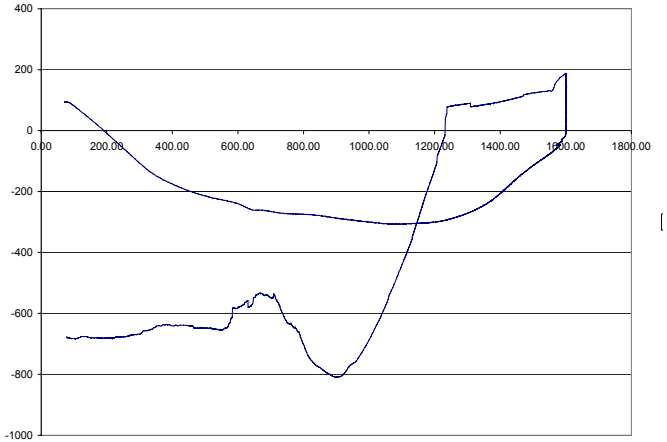
Test Results on Test Item 2 (CC)

- Heat Item to about 500ºF (260ºC) using heat gun for the apparent strain curve
- F42 did not return to zero με
- F37 had small response
- Strain gage had noisy signal
- Mixed results
- Continue to heat specimen in an oven to search for new insights.

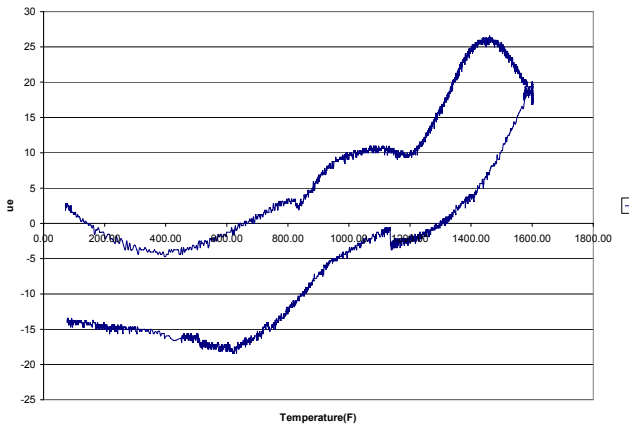


After Heat Gun Test to 500ºF

Test Results on Test Item 2 (CC)



F-42 vs Temperature for 2 hour soak at 1600°F

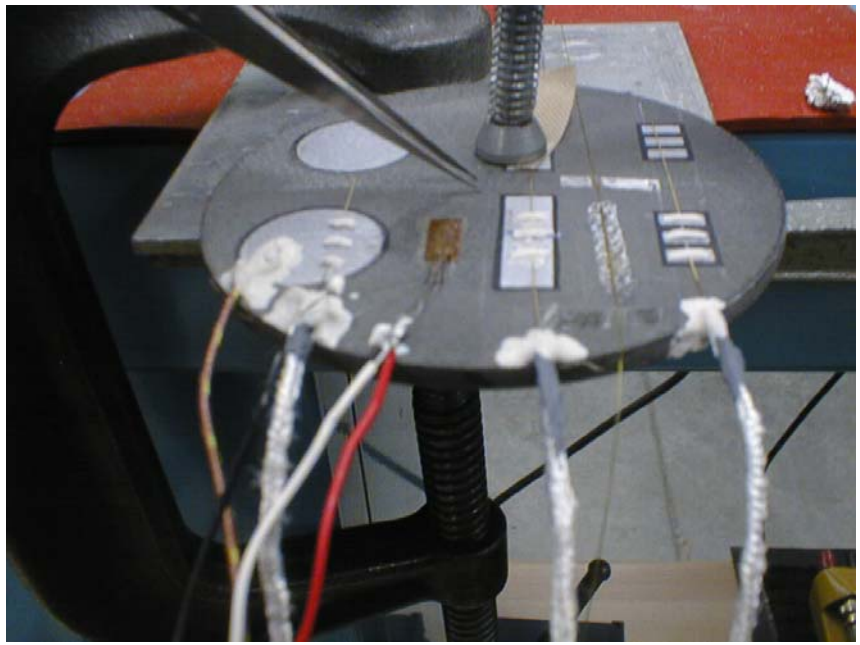


F-37 vs Temperature for 2 hour soak at 1600°F

- **Fiber 42 has large step changes**
- **F-37 lower apparent strain reading**
- **Strain gage fails at ≈ 800ºF(426.7ºC)**

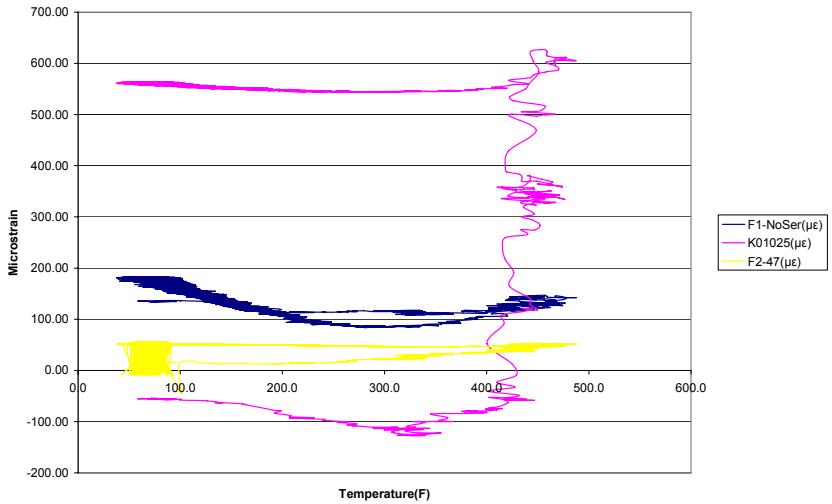
Test Item 4 (Round CC) Laboratory Bending and Heat Gun Tests

- **Round CC coupon**
- **Strain gage and commercial EFPI strain sensor mounted with M-Bond 610 adhesive**
- **3-EFPI sensors and 1-TC mounted with Sauereisen 13**



Lab Bending & Heat Gun Tests
(Sensors: L-R)
TC, F3-52, SG, F2-47, COTS-K01025, F1-No ID

Apparent Strain Results-Test Item 4 (CC)



Test Item 4 Apparent Strain versus Temperature during Heat Gun Test

- Apparent strain to 450ºF using heat gun
- F3-optical signal conditioner displayed "CHECK SENSOR," - connector failed
- Bending tests does not demonstrate good correlation since the round specimen did not produce equal strains
- Commercial sensor (k01025) did not return to zero after heat gun removal
  - May indicate improper cure time
  - Found sensor unbonded at one end
- F2 and F3 show similar apparent strain
  - Apparent strains < 120 με up to 440ºF (226.7 ºC)
  - F2 much lower response than F1.
  - Zero shifts for F2 and F3 after bending test

Results of High Temperature EFPI Sensors Test on Specimens

- EFPI sensors operate to 1600ºF(871.1 ºC)
- GL needs correction for ideal correlation between EFPIs and SGs
- Need to understand physics of using Sauereisen 13 with the CC
- Need evaluations of attaching EFPI sensors using the flame spray
- Large number of control factors needed
- Testing is slow and tedious
- Goal: Measure strain on structures exceeding 2000 ºF (1093.3 º C)
- EFPI strain sensors can survive extreme thermal environments
- Preliminary experiments using ceramic adhesives are not conclusive
- Effort requires more practice and experimental iteration
- Developed oven to evaluate high temperature strain measurement techniques in timely and realistic manner
  - i.e. heat specimen to 2000 ºF (1093.3 º C) in less than a half hour
- Future High Temp Tests May Use Flame Spray Attachment Technique

New Thermal Spray Chamber and Quartz Oven

- Flame Spray Capability activated December 2005
- Developed Quartz Lamp Oven for tests over 3000°
- Finish Item 4 Testing in New Oven Soon
- Plasma Spray Capability planned for September 2006
- Continue to Study Attachment Techniques

Survival Results of EFPI Sensors on a C-C Test Item during Aug04

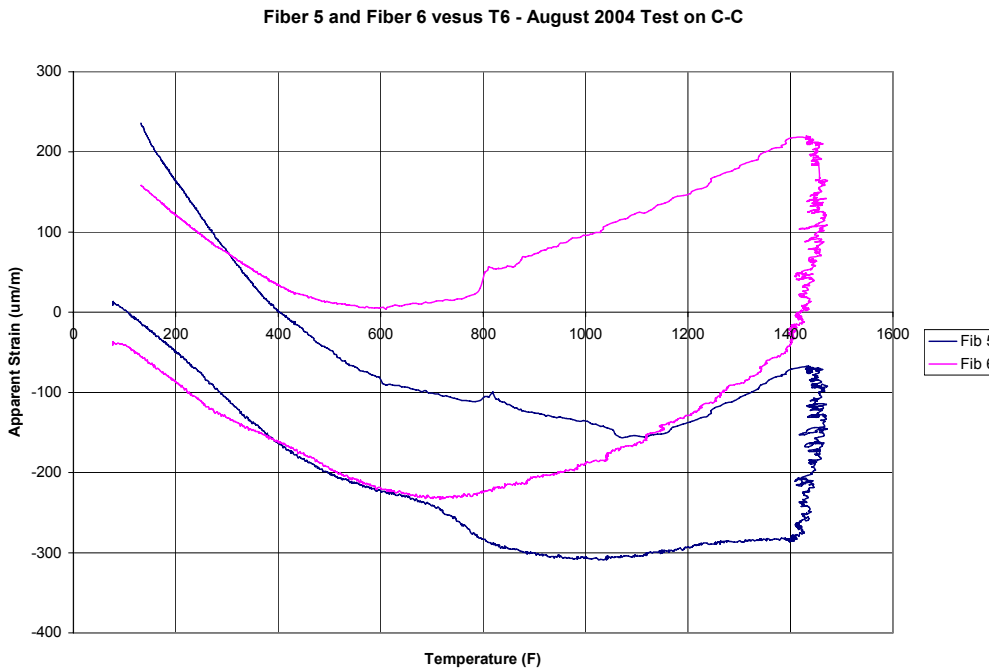
- EFPI Sensors and TCs installed on a high temperature structure.
- Test Item heated with no mechanical loads
- Use the high temperature EFPI sensors
  - Sensors flame sprayed on by LaRC
  - Fibers are gold plated
- Nine of Ten EFPI Sensors on C-C Survived
- EFPI Sensor on Inconel Failed

Highest Temperatures and Apparent Strain on C-C Test Item

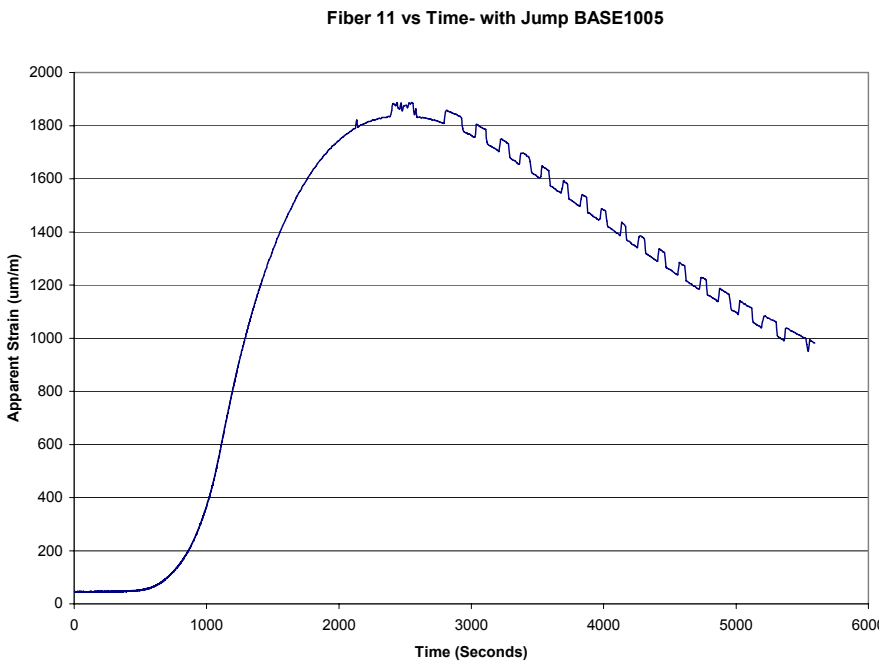
Max Temperature (°F) from Time History Plots

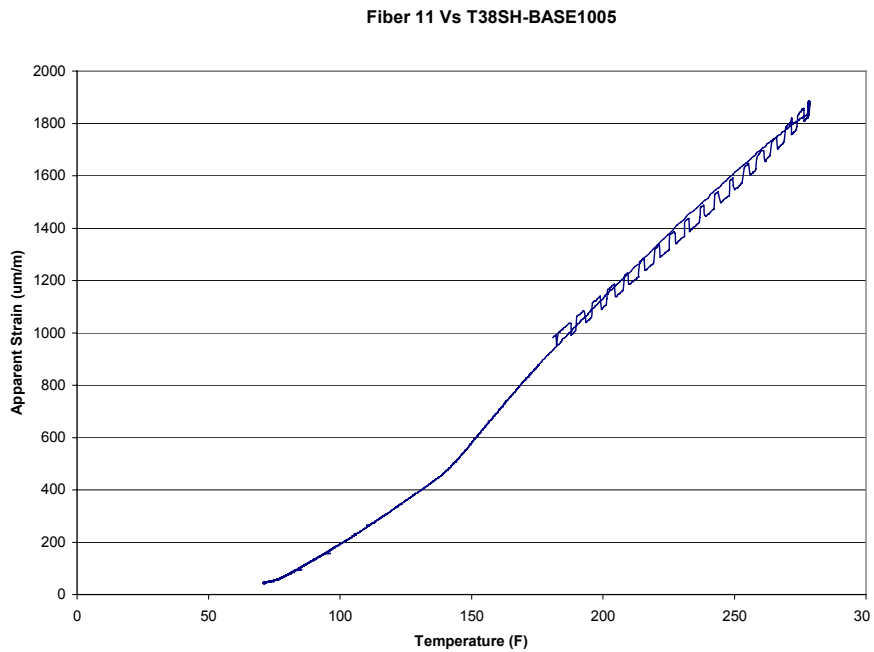
	1000	1001	1002	1003	1004	1005	1006	2000
T8 - F1 & 2	170	490	880	1150	1200	1275	1050	1275
T35 - F3 & 4	90	170	370	590	510	630	950	780
T6 - F5 & 6	162	255	450	605	620	750	1420	800
T12 - F7 & 8	115	290	605	870	900	1050	1100	1190
T17 - F9 & 10	95	120	230	390	390	420	970	610
T29 - F11	70	120	180	250	240	280	880	850
T38SH - F11	78	110	170	230	220	280	810	380

Fiber F9 went bad during run 1001
Fiber 11 went bad during run 1006 at T = 469 °F
Maximum Temperature on Specimun was 2290 °F

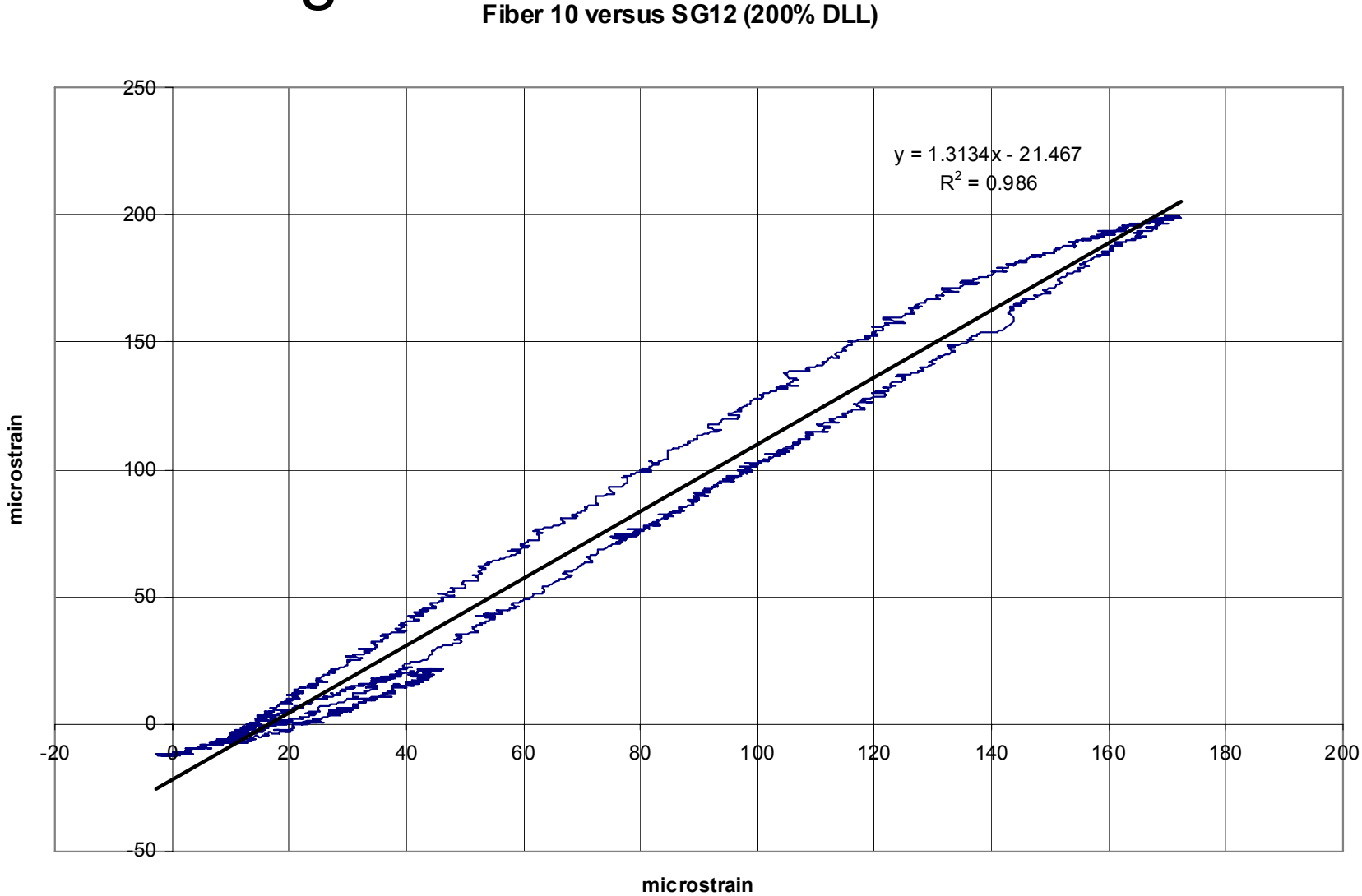


Highest Temperatures and Apparent Strain on Inconel



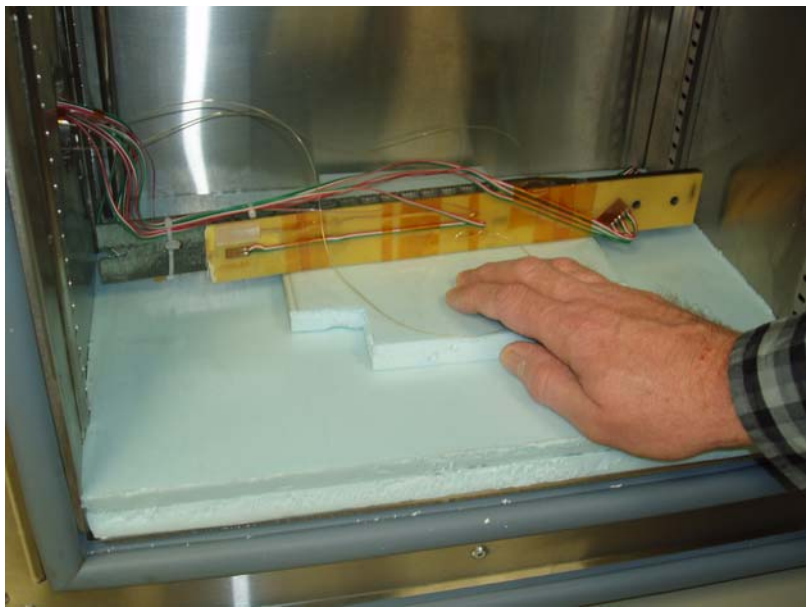


Comparison of EFPI sensors and Strain Gages on a C-C Test Item at RT

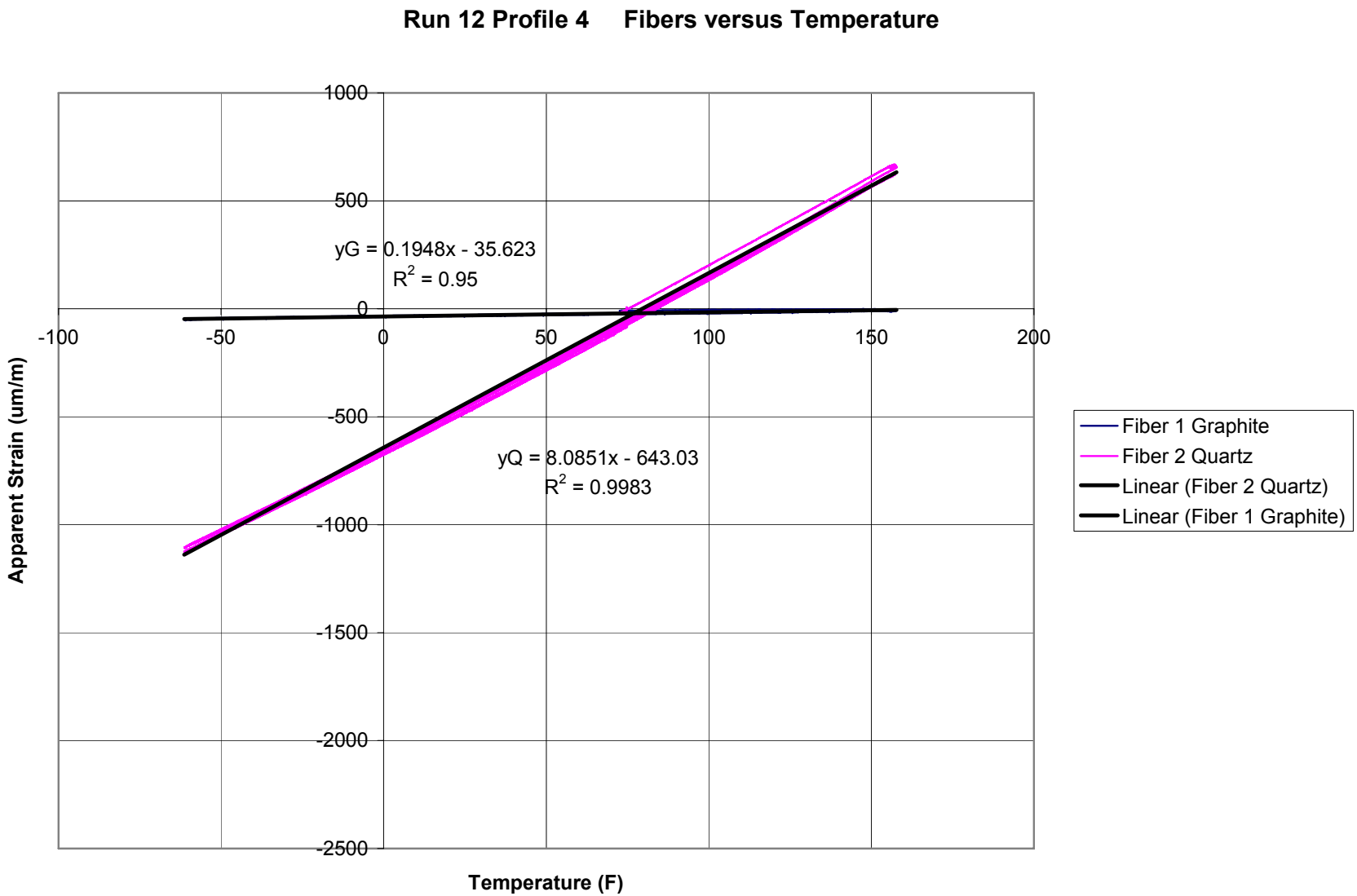


Initial EFPI COTS Sensor Evaluations in Small Chamber

- COTS EFPI Sensors and Strain Gages
- 18 Runs Heat&Cool (Usually -60 to +160° F)
- Free End of Astro Quartz and Graphite Side
- SG , EFPI Fiber and TC adjacent to each other)

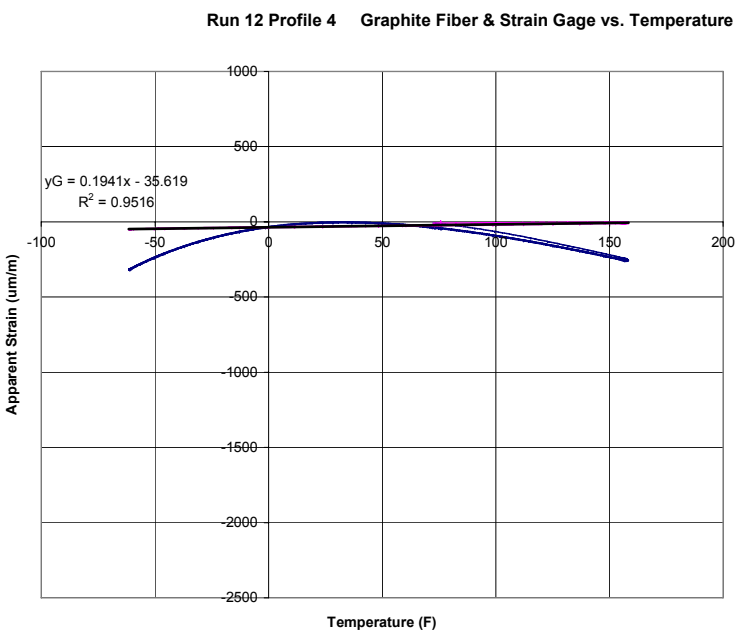


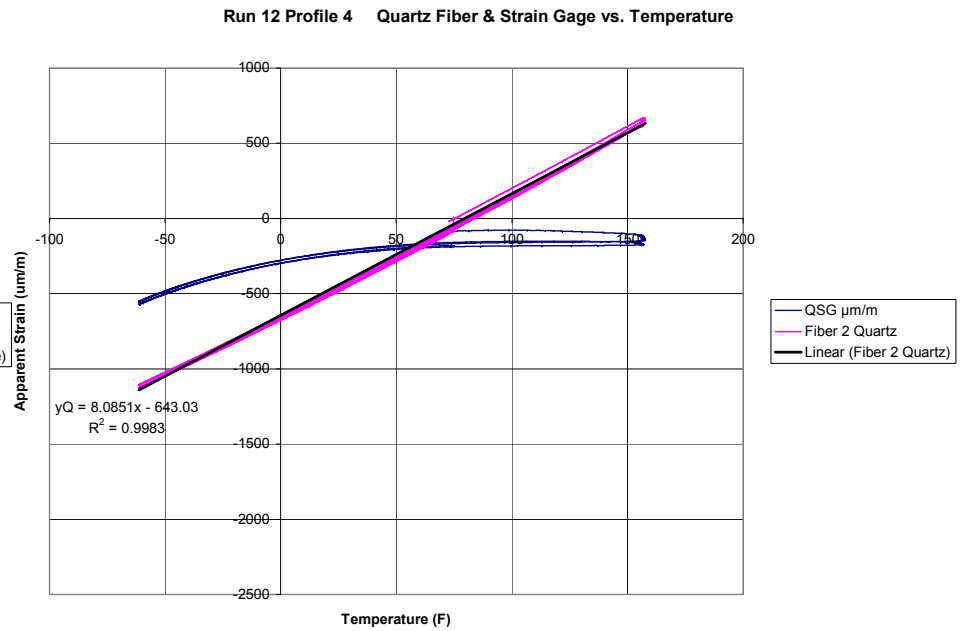
Typical Apparent Strain vs Temperature for COTS EFPI Fibers



Apparent Strain-COTS EFPI Sensors Compared to Strain Gages

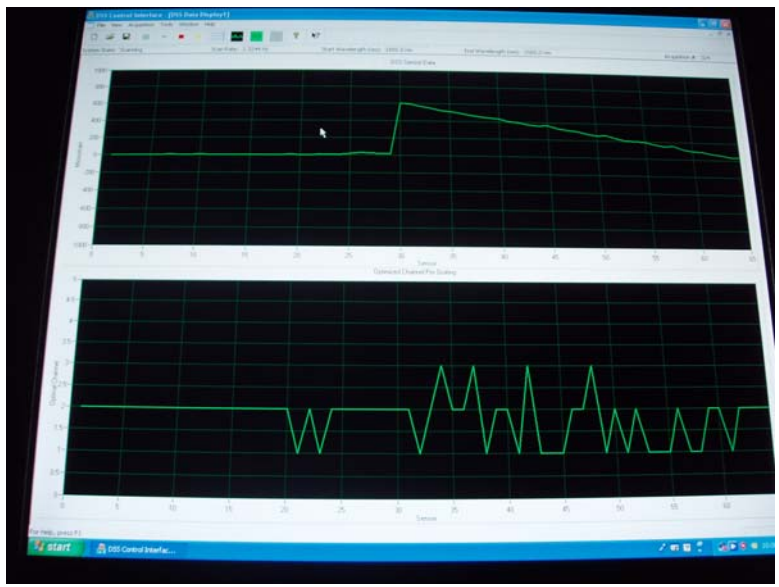
- Fiber Linear but not Compensated
  - Graphite - Lower CTE - 9.3 x 10^{-7} m/m/°F
  - Quartz Composite - Higher CTE - 3.1 x 10^{-6} m/m/°F





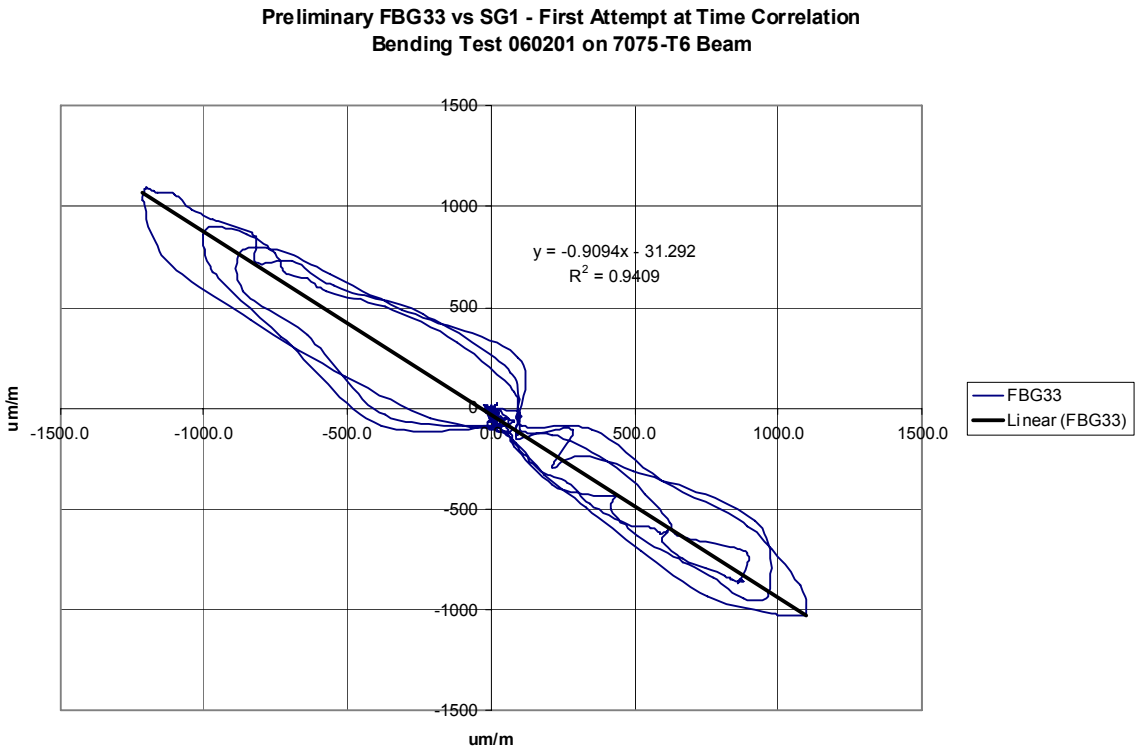
Initiatial Evaluation of Fiber Bragg Grating (FBG) Fibers

- Evaluating a DSS Systems by LUNA Innovations, Inc.
- Allows Viewing of of Strain Profile
- FBG Fiber Gratings Detect Strain every Centimeter.
  - e.g. 50 Sensors per .5m on 3 Test Beams
  - 7075-T6, 2024-T3, Ti-64

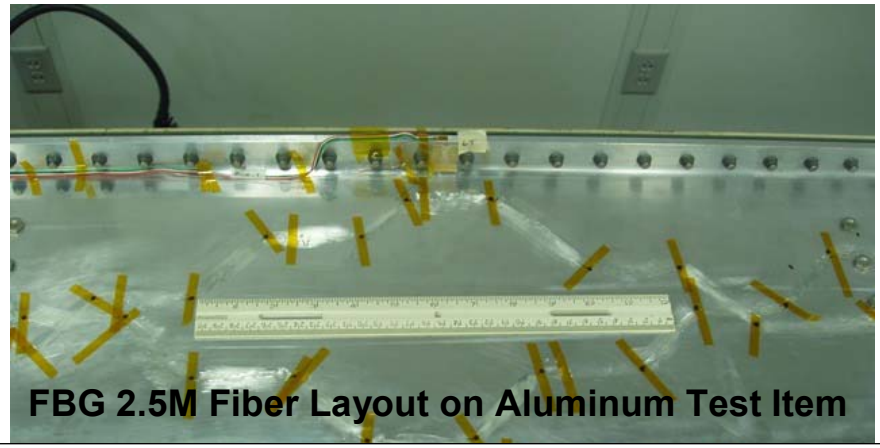


Comparing FBG to Strain Gages

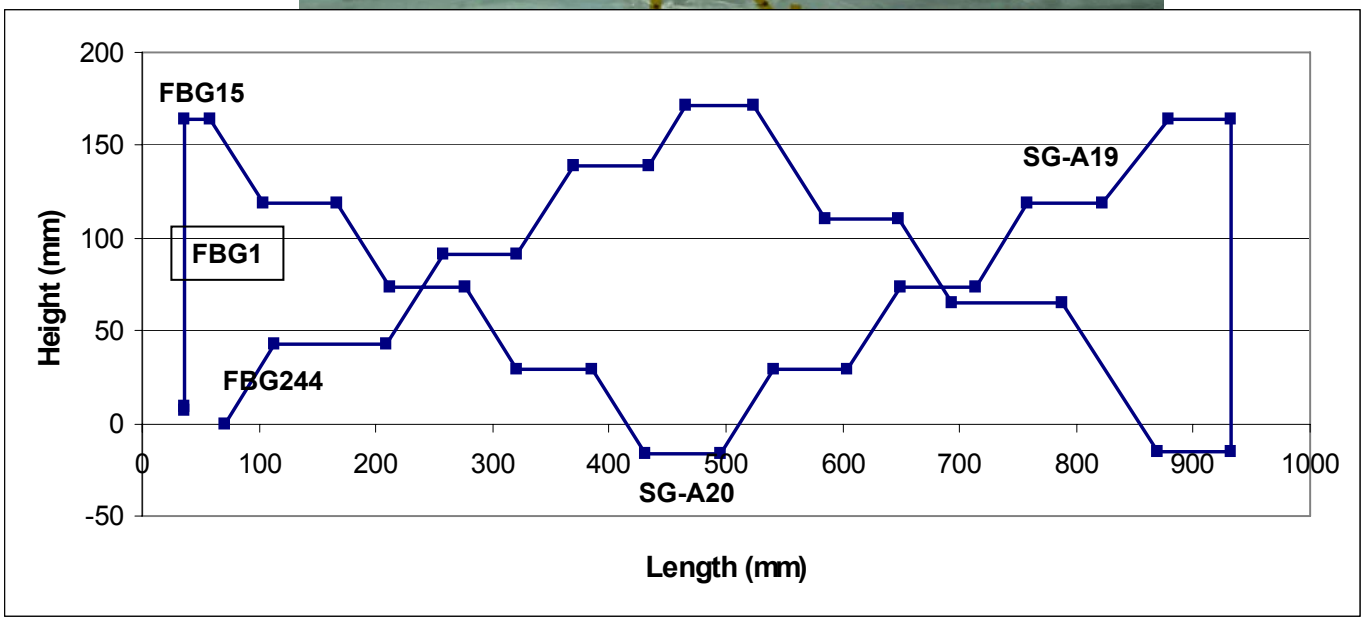
- Each FBG Detects Strain every 1 Centimeter
- Need to Correlate SG position with Fiber Sensor
- Hard to Correlate Fiber & Strain Gage Time.



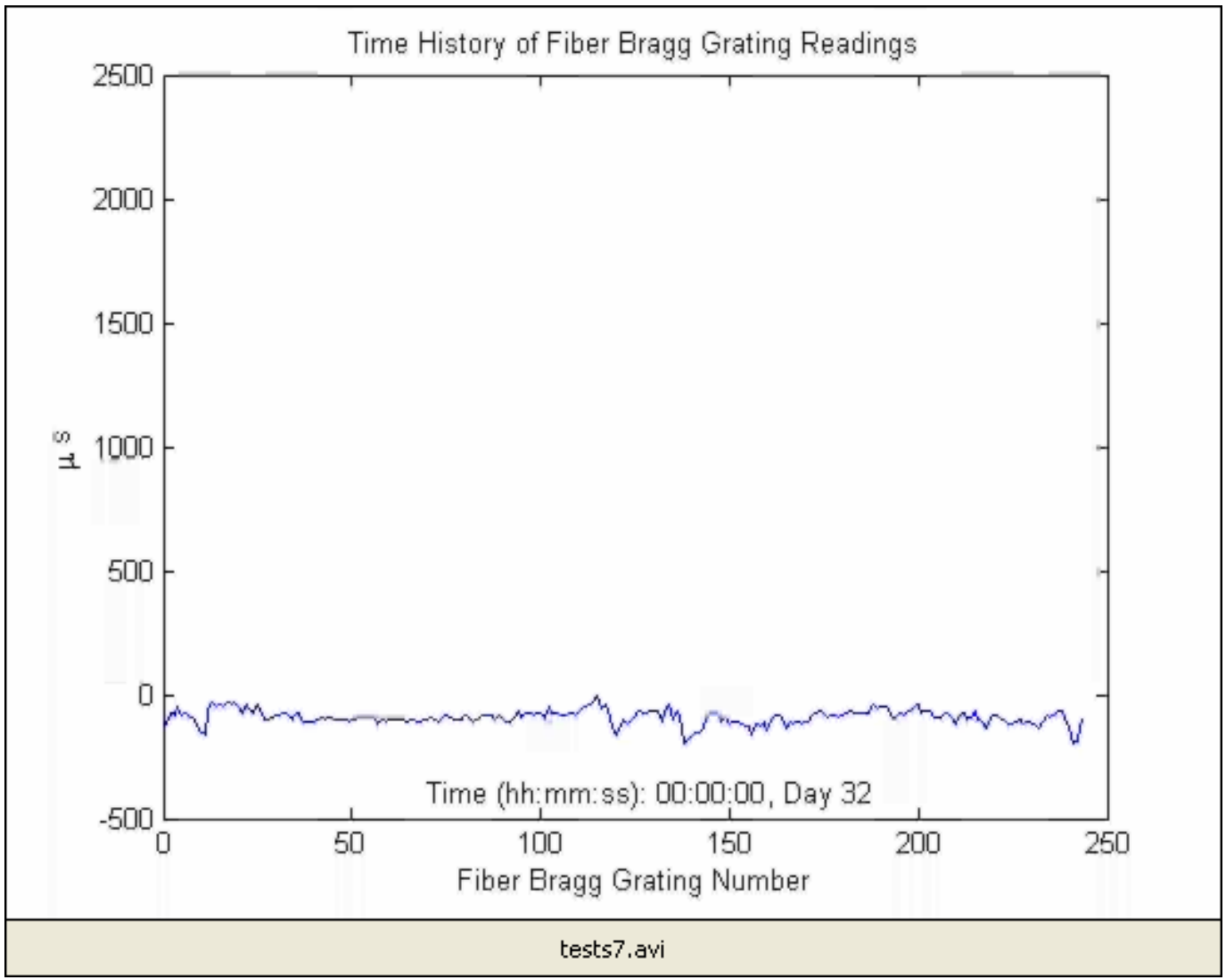
2.5 Meter FBG Fiber on Structural Aluminum Test Item (1.25×10^{-5} m/m/°F)



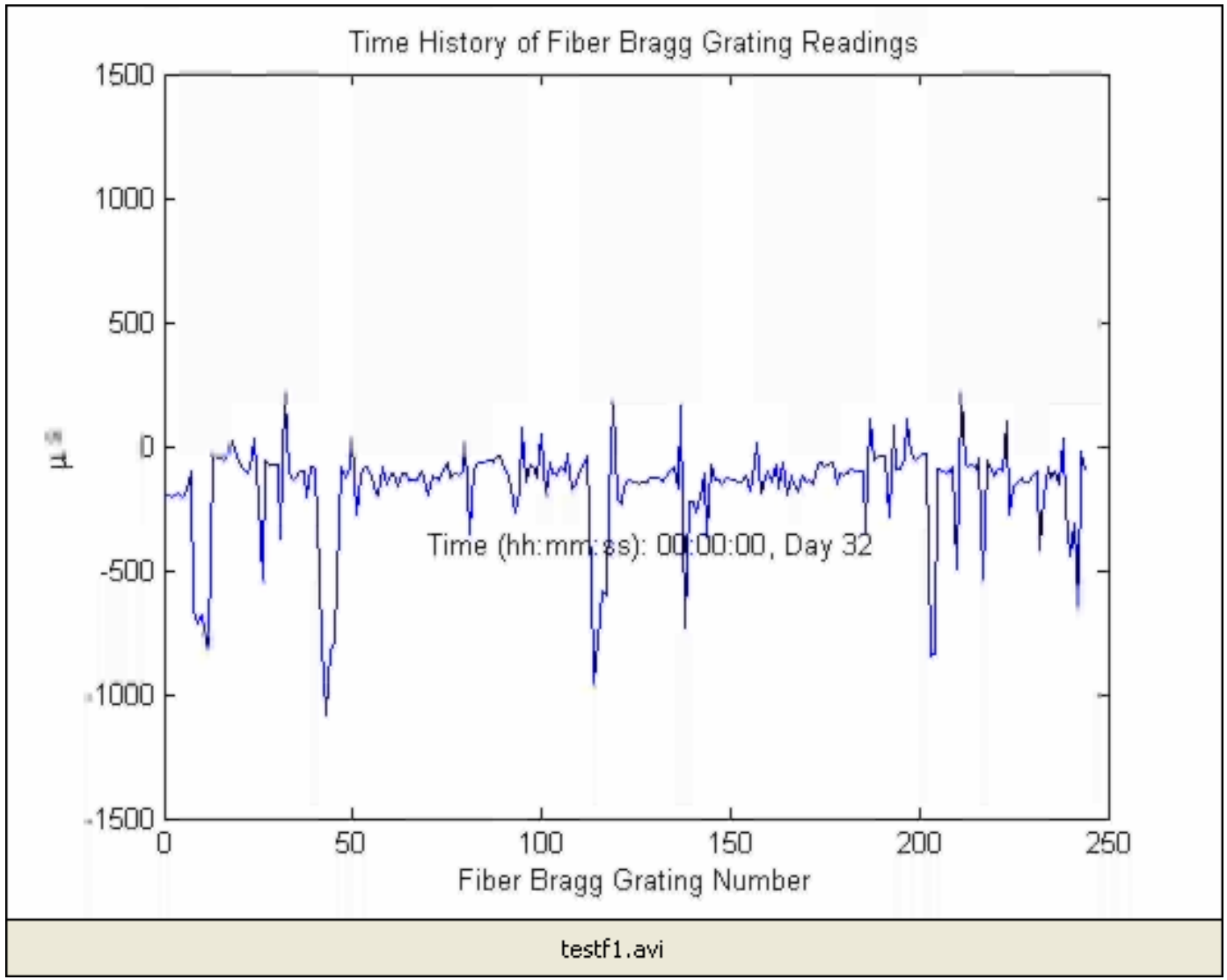
FBG 2.5M Fiber Layout on Aluminum Test Item



244 FBG Sensors
Sample Thermal Test From RT to 160°F



244 FBG Sensors
Sample Fatigue Cycling at Room Temperature



Conclusions

- Tests using EFPI High Temperature
  - Results on survivorability looks promising.
  - Needed more study of material, adhesive and fiber interactions and properties at high temperature.
  - Attachment techniques are very experimental.
- COTS EFPI Sensors operate satisfactory
  - May need compensation for high CTE Materials
- Initial FBG seem to work at Room Temperature
  - Need to complete more detailed evaluations
- So far all fiber sensors evaluated operate at very low frequency response (i.e. less than a few hertz).
- Displays on aluminum test item are very interesting.

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