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 2000°F (1093.3 °C)
  – COTS sensors specified to 350 °C.
• 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

- 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 (1648.9°C)

• Above 1800 °F (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 °F (1093.3 ° 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 2000°F (1093.3°C) 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 1832°F (1000°C) in extreme thermal environments and high vibratory strain loads.

- High apparent strain curves obtained using valid strain measurements at temperatures up to 1250 °F (667.7 °C).

- Convert $\Delta R/R$ to strain by using the strain gage factor (GF) for conventional resistance gages.

Apparent Strain-Convention 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 “overlay” creates Microsoft® Excel readable file.
- Import data to Excel-generate time history and apparent strain plots

Notes:
- VI Acquirer DT2 for Data Acquisition
- VI The Overlayer for Post Processing
- 0 = Ref Junction Temperature (0 in–9805-de)
- 1 = TC Temperature (1 in – 9805-de)
- 2 = 0 Volts DC in (0 in – 9806-se)
- 3 = SG Channel (1 in – 9806-se)
- 4 = Fiber Channel (2 in – 9806-se)
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 1600°F (871.1°C)
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

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Specimen Material</th>
<th>Specimen Shape/Size</th>
<th>Attachment Techniques</th>
<th>Fiber &amp; SG Location</th>
<th>Specimen Side</th>
<th>Test Temperature</th>
<th>Max Test Strain</th>
<th>Atmosphere</th>
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</thead>
<tbody>
<tr>
<td>Room Temperature</td>
<td>C-C Samples With Flame Spray</td>
<td>Round Diameter 2.75 “inches”</td>
<td>LaRC Flame Spray</td>
<td>Center For In-Plane</td>
<td>Top</td>
<td>Room Temperature</td>
<td>0με</td>
<td>Normal Air</td>
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<td>Load</td>
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<tr>
<td>Apparent Strain</td>
<td>2024-T3 AL</td>
<td>Rectangular 1.5x8x.125</td>
<td>Ceramic Cements (e.g. Sauereisen 13)</td>
<td>Near End For Bending</td>
<td>Bottom</td>
<td>Low 550 F</td>
<td>500με</td>
<td>Nitrogen Purged</td>
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<tr>
<td>Combined</td>
<td>Inconel 718</td>
<td>Rectangular 1x12x.125</td>
<td>M Bond 610</td>
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<td>Medium 1100 F</td>
<td>2000με</td>
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## Preliminary Design of Experiments (DOE)
### Partial Test Matrix

<table>
<thead>
<tr>
<th>No.</th>
<th>Test Type</th>
<th>Material</th>
<th>Size</th>
<th>Attachments</th>
<th>Location</th>
<th>Gages</th>
<th>Atm</th>
<th>Oven</th>
<th>Temp.</th>
<th>Strain</th>
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<tbody>
<tr>
<td>1</td>
<td>Bending</td>
<td>AL2024</td>
<td>1.5x8.25</td>
<td>Sauereisen 13 or Ceramic Cements</td>
<td>Center</td>
<td>Fiber Optic &amp; Foil &amp; TC</td>
<td>None</td>
<td>None</td>
<td>Room Low</td>
<td>1000 µε</td>
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<tr>
<td>2</td>
<td>Apparent Strain</td>
<td>X-37 #1</td>
<td>1-1/4x4</td>
<td>Flame Spray &amp; Sauereisen 13</td>
<td>Center</td>
<td>Fiber Optic &amp; Foil &amp; TC</td>
<td>N2</td>
<td>L &amp; L</td>
<td>500F 2000F</td>
<td>None</td>
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<tr>
<td>4</td>
<td>Apparent Strain</td>
<td>Round</td>
<td>2.75</td>
<td>Flame Spray – Then Cements</td>
<td>Center</td>
<td>Fiber Optic &amp; Foil &amp; TC</td>
<td>N2</td>
<td>Lamp Bank (L&amp;L)</td>
<td>2000F</td>
<td>None</td>
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<tr>
<td>11</td>
<td>Apparent Strain</td>
<td>Round C-C</td>
<td>2.75</td>
<td>Flame Spray</td>
<td>Center</td>
<td>Fiber Optic &amp; Foil &amp; TC</td>
<td>N2</td>
<td>Lamp Bank (L&amp;L)</td>
<td>2000F</td>
<td>None</td>
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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°F (260°C) using a heat gun
    - Placed specimen in oven for apparent strain up to 2000°F (1093.3°C)

- 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 °C) 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

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 2000°F (1093.3°C)
- 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 500°F (260°C)

Test Item 2 (CC2) After 1600°F Heat Test (F-42, TC, SG-Center & F-37-Hole)
Test Results on Test Item 2 (CC)

- 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

Lab Bending F-42 (Red) and Strain Gage (Blue) – F-37 (Yellow)-no Correction
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 \( R^2 = 0.99 \) relates the fiber output to the strain gage output
- BFSL should have slope=1
- Correct fiber output by dividing GL by slope (1.4993)

Lab Bending - F42 versus Strain Gage
Test Results on Test Item 2 (CC)

• 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

Lab Bending  F-42 (Corrected) and Strain Gage
Test Results on Test Item 2 (CC)

- Heat Item to about 500°F (260°C) 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 500°F
Test Results on Test Item 2 (CC)

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

- Apparent strain to 450°F 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 440°F (226.7 °C)
  - F2 much lower response than F1.
  - Zero shifts for F2 and F3 after bending test

Test Item 4 Apparent Strain versus Temperature during Heat Gun Test
Results of High Temperature 
EFPI Sensors Test on Specimens

- EFPI sensors operate to 1600°F (871.1 °C) 
- 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 °F (1093.3 °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 °F (1093.3 °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°F
- 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

<table>
<thead>
<tr>
<th></th>
<th>1000</th>
<th>1001</th>
<th>1002</th>
<th>1003</th>
<th>1004</th>
<th>1005</th>
<th>1006</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>T8 - F1 &amp; 2</td>
<td>170</td>
<td>490</td>
<td>880</td>
<td>1150</td>
<td>1200</td>
<td>1275</td>
<td>1050</td>
<td>1275</td>
</tr>
<tr>
<td>T35 - F3 &amp; 4</td>
<td>90</td>
<td>170</td>
<td>370</td>
<td>590</td>
<td>510</td>
<td>630</td>
<td>950</td>
<td>780</td>
</tr>
<tr>
<td>T6 - F5 &amp; 6</td>
<td>162</td>
<td>255</td>
<td>650</td>
<td>620</td>
<td>750</td>
<td>1420</td>
<td>800</td>
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<td>T12 - F7 &amp; 8</td>
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<td>290</td>
<td>605</td>
<td>870</td>
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<td>1050</td>
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<td>T17 - F9 &amp; 10</td>
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<td>T29 - F11</td>
<td>70</td>
<td>120</td>
<td>180</td>
<td>250</td>
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<td>280</td>
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<tr>
<td>T38SH - F11</td>
<td>78</td>
<td>110</td>
<td>170</td>
<td>230</td>
<td>220</td>
<td>280</td>
<td>810</td>
<td>380</td>
</tr>
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</table>

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

Fiber 10 versus SG12 (200% DLL)

\[ y = 1.3134x - 21.467 \]

\[ R^2 = 0.986 \]
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

Run 12 Profile 4 Fibers versus Temperature

\[ y_Q = 8.0851x - 643.03 \]
\[ R^2 = 0.9983 \]

\[ y_G = 0.1948x - 35.623 \]
\[ R^2 = 0.95 \]
Apparent Strain-COTS EFPI Sensors Compared to Strain Gages

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

\[
y_G = 0.1941x - 35.619 \quad R^2 = 0.9516
\]

\[
y_Q = 8.0851x - 643.03 \quad R^2 = 0.9983
\]
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 FBGDetects 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 (1.25x10^{-5} m/m/°F)
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 survivability 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.
References

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• Poland, Steve (2002), “Luna Fiber Optic Strain Gages and their Applications” Western Regional Strain Gage Committee-2002 Winter Meetings, Society Experimental Mechanics, Bethel, CT.
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