High-Temperature Strain Sensing for Aerospace Applications

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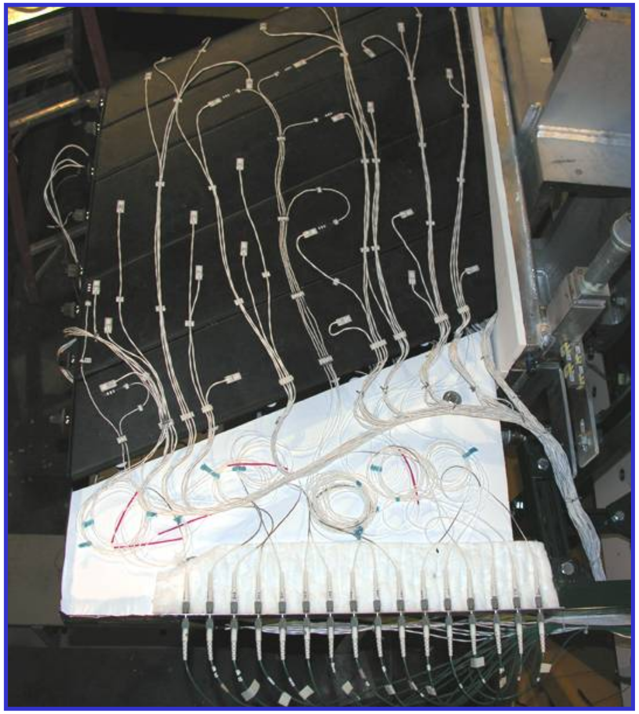
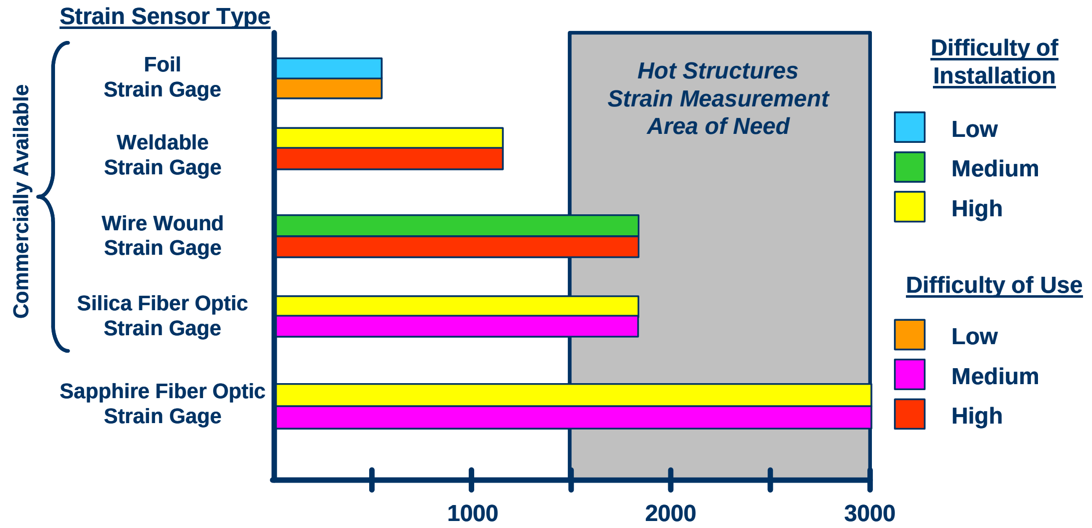
Outline

- Background
- Objective
- Sensors
- Attachment Techniques
- Laboratory Evaluation / Characterization
- Large-Scale Structures



Background

Sensor Development Motivation



Lack of Capability

- TPS and hot structures are utilizing advanced materials that operate at temperatures that exceed our ability to measure structural performance
- *Robust strain sensors that operate accurately and reliably beyond 1800°F are needed but do not exist*

Implication

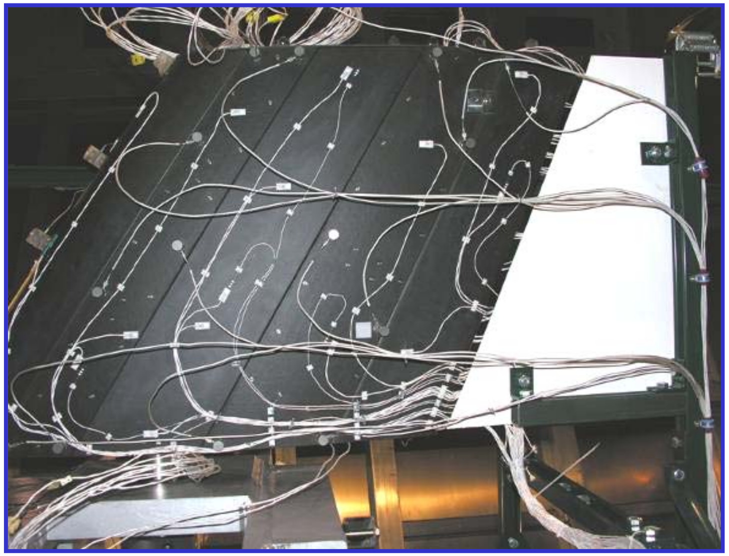
- Hinders ability to validate analysis and modeling techniques
- *Hinders ability to optimization structural designs*

Objective

Measurements Lab

Provide strain data for validating finite element models and thermal-structural analyses

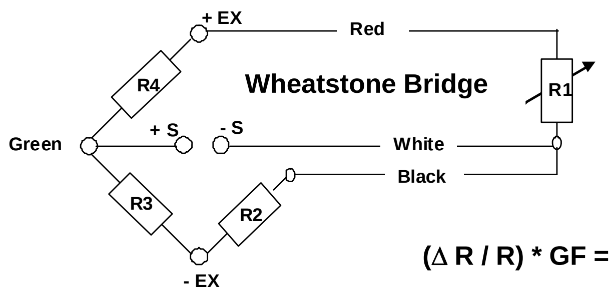
- Develop sensor attachment techniques for relevant structural materials at the small test specimen level
  - Apply methods to large scale hot-structures test articles
- Perform laboratory tests to characterize sensor and generate corrections to apply to indicated strains



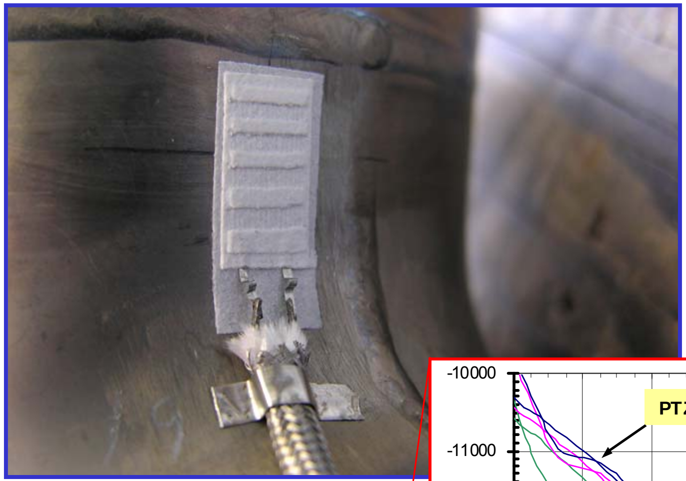
Sensors

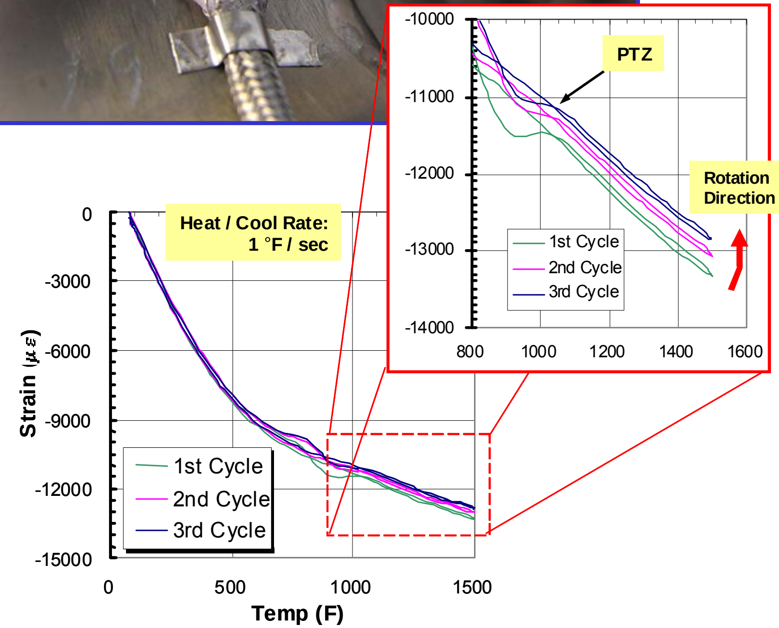
Dynamic Measurements (Max Op 1850°F)

High-Temp Quarter-Bridge Strain Gage



$(\Delta R / R) * GF = RT\xi$





Pro's

- Sturdy / rugged thermal sprayed installation and spot-welded leadwire stakedown
- Available high sample rate DAS, usually AC coupled to negate large ξapp

Con's

- Large magnitude ξapp primarily due to wire TCR, slope rotates cycle-to-cycle
- Sensitivity (GF): Function of temperature

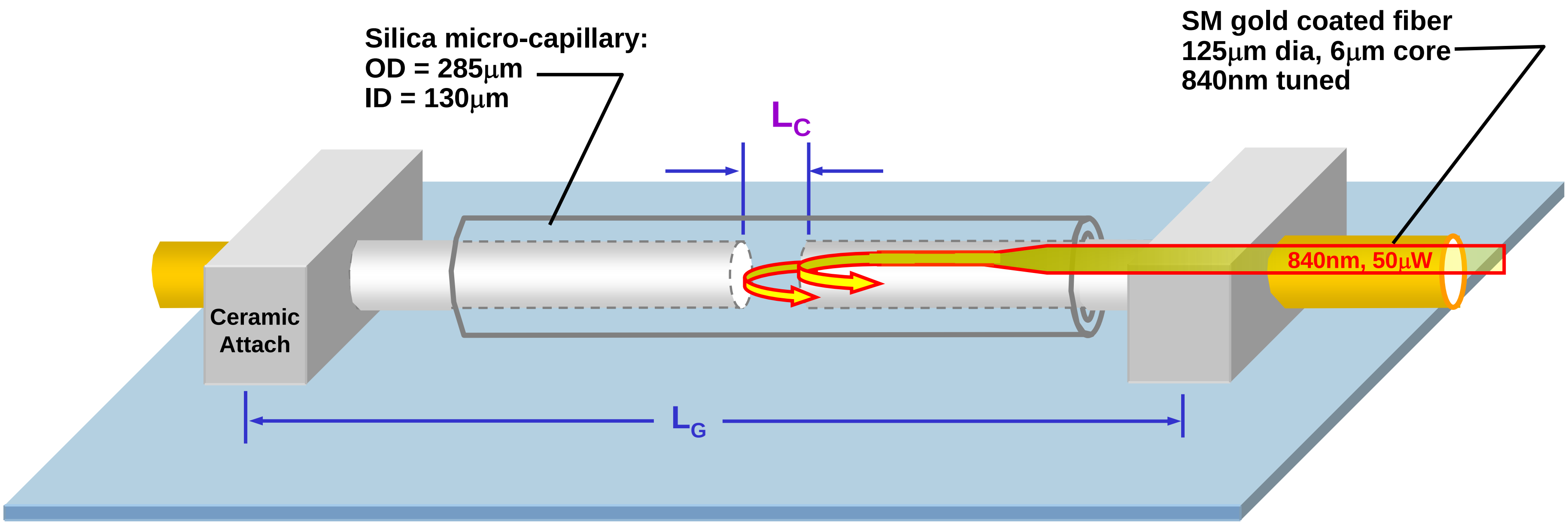
Apparent Strain $= [TCR_{gage} / GF_{set} + (\alpha_{sub} - \alpha_{gage})] * (\Delta T)$

Sensors

Static Measurement (Max Op 1850°F)

Extrinsic Fabry-Perot Interferometer (EFPI)

Commercially Available



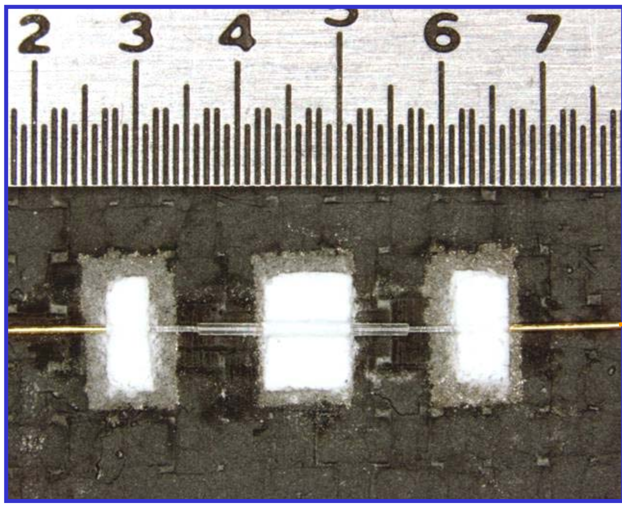
Strain = δL_C / $L_{G\ (initial)}$, where sensitivity = L_G

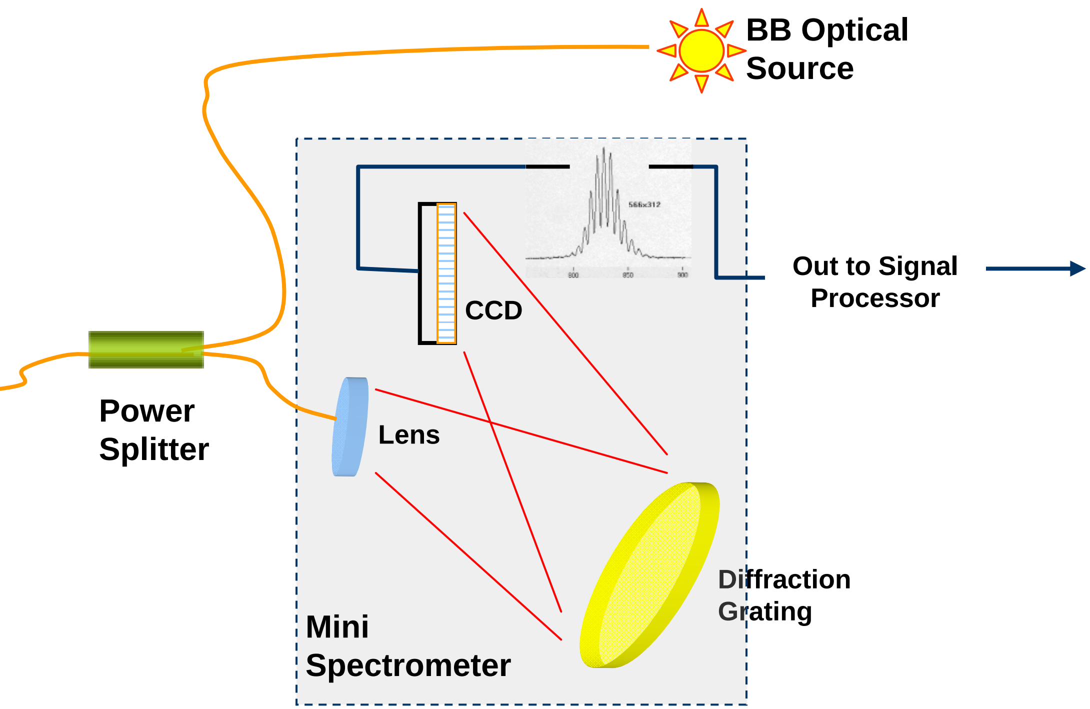
Apparent Strain (ξapp) = $(\alpha_{sub} - \alpha_{fiber}) * \Delta T$

Sensors

Static Measurement

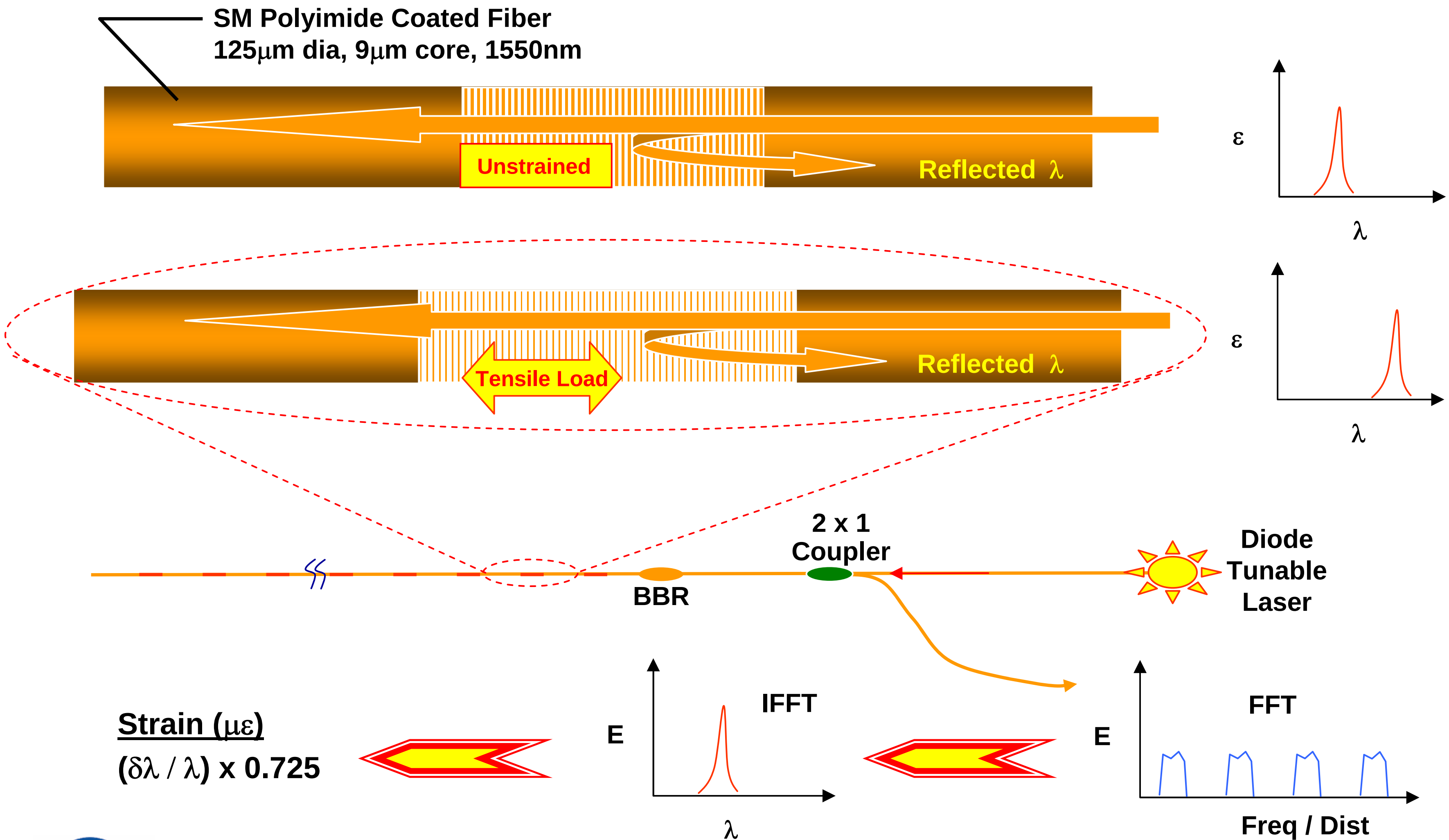
Single Mode EFPI Signal Conditioning





Sensors

Static Measurement (Max Op 600°F)



Attachment Techniques

Applications Above 600°F

Develop sensor attachment techniques for relevant structural materials

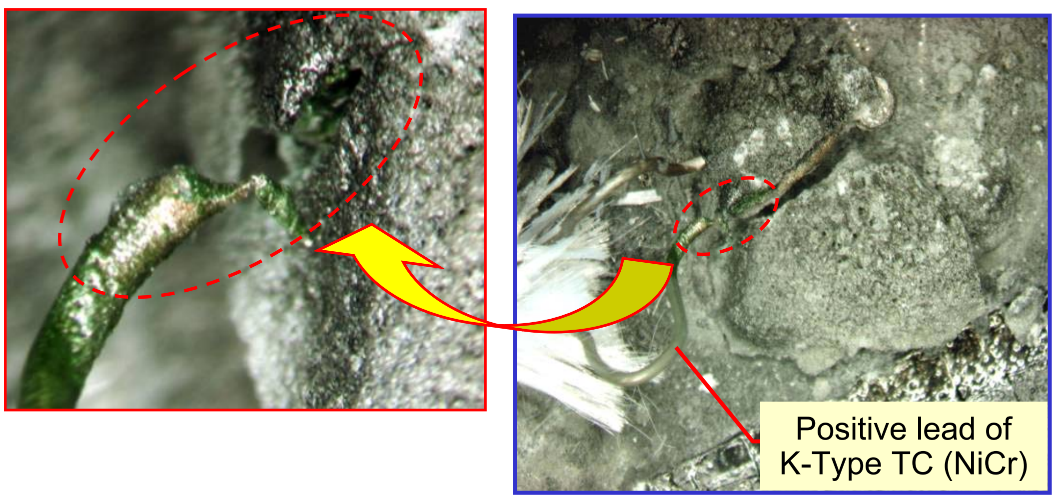
- Derive surface prep and optimal plasma spray parameters for applicable substrate
  - i.e., powder media / type, power level, traverse rate, feed rate, and spraying distance
- Or, optimize / select cement that best fits application
- Improve methods of handling and protecting fragile sensor during harsh installation processes

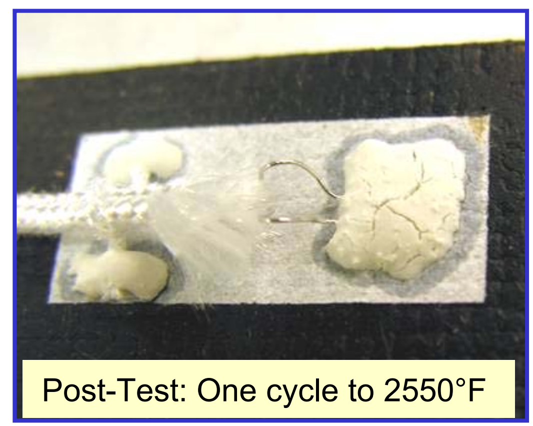
Attachment Techniques

Thermal Spray vs. Cement

Thermal sprayed attachments are preferred even though cements are simpler to apply

- Cements are often corrosive to TC or strain gage alloys
  - Si / Pt, NaF / Fe-Cr-Al alloys, alkali silicate / Cr
- Cements are more prone to bond failure due to shrinkage and cracking caused when binders dissipate
- *Tests indicate increased EFPI gage-to-gage scatter on first cycle*





Attachment Techniques

Thermal Spray Equipment

Thermal Spray Room

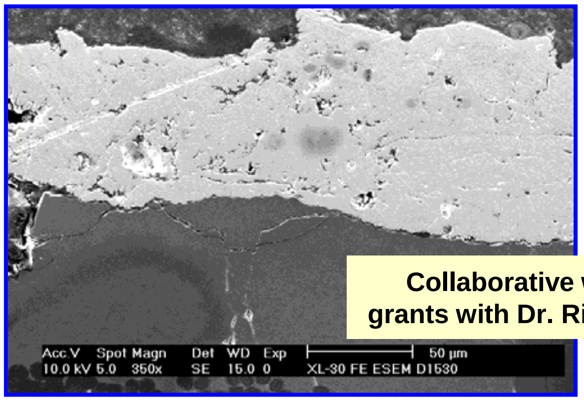
- 80KW Plasma System
- Rokide Flame-Spray System
- Powder Spray System
- Grit-Blast Cabinet
- Micro-Blast System
- Water Curtain Spray Booth

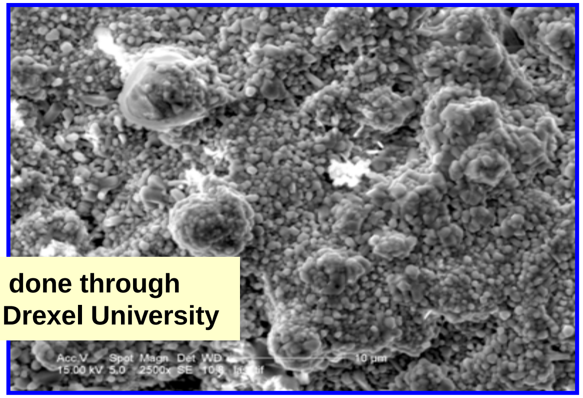
Attachment Techniques

Thermal Spray

Arc-plasma sprayed base coat

- Metallic Substrates: Used to transition high expansion substrate metal with low expansion sensor attachment material (Al_2O_3)
- CMC Substrates (inert testing): High melting-point ductile transitional metals (i.e. Ta, TiO_2, & Mo) more conducive for attachment to smooth surfaces like SiC





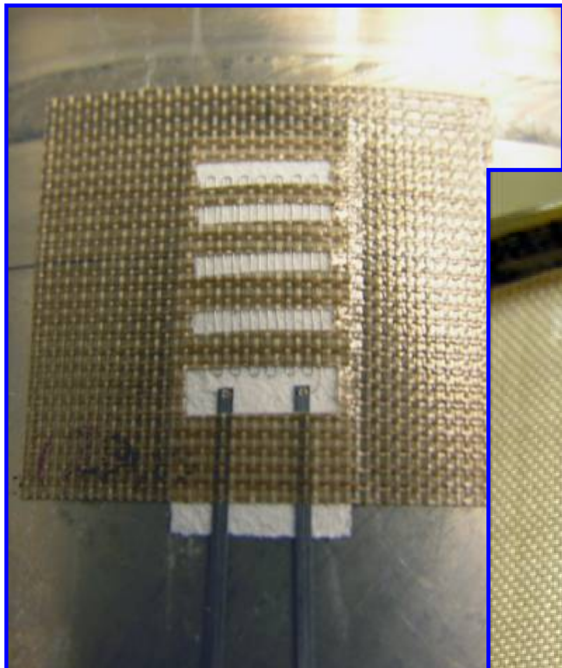
Collaborative work has been done through grants with Dr. Richard Knight, Drexel University

Rokide flame-sprayed sensor attachment

- Applies a less dense form of alumina than plasma spraying
- Electrically insulates (encapsulate) wire resistive strain gages

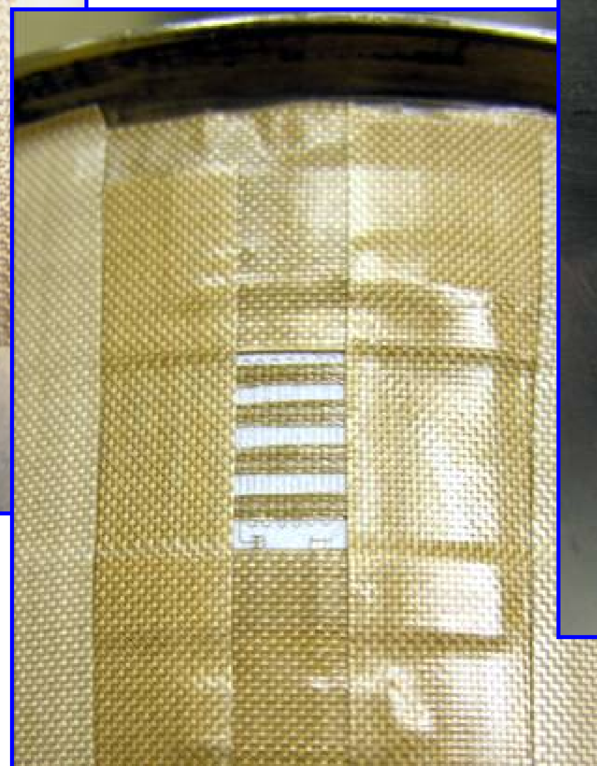
Attachment Techniques

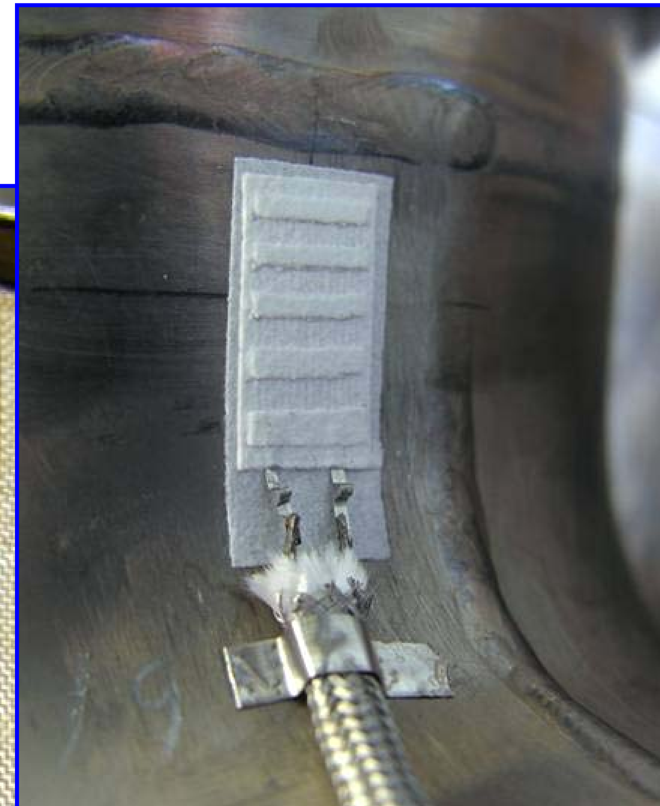
Wire Strain Gage Installation



Place SG on thermal sprayed basecoats via carrier tape

Apply flame-sprayed tack and cover coats

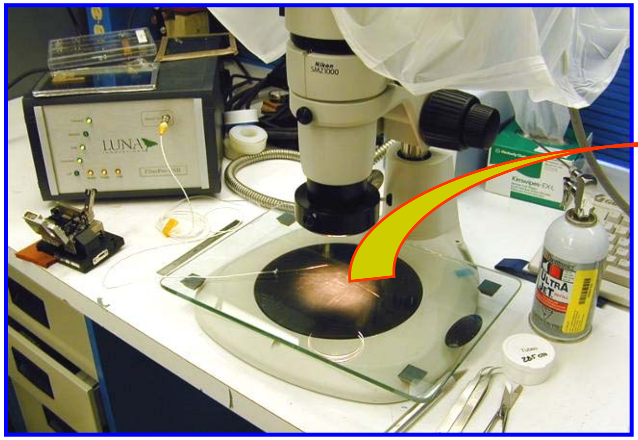




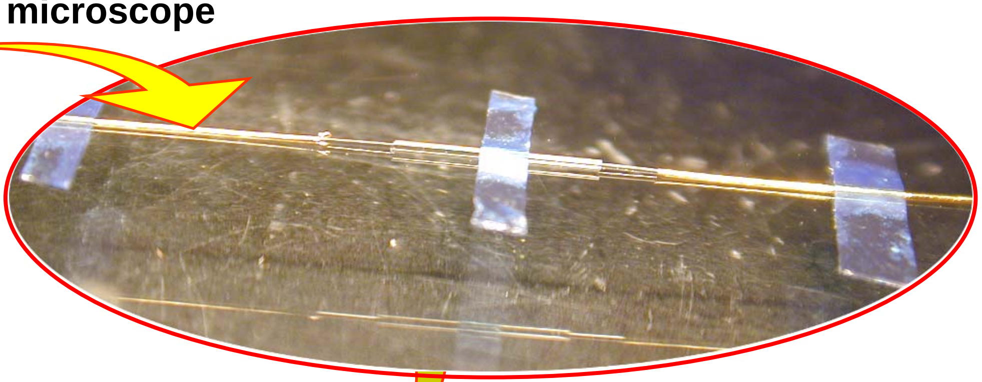
Spot weld three-conductor leadwire

Attachment Techniques

Fiber Optic EFPI Installation

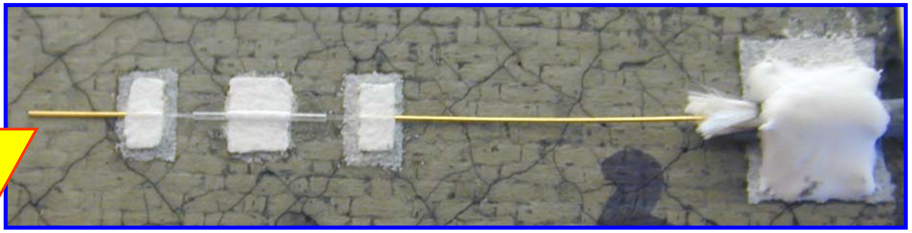


Fabricate sensor under microscope



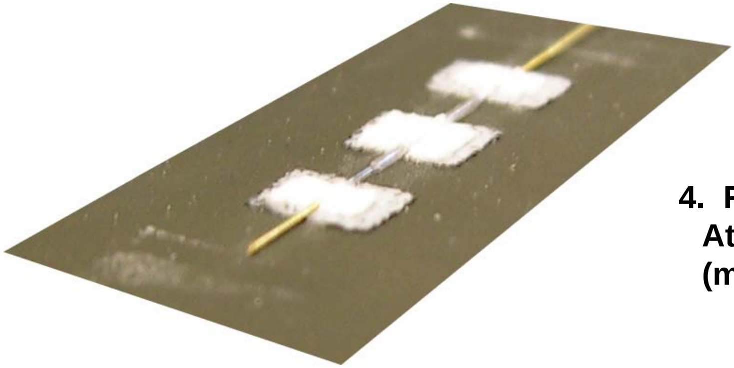
Transfer to thermal sprayed base coat using carrier tape

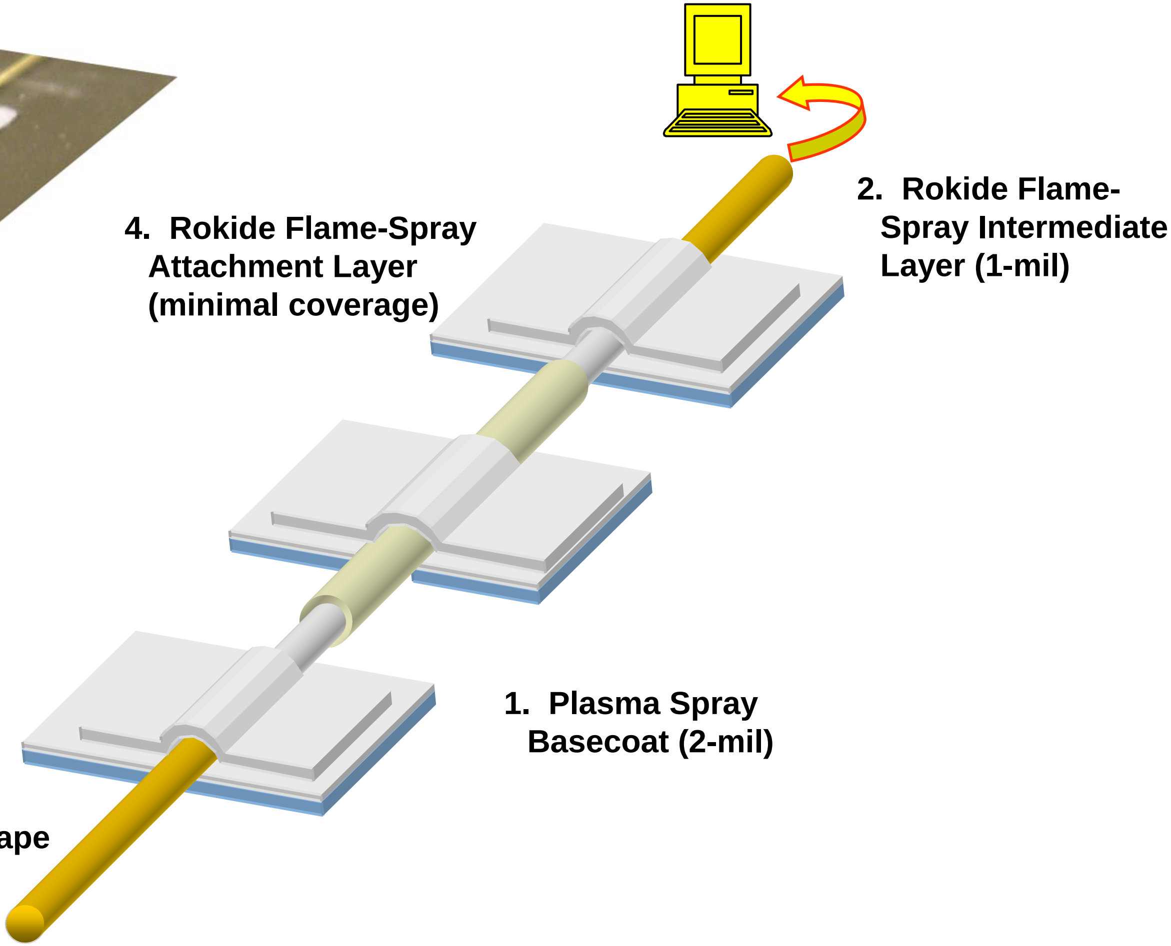
Flame-spray sensor attachment



Attachment Techniques

Fiber Optic EFPI Installation

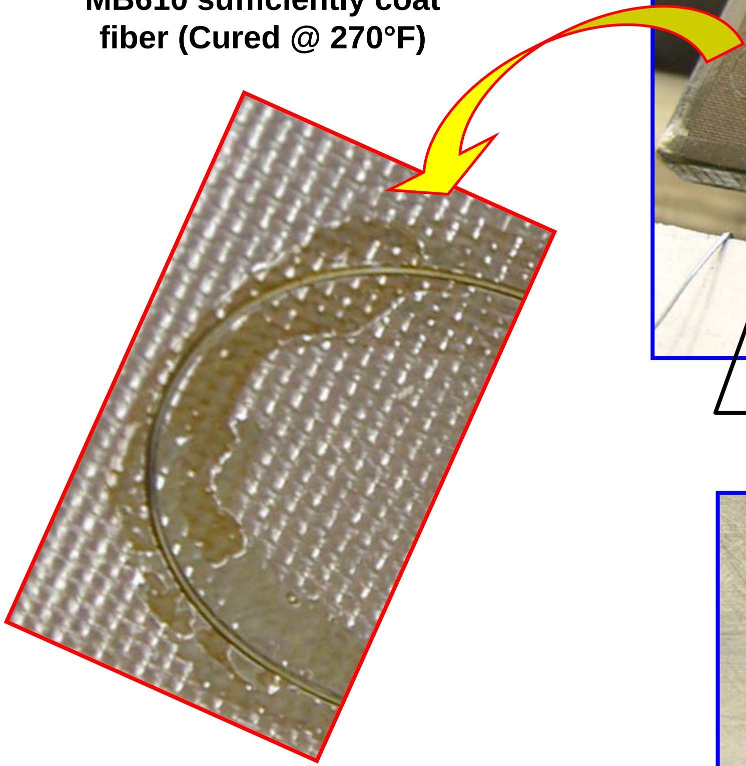


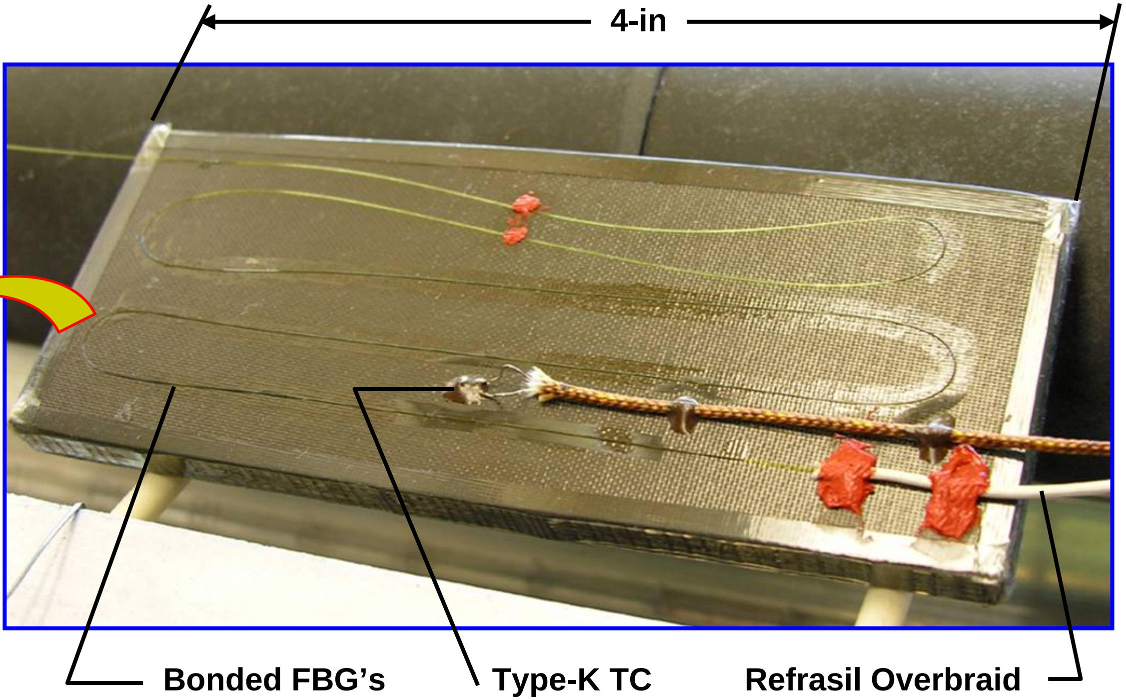


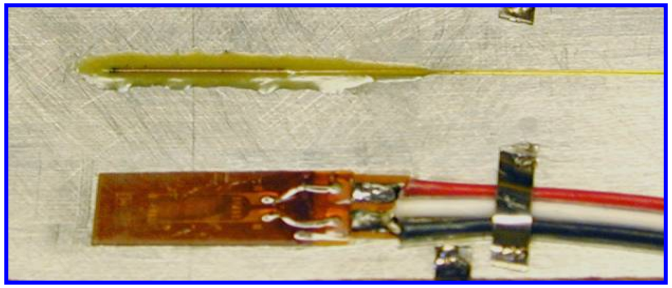
Attachment Techniques

Applications Below 600°F

Two applications of MB610 sufficiently coat fiber (Cured @ 270°F)







Polyimide coated EFPI bonded with mixture of GA-61 and MB610

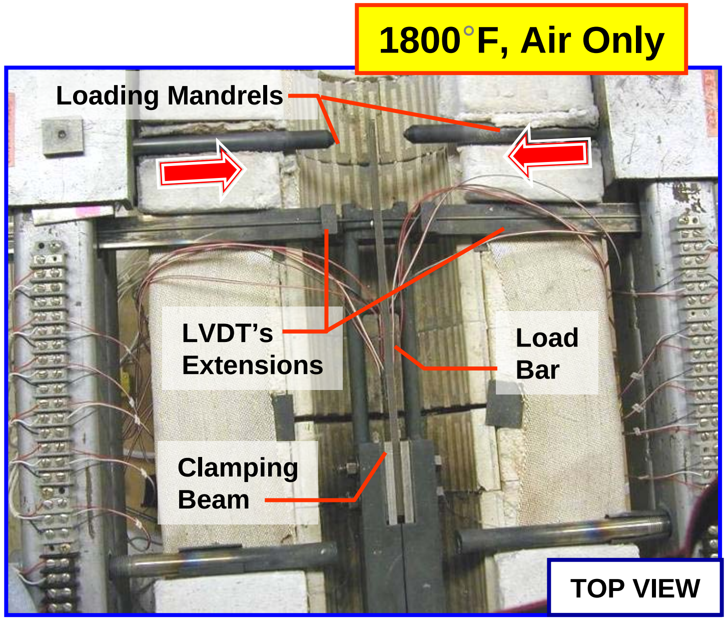
Evaluation / Characterization

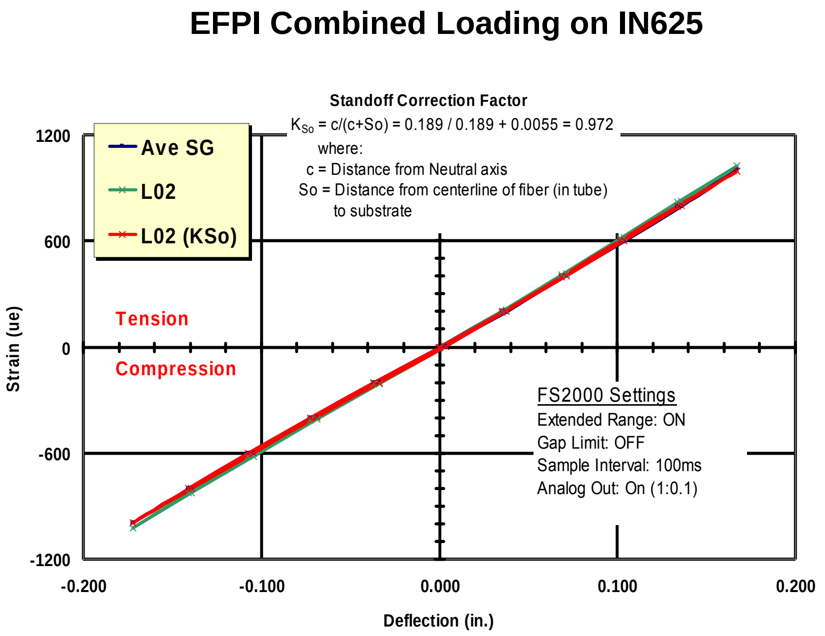
Validate and characterize strain measurement

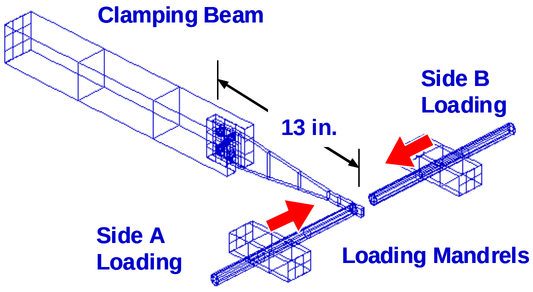
- *Base-line / characterize high-temperature strain sensors on monolithic Inconel specimens*
  - Known material spec's isolate substrate from inherent sensor traits prior to testing on more complex composites
- Evaluate / characterize sensitivity (GF) of strain sensors on ceramic composite substrates using laboratory combined thermal / mechanical load fixture
- Generate apparent strain curves for corrections of indicated strains on relevant ceramic composite hot-structures

Evaluation / Characterization

Combined Thermal / Mechanical Loading (Obsolete)





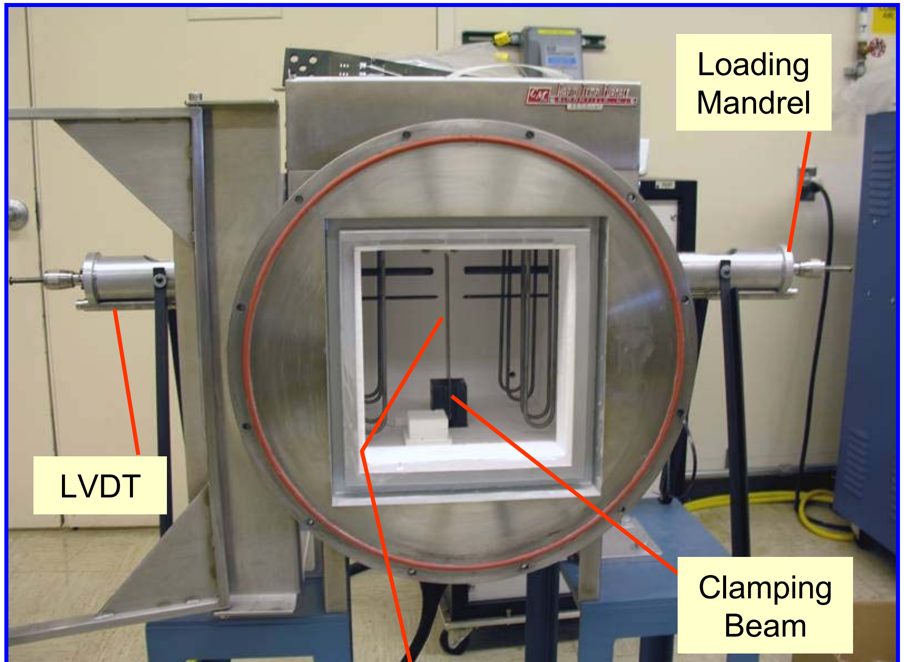


Thermal / Mechanical Cantilever Beam Testing of EFPI's

- *Excellent correlation with SG* to 550°F (3%)
- Very little change to 1200°F
- Slight drop in output slope above 1200°F
- Maximum gap readability uncertain at upper range temperatures on high expansion material

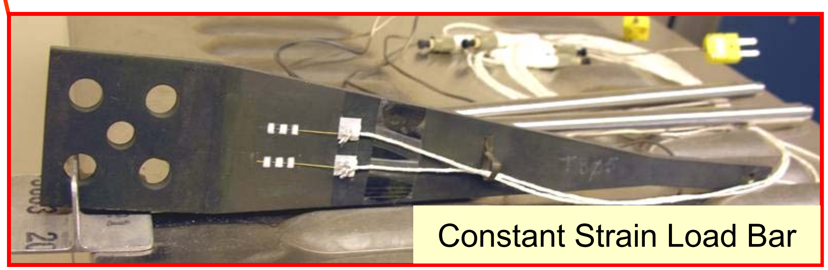
Evaluation / Characterization

Combined Thermal / Mechanical Loading (Current)



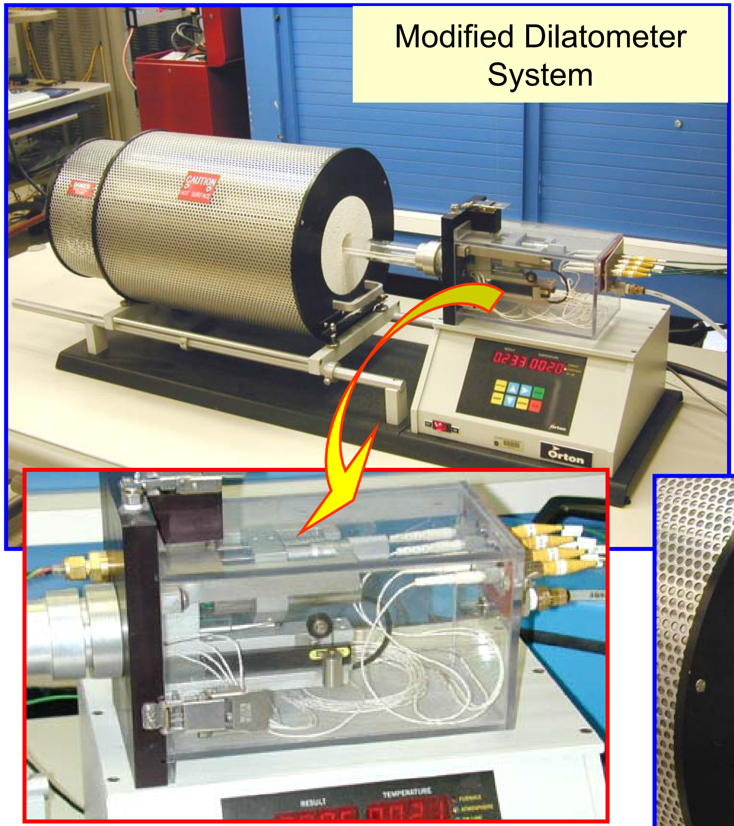
Furnace / cantilever beam loading system for sensitivity testing

- *Air or inert (3000°F max)*
- 12-in^3 inner furnace with Molydisilicide elements
- Micrometer / mandrel side loading
- LVDT displacement measurements
- POCO Graphite hardware for inert environment testing of ceramic composites
- IN625 hardware for metallic testing in air
- Sapphire viewing windows



Evaluation / Characterization

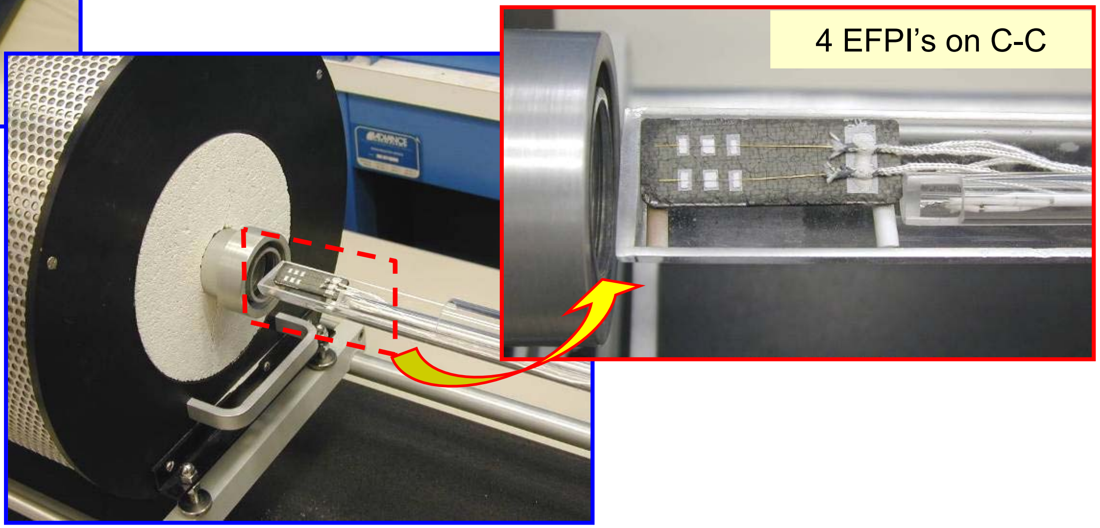
Dilatometer Testing



Sensor Characterization

Air or inert (3000°F max)

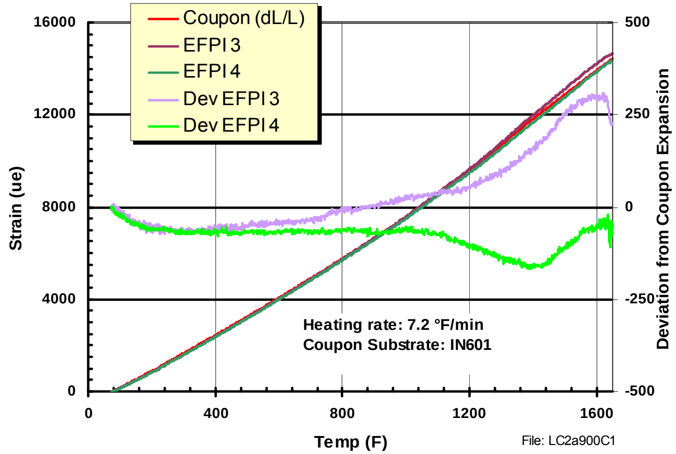
- Evaluate bond integrity
- Generate ξapp correction curves
- Evaluate sensitivity and accuracy
- Evaluate sensor-to-sensor scatter, repeatability, hysteresis, and drift



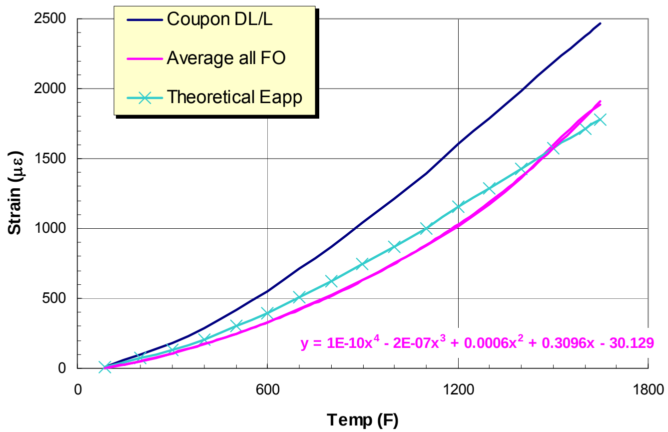
Evaluation / Characterization

EFPI Apparent Strain

Inconel Substrate



CMC Substrate



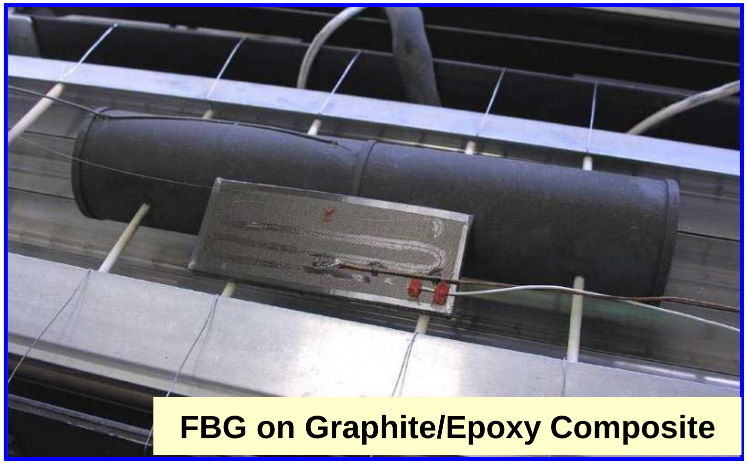
ξ_{app} Correction: Removal of inherent sensor traits and substrate expansion from indicated strain to acquire true strains or thermal stresses

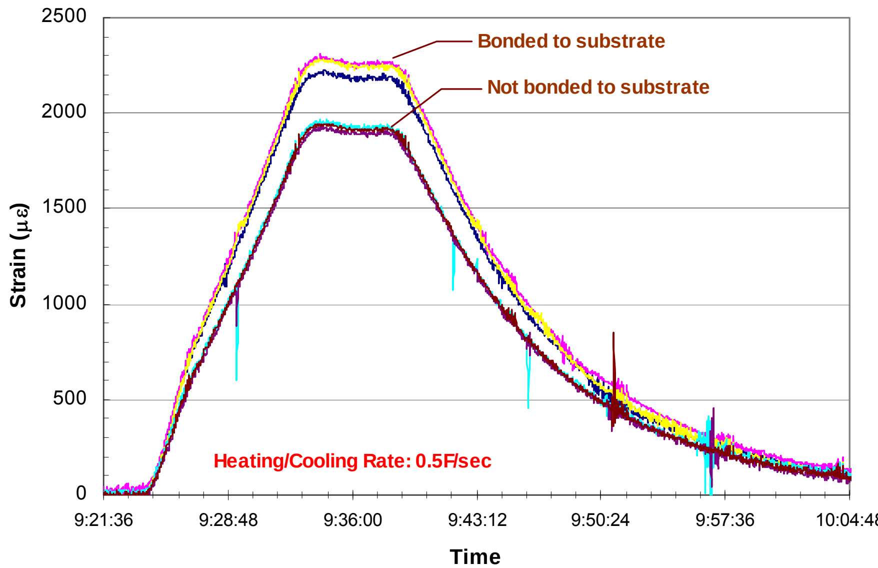
$$\xi_{true} = \xi_{indicated} - \xi_{app}, \text{ where } \xi_{app} = (\alpha_{sub} - \alpha_{fiber}) * \Delta T$$

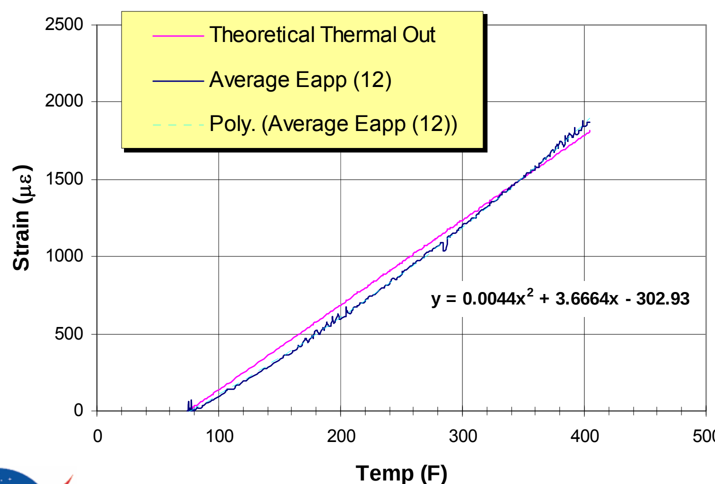
- Inconel (LH chart): Large expansion differential between IN601 and Si
  - output primarily substrate expansion, CTE * ΔT
- CMC (RH chart): Small expansion ratio between C-SiC and Si
  - requires correction for fiber expansion (lessening cavity gap)
- *Graphs demonstrate how well actual ξapp curves followed theoretical*

Evaluation / Characterization

FBG Apparent Strain


FBG on Graphite/Epoxy Composite





Thermal Out (unbonded) = (α_{fiber} + ξ / Pe) * ΔT

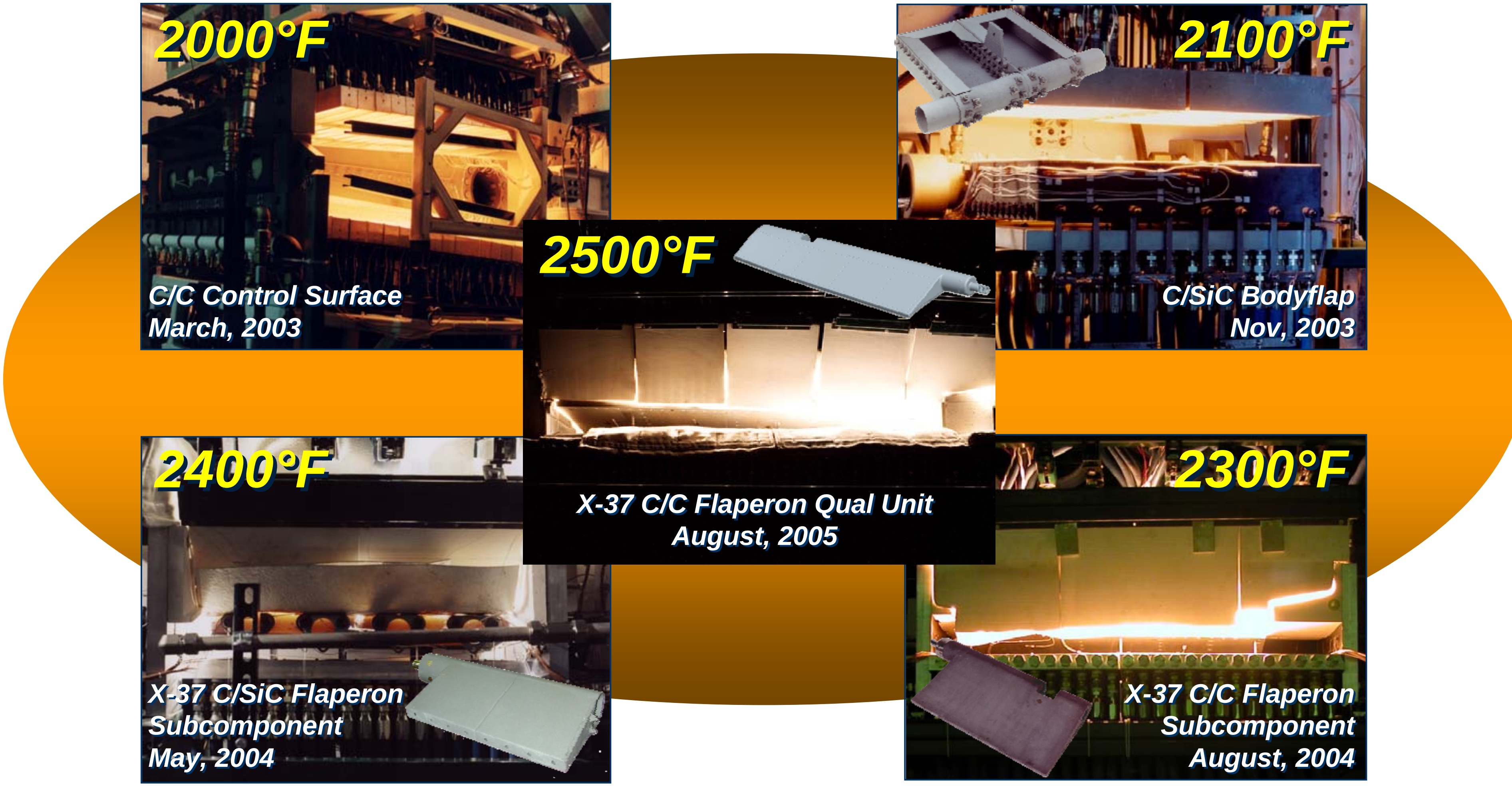
where:

Thermal Optic Effect (ξ) = 3.78 με/F

Strain Optic Constant (Pe) = 0.725

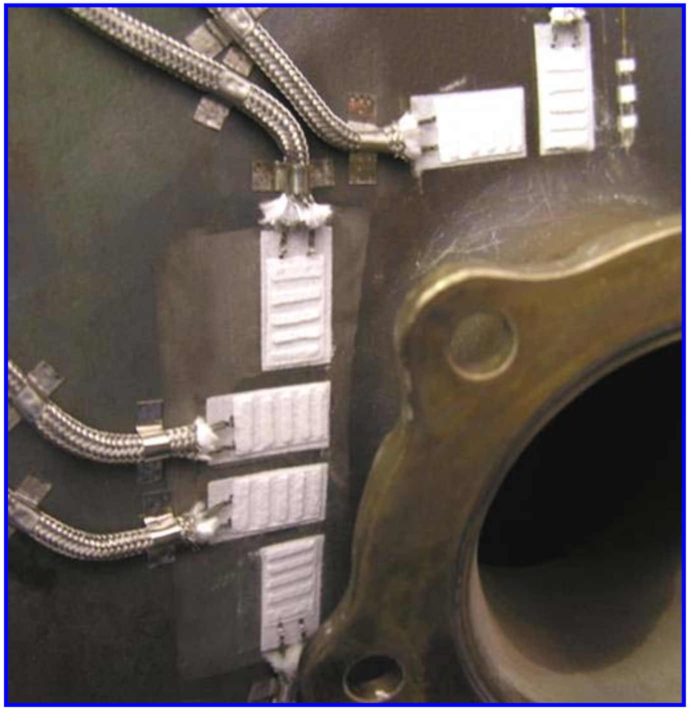
Large Scale Structures

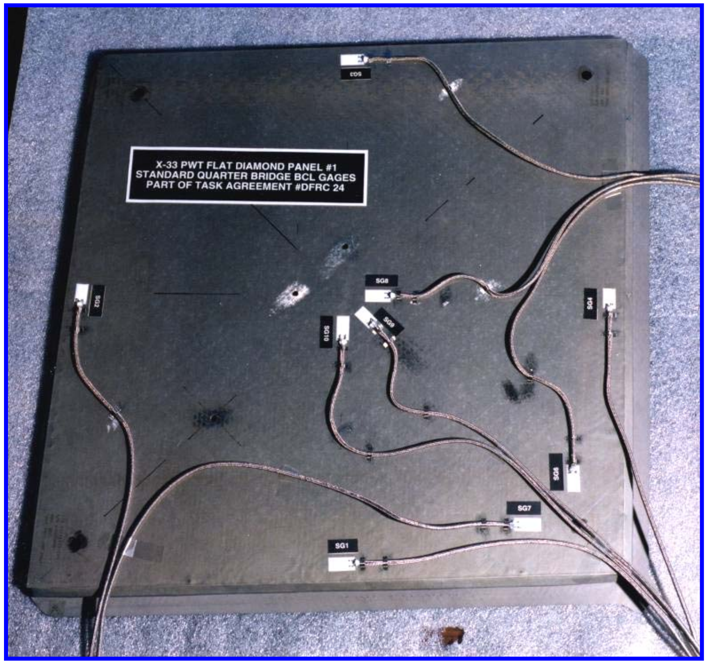
Ceramic Composite Control Surfaces



Large Scale Structures

Metallic Dynamic Environment





X-33 Sonic Fatigue Testing

- Dynamic loads as high as -158db
- Test temperatures above 1500°F
- High transient heating rates producing large thermal stresses

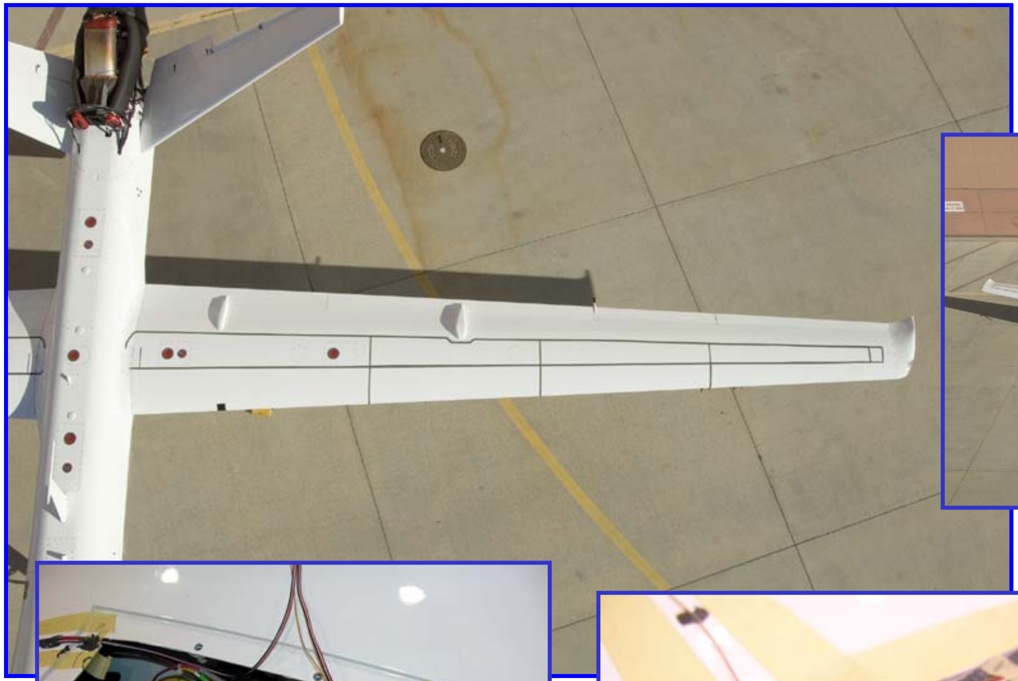
C-17 Engine Testing

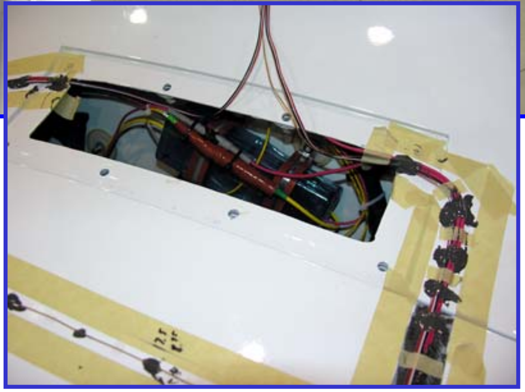
- Test temperatures above 1100°F
- Engine intentionally unbalanced creating large peak-to-peak vibrations

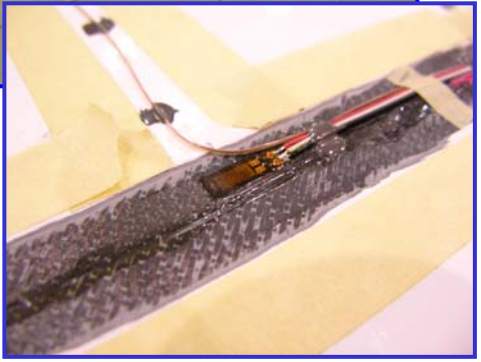
Large Scale Structures

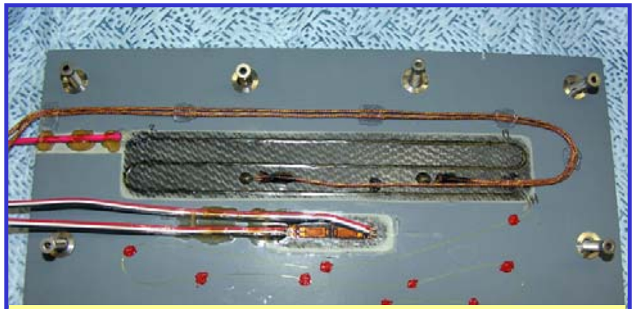
Fiber Optic Wing Shape Sensing

NASA Dryden Predator B (Ikhana)









ξapp coupon tested from -60°F to 150°F