Multifunctional Sensing using Fiber Bragg Gratings

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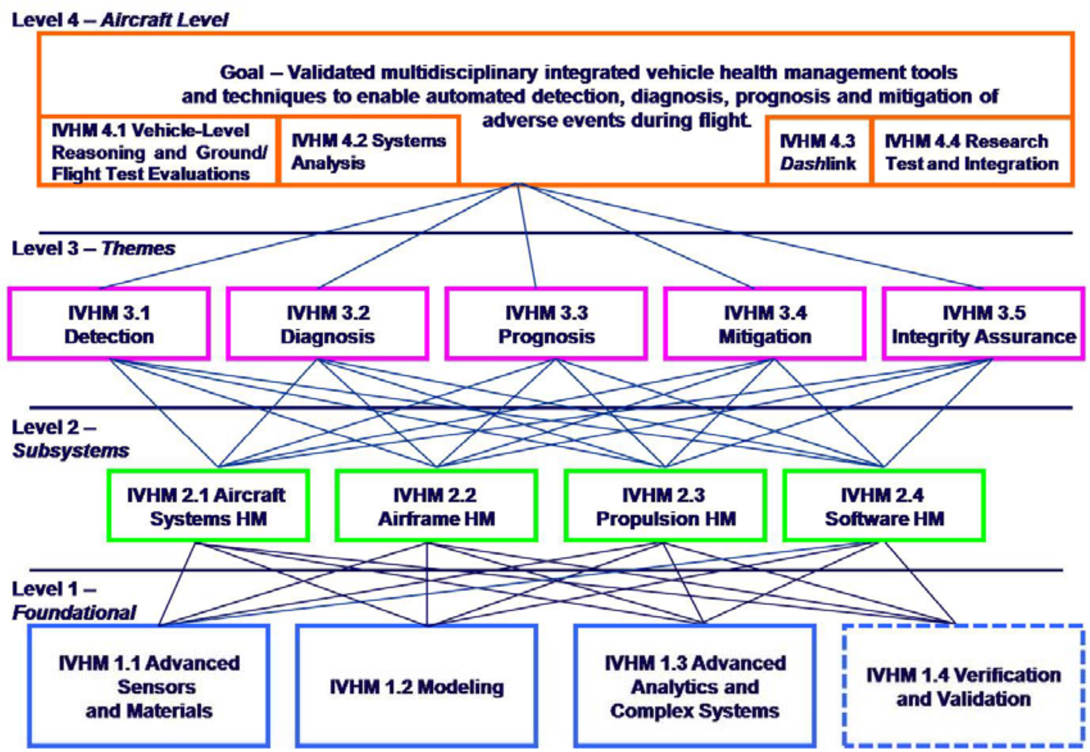
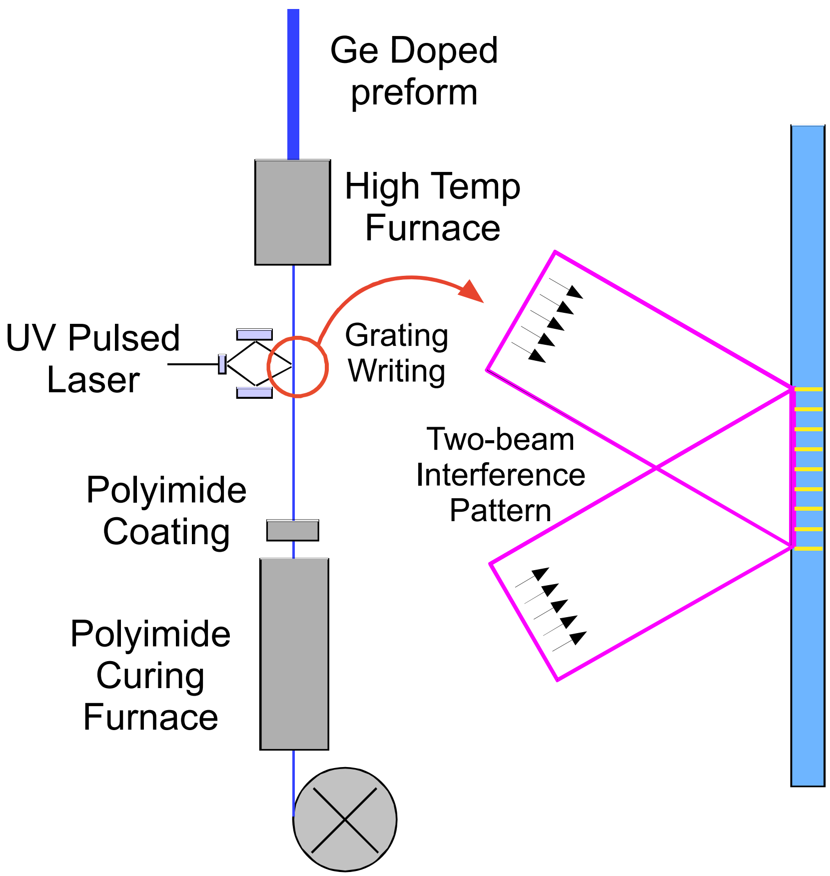


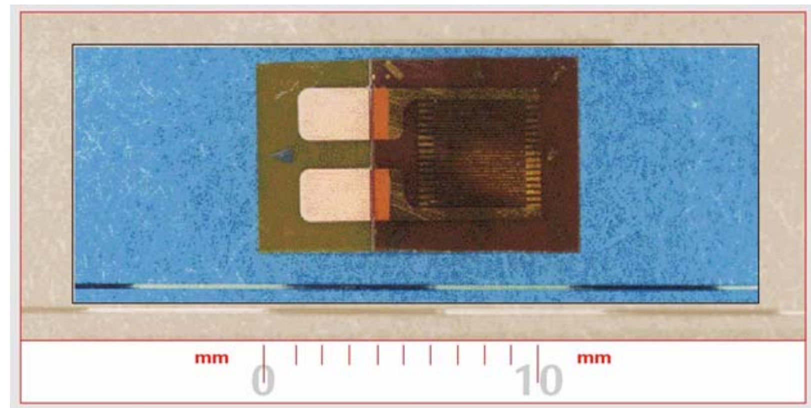
Problem Statement

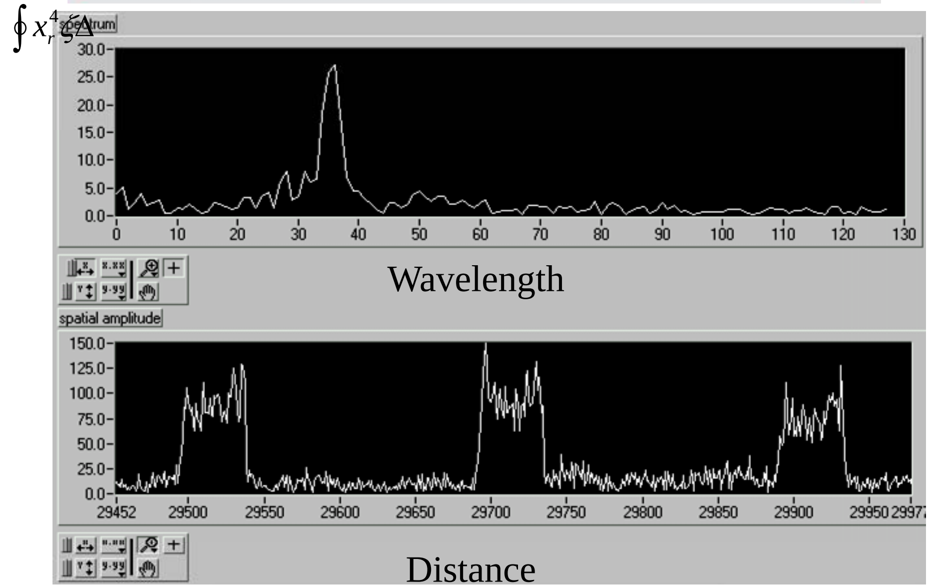
- This work addresses three aircraft problems: Overloading Conditions, Fatigue and Crack Detection.
- The IVHM project recommends strain as one of nine priorities for future IVHM research. Standard strain gages can be been used to monitor loading, fatigue and to detect cracks in aircraft.   Cracks such as 0.01 mm have been detected in airframes using strain sensors.

- Fiber Bragg Grating (FBG) Sensors have demonstrated an ability to address all three of the problems.
  - Fiber optic Bragg grating sensors are distributed strain and temperature sensors.
  - Many sensors can be written on a single fiber (3000 sensors were tested on 4 eight meter fibers at Langley).
  - The fiber can be interrogated in-situ to collect structural information during and after flight (flown on STS-96 for hydrogen leak detection).
  - FBG sensors operate in extreme temperatures, they have been tested at -22˚K at Langley, and have a maximum theoretical operating temperature of 600˚C.

Background on FBG Sensors





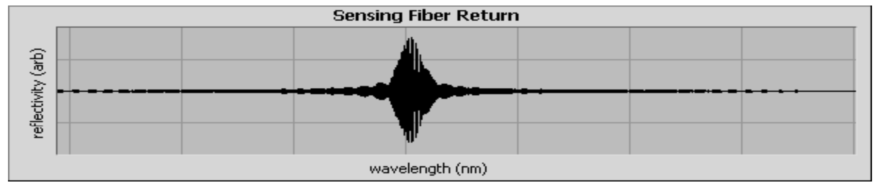


Real-time Bragg Grating Sensor Demodulation

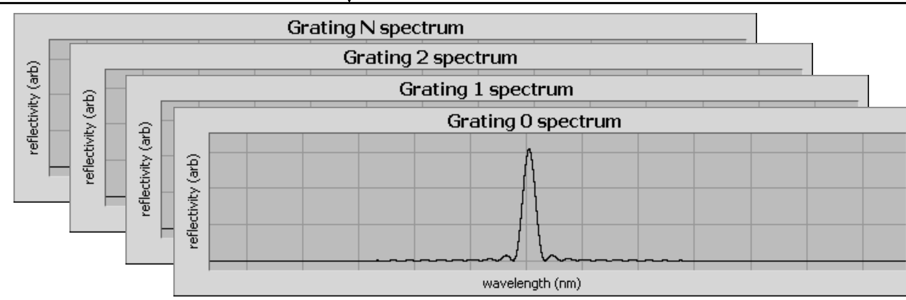
Laser
Wavelength-sweeping
- Continuous output
- Fiber-coupled

Sensing Fibers
- 100's of low-reflectivity Bragg Grating sensors
- Minimal separation between sensors (1 cm.)

Optical Network
- Houses wavelength-tracking in-fiber interferometer
- Sends & receives power to/from the sensor fibers



Analog Electronics
- Converts optical signals to electrical signals
- Decouples individual sensor reflection spectra
- Detects spectral peaks of each sensor



Digital Electronics
- Records wavelength of each sensor spectral pea
- Programs analog sensor decoupling circuitry

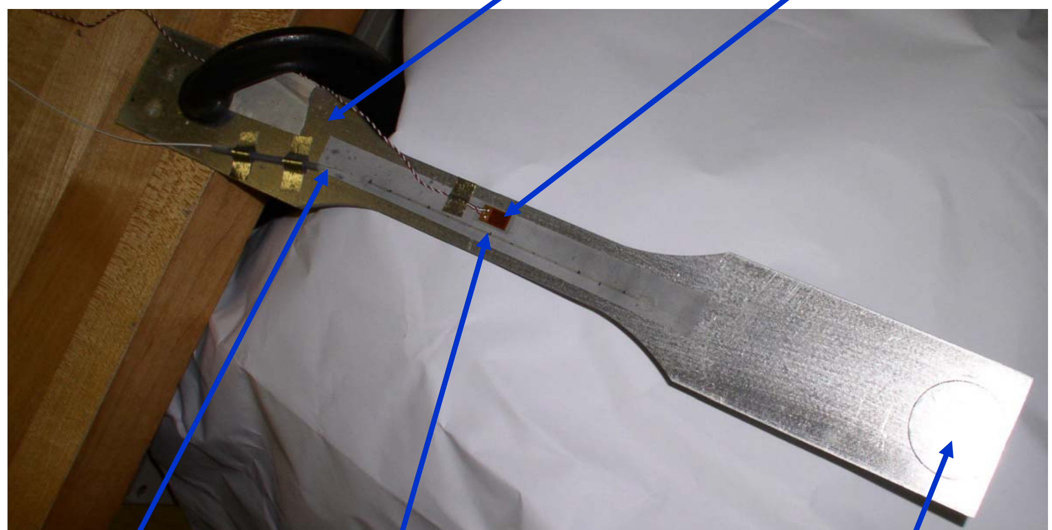
grating 0	1550.23
grating 1	1550.18
grating 2	1550.46
grating N	1551.02

IVHM milestones being worked

- This work was performed under milestone 1.1.1.7.
  - High density multi-functional fiber optic based sensor array capable of better than 10% FSR μstrain (με) resolution and temperature resolution.
  - Real-time Bragg Grating demodulation technology to measure the strain of 3-core fiber to with 90% accuracy.
- The results from 1.1.1.7 flow directly into milestone 2.2.1.1.
  - Demonstrate one or more technologies capable of detection of physical changes to airframe structural components that can accurately distinguish between damaged and undamaged component states to better than 80% area under the ROC curve using new sensor technologies with physics based models. Sensors must be complementary, and have the potential for enhanced detection when integrated. Technologies to be investigated include fiber optics, MEMS, and nano-technology

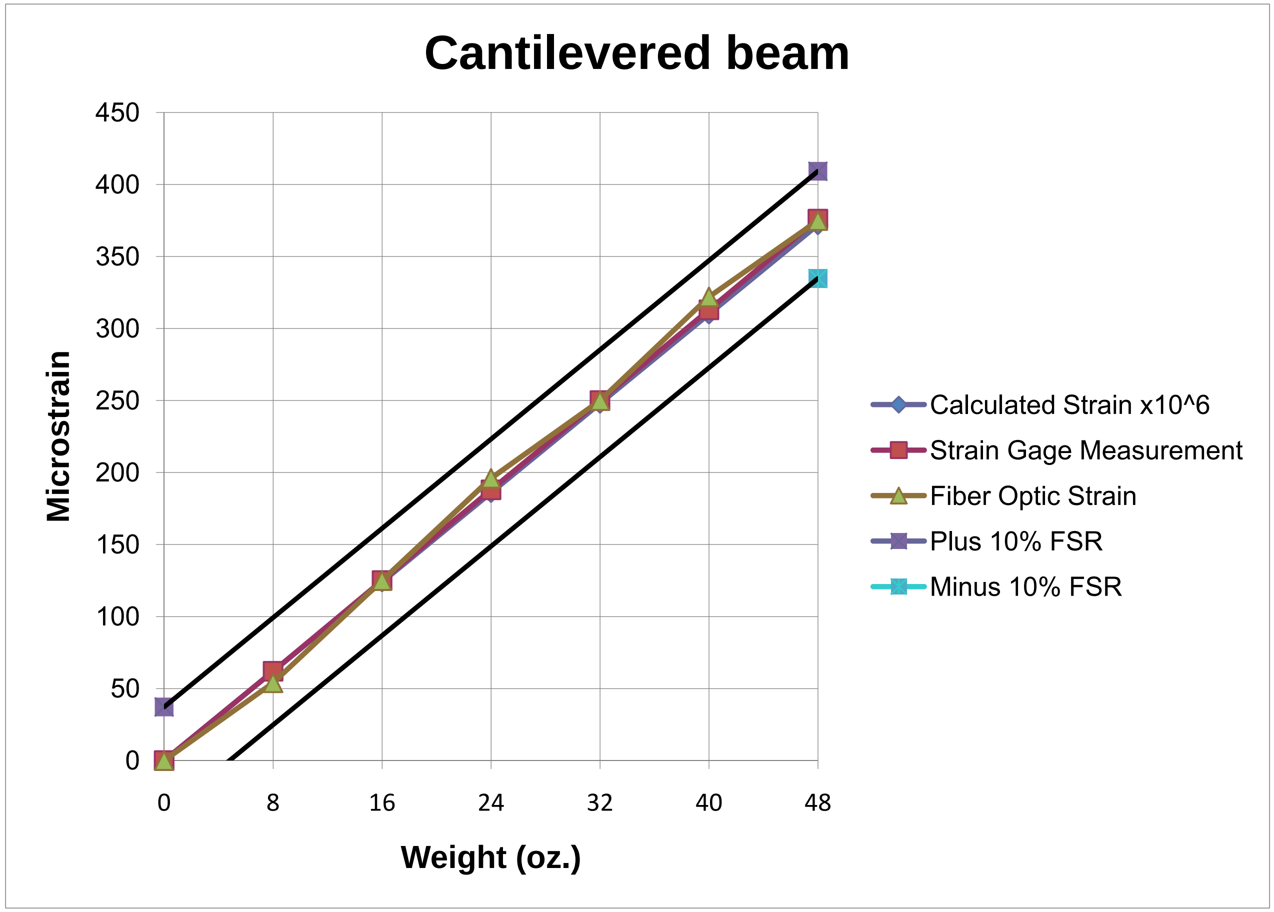
Approach for Strain Measurements

- Optical fiber with FBG strain sensors is bonded near the center of the cantilevered beam test sample.
- Conventional strain gage attached to test sample.
- Compared FBG to strain gage readings.



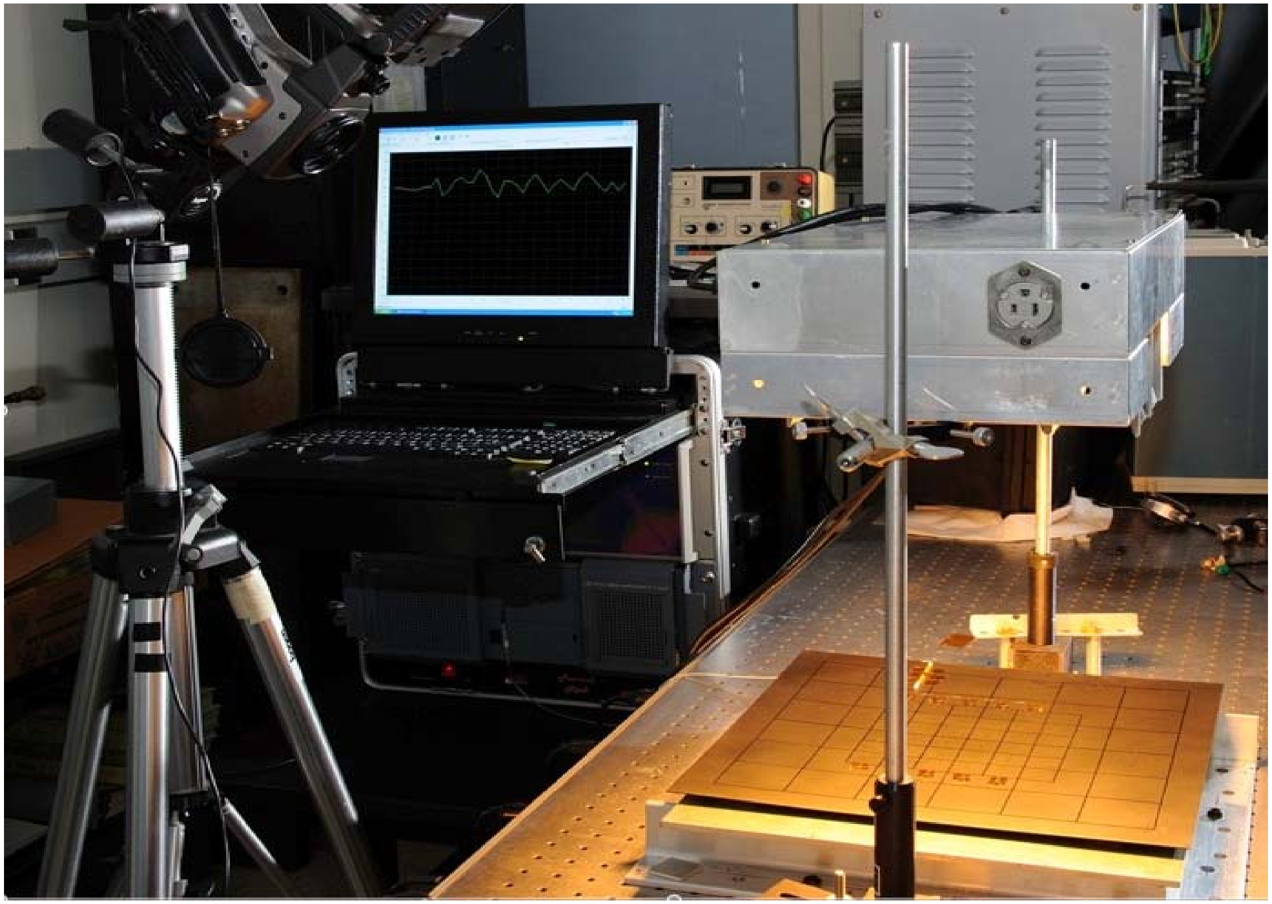
Results for Strain Measurements

- Weight was added in 8 oz. increments.
- FBG strain sensors show good agreement with calculated values and strain gage measurements.
- Better than 10% FSR at room temperature and down to liquid helium temperatures of -204°C



Fiber Optic Thermographic Test Setup

- One channel OFDR on left, 2.8 Hz data acquisition rate.
- Test article and quartz lamp on optical table
- Heated 15-20 sec.
- Took data before, during, after heating.

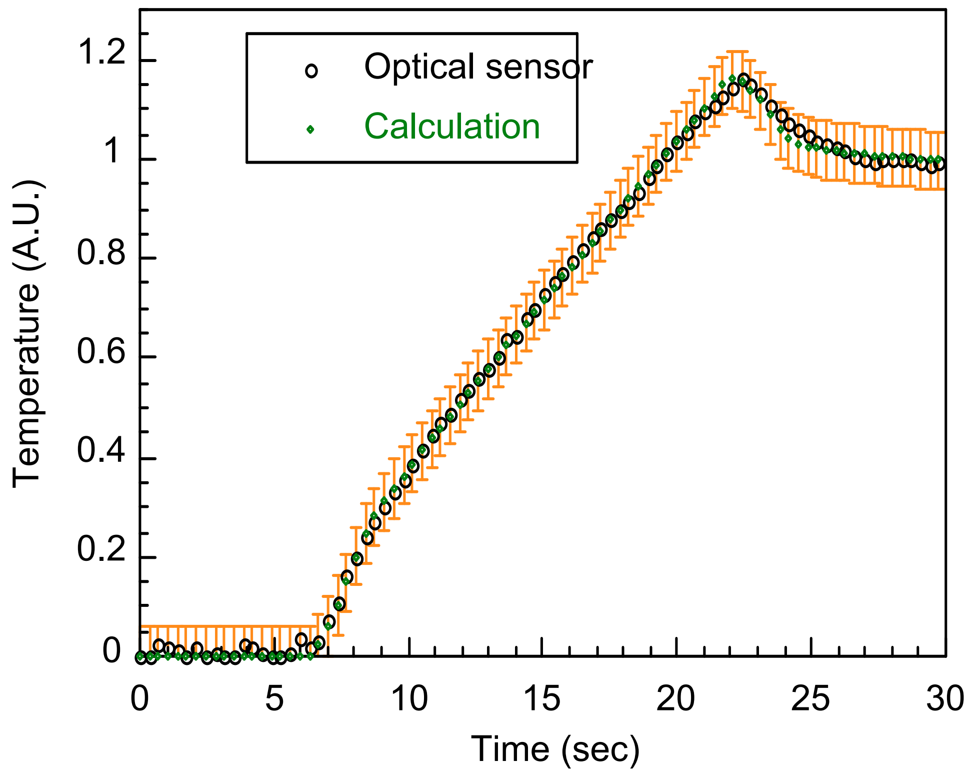


Fiber optic thermal health monitoring system with a quartz lamp as the heating source and a conventional IR camera for comparison.

Thermographic Results

- The developed fiber optic thermographic system is capable of better than 10% temperature (μstrain) FSR.
- The fiber optic thermographic system using fiber Bragg grating array has the capability of dynamic temperature and strain measurements.
- Heating ranges were about 50 -70 C (equivalent to 400 -600 μstrain) For some data the agreements are even within 5%. Thermographic modeling was applied to the calculations of temperatures based on the conventional IR imaging system. .
- Future work is planned for back surface heating as well as front surface heating on the specimens with damages.

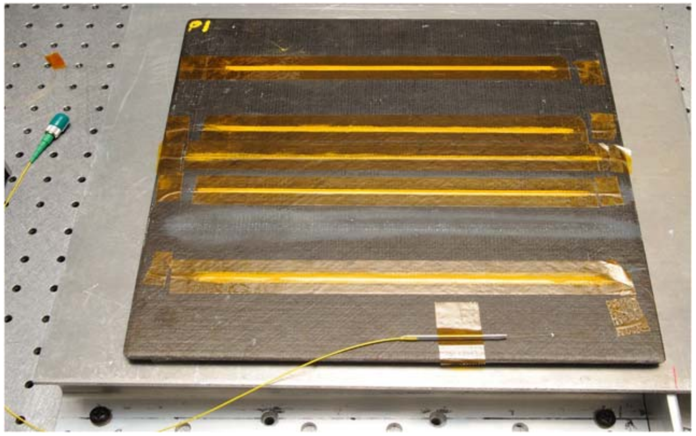
Fiber optic thermographic measurement



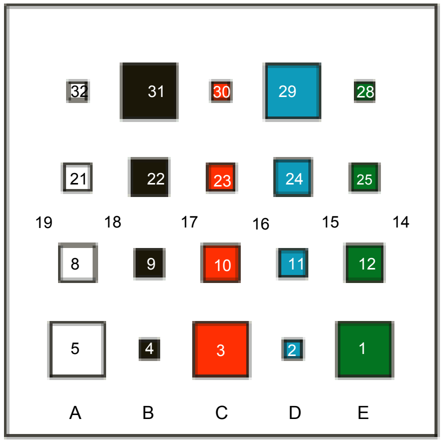
Surface temperature change of a composite during and after heating. The orange bars show a 5% FSR.

Fiber optic thermography

- A composite specimen with 10 ply quasi-isotropic composite panel with a lay-up of [0,45,90,-45,0/,45,90,-45/,0,90/] was 31.75 x 31.75 centimeters and 0.19 centimeters thick.
- The delamination defect areas were squares with sizes of 14.5, 6.54, 3.6, and 1.6 square centimeters. The defects were buried at depths of 10, 20, 30, 40, and 50 percent of the total thickness, between plies 1-2 (A), 2-3 (B), 3-4 (C), 4-5 (D), 5-6 (E). At the center of each square one FBG senosr was seated.
- A quartz lamp was used to heat the front surface of the specimen for 10-15 seconds. The grating data acquisition was performed at a rate of 2.85 Hz, during and following the application of the heat. An IR camera was also used to record the temperatures of the surface separately.
- The system detected down to 3.6 cm^2 defects at all depths including 50%.
- Thickness variations representing corrosion in steel were also detected using fiber optics.



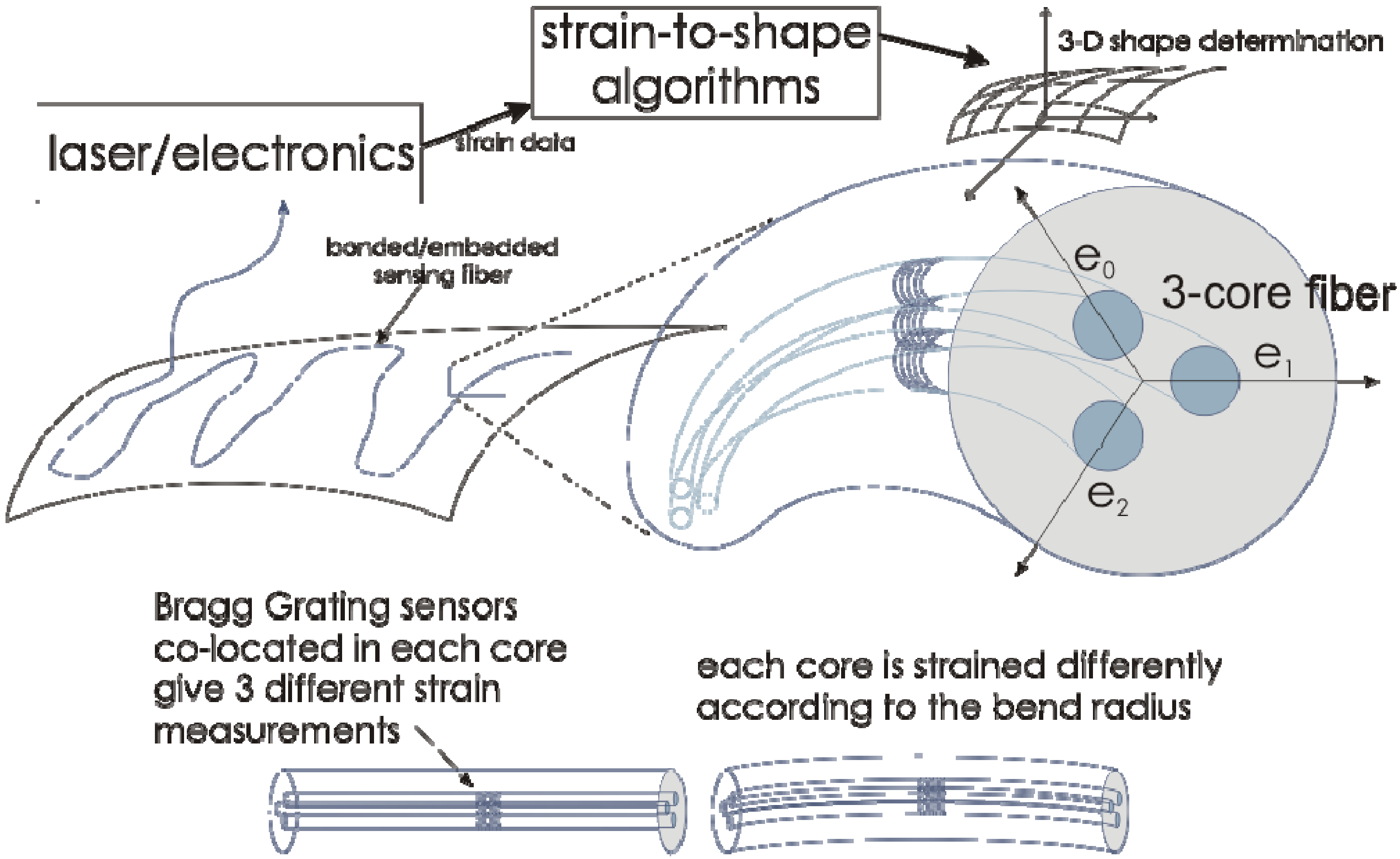
Test panel with fiber installed



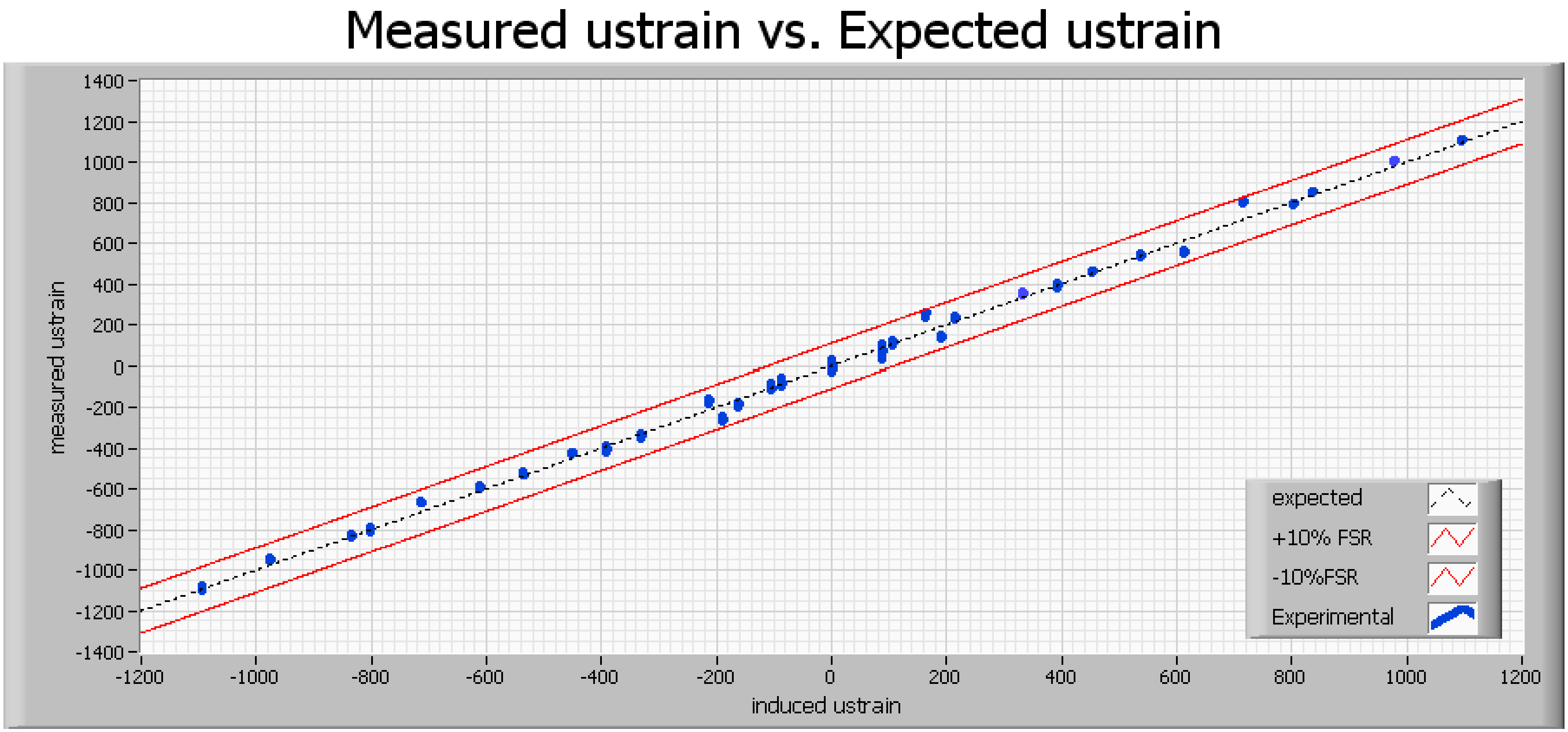
Depth
A - 10%
B - 20%
C - 30%
D - 40%
E - 50%

Map of defects.

3-Core Fiber Optic Shape Sensing



Results from 3-Core FBG Sensors



3-core fiber was placed in a series of bends of varying known curvatures. From these known curvatures, expected strain values were calculated for a triplet of co-located Fiber Bragg Gratings. A Real-time prototype system was used to make 50 strain measurements of the FBG triplet at each curvature. A “zero-bend” case was also measured.

Advantages over State of the Art

- The FBG systems use optical frequency domain reflectometry in contrast to typical FBG systems which use a time domain system. The exception is Luna Innovation's demodulation system which is licensed from NASA.
- Although, universities are researching the use of FBGs for thermography, only NASA has demonstrated detection of delaminations in composites and thickness variations (representing corrosion) in steel using fiber optics.
- The real-time, non-computational, system was designed to reduce or eliminate sampling and processing while still interrogating multiple Bragg Grating sensors. There is currently no published information suggesting that any other system exists which matches the potential speed and quantity of measurements of the real-time system.
- To obtain 3-D location and shape characterization of the multi-core fiber optic cable. The NASA method uses curvature and bend direction functions, derived from the multi-core fiber optic cable, to numerically solve a set of 3-dimensional elastic tube equations, yielding spatial functions describing the location of the cable in 3-D space. While an order-of-magnitude accuracy increase over prior art has been demonstrated, lab testing has shown the potential for much greater accuracy improvements.

Conclusions

- FBG sensors have been demonstrated that can monitor strain using single core and multiple core fiber, and can measure temperature.
- The three core fiber FBG sensors can measure shape in addition to strain.
- The single core fiber can be used a relative temperature sensor, or as a thermography sensor to detect delaminations in composites.

Next Steps

- Integrate all of the Fiber Optic sensors on a panel along with conventional strain gages and other technologies such as Carbon Nanotubes and Surface Acoustic Wave sensors, etc.

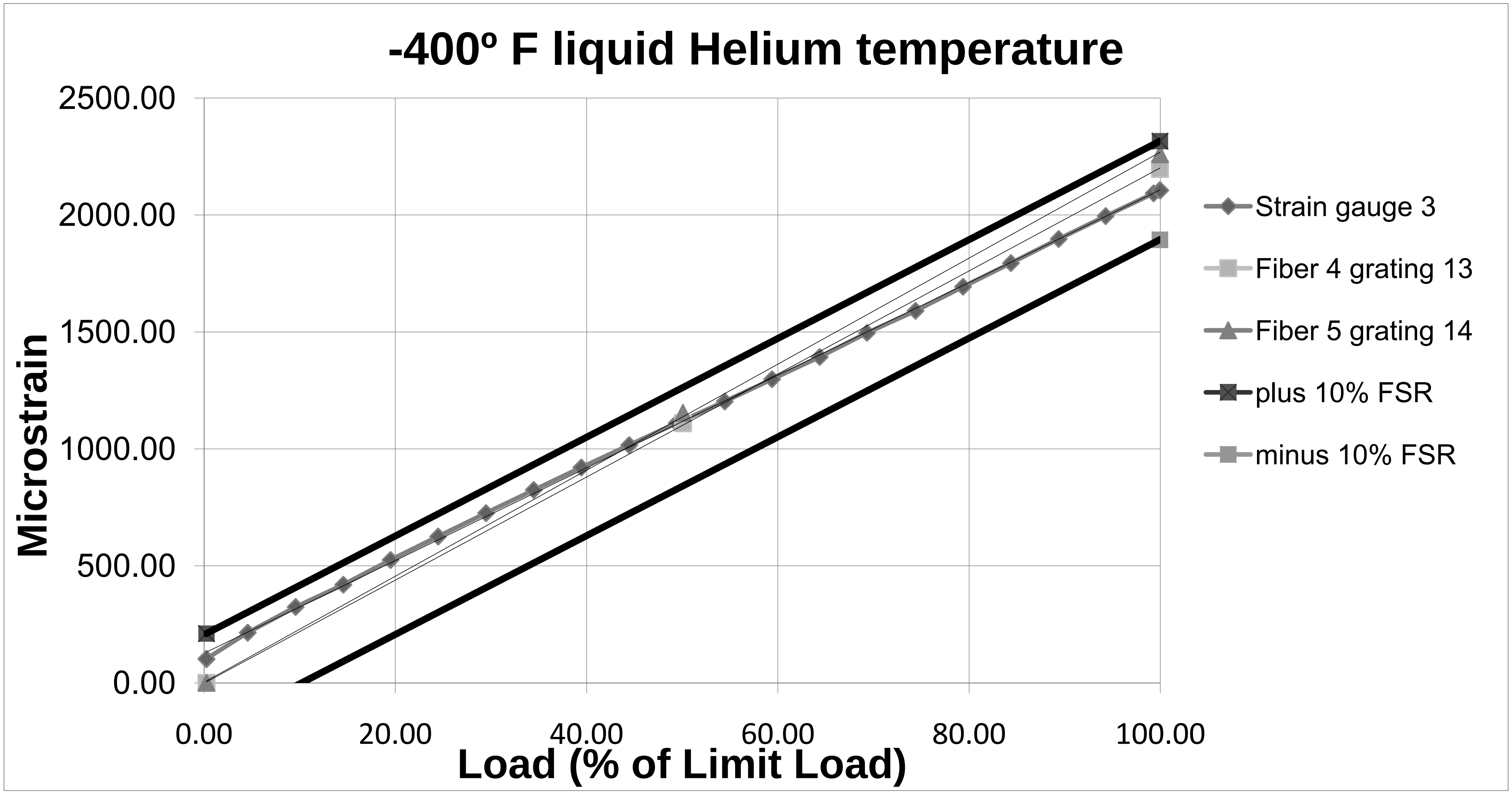
- Simulate fastener failures and compare data on all sensors to determine the ability to detect damage.

- Investigate twisting of 3-core fiber during small radius bending.

- Validate dual-use of fiber optic Bragg grating sensors for thermographic corrosion detection in addition to conventional IVHM strain sensing.

Auxiliary Slides

Temperature Results

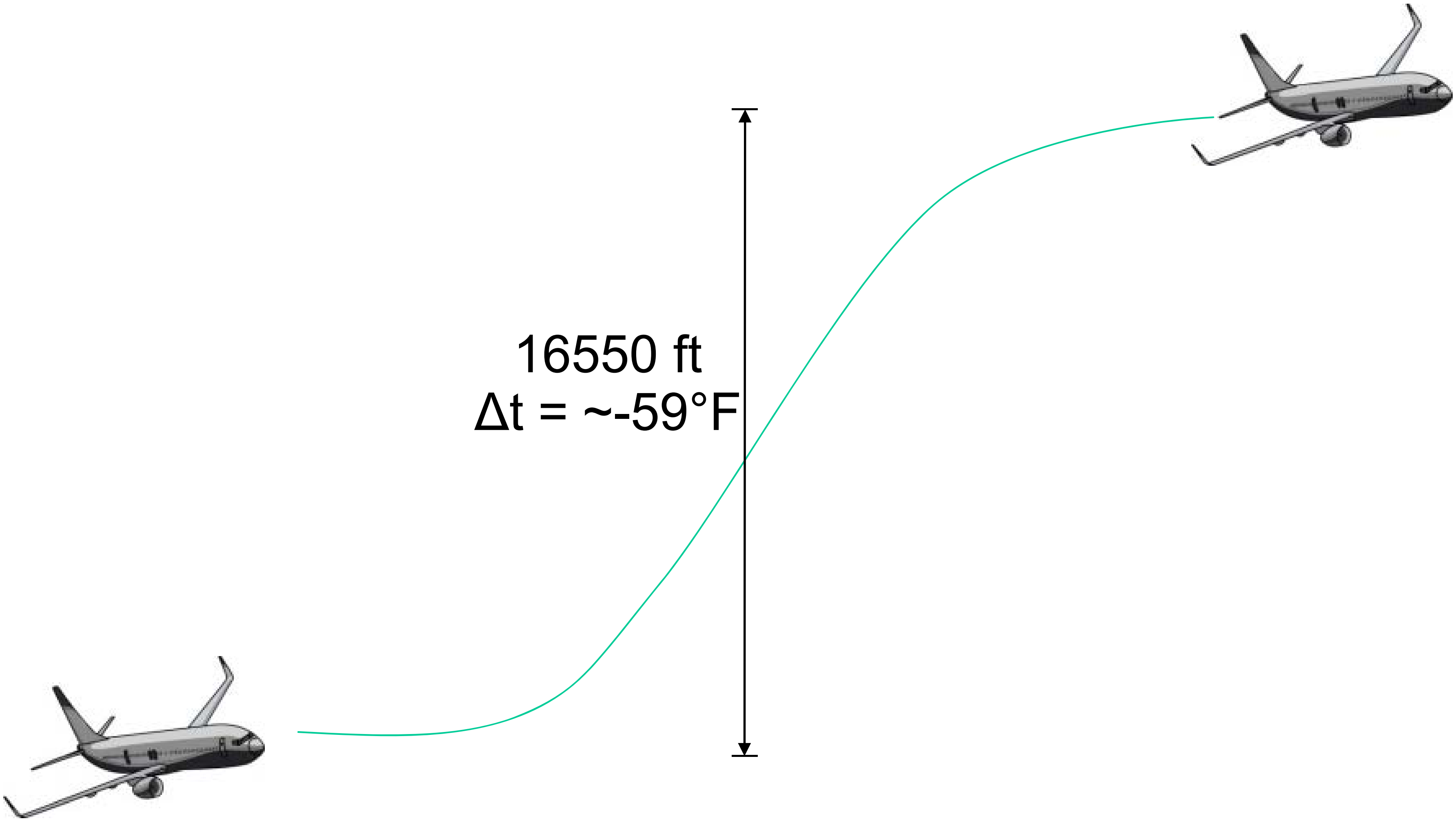


- Optical fibers with FBG strain sensors are bonded with strain gages, along the center of the Y-Joint test article.

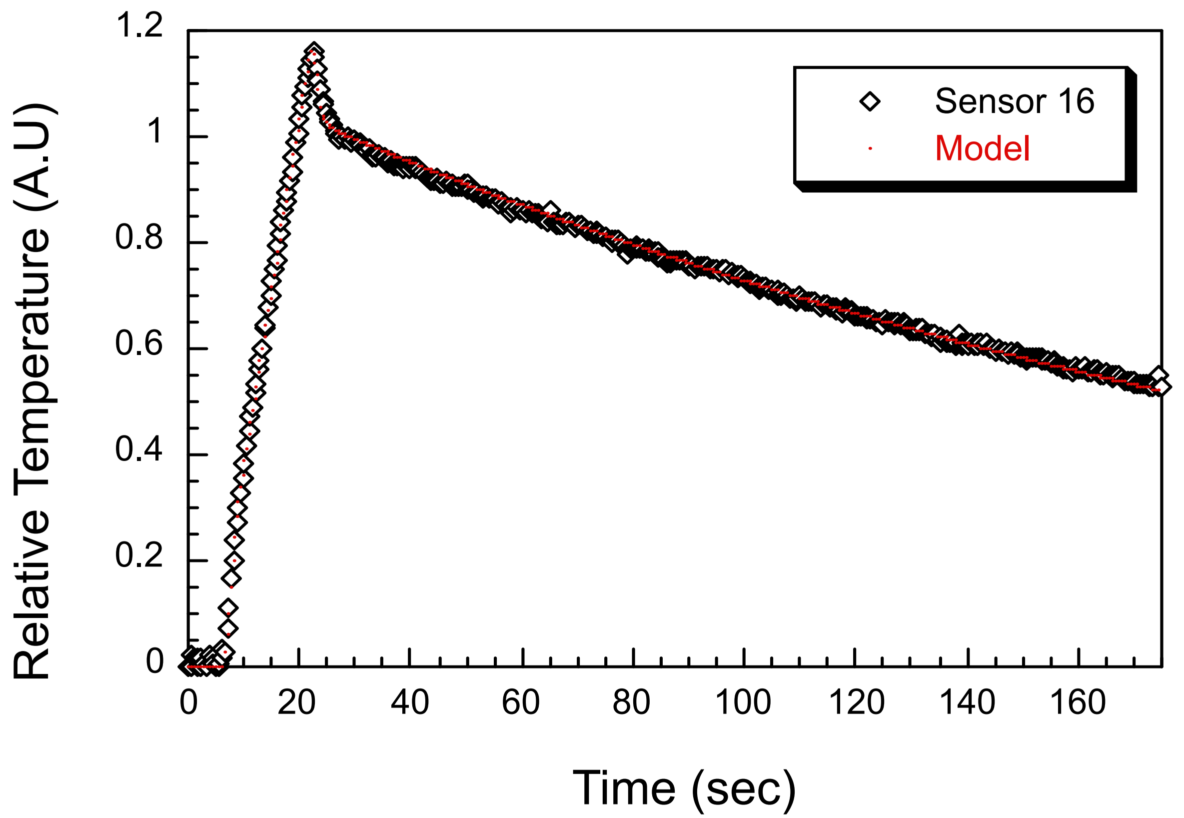
S. G. Allison, W. H. Prosser, D. A. Hare, T. C. Moore and W. S. Kenner "Optical Fiber Distributed Sensing Structural Health Monitoring (SHM) Strain Measurements Taken During Cryotank Y-Joint Test Article Load Cycling at Liquid Helium Temperatures" Proc. SPIE Optics East, Boston, MA, Vol 6770, Paper No. 677003-2, September 2007.

FBG Thermography

- Temperature differential for aircraft climbing to 16550 ft.



Thermal response of FBG sensor and the model at a location without delamination.



FBG Thermography

Thermal responses of the fiber optic sensor and the model at a location with a delaminations