Fiber-Optic Strain Sensing (FOSS)

# Shape and Load Measurement Demonstration Tests

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# Technology Overview

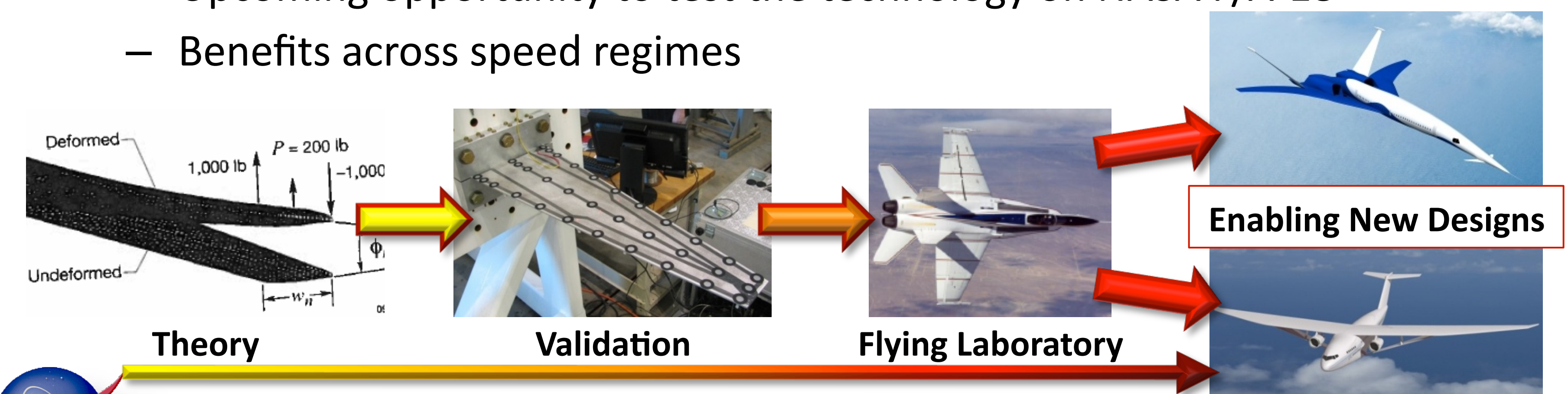
- Fiber-optic strain sensing (FOSS) allows nearly continuous strain measurements
  - Measurements every half inch
  - Hundreds of measurements per channel
  - Flight-capable system
- FOSS offers several notable advantages to foil strain gages:
  - Lightweight sensor package (no copper leadwires)
  - Immune to EMI/radio-frequency interference and radiation
  - Fibers can be embedded within a composite part
- Strain values can be used to calculate structural deflections and loads*
  - Based on classical beam and basic bending equations
  - Structure discretized into many span-wise analysis station

***PATENT NOTICE**

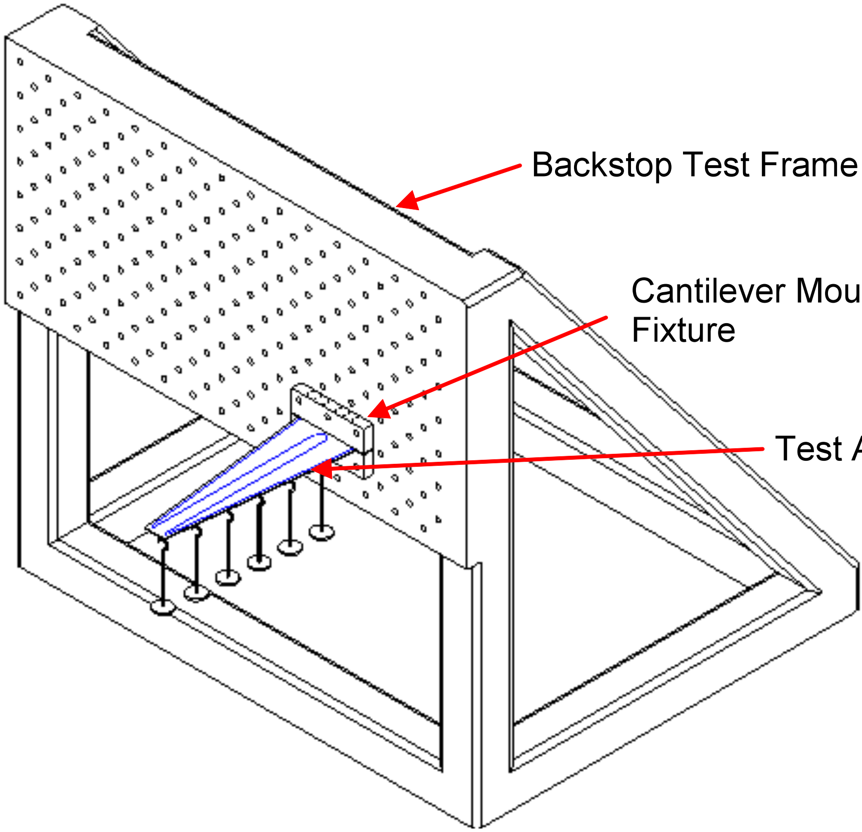
The structural shape and load prediction methods described in this technical paper (or presentation) are protected under U. S. Patent No. 7,520,176, issued April 21, 2009, and U. S. Patent No. 7,715,994, issued May 11, 2010. Therefore those interested in using the method should contact the NASA Innovative Partnership Program Office at NASA Dryden Flight Research Center for more information.

# Technology Progression

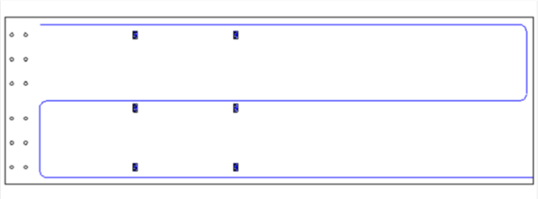
- Deflection and load equations had been analytically verified
  - Questions remained about practical implementation
- The capability is desired in order to improve aircraft design
  - Real-time shape and load measurement during flight enable:
    - Efficient, lightweight design
    - Maneuver/gust load alleviation
    - Structural feedback to control system
    - Structural health monitoring and damage detection
  - Upcoming opportunity to test the technology on NASA F/A-18
  - Benefits across speed regimes



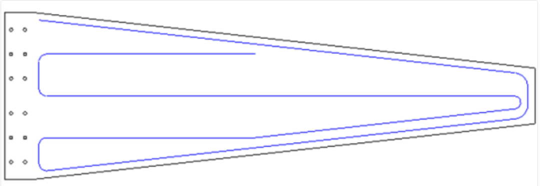
# Test Setup



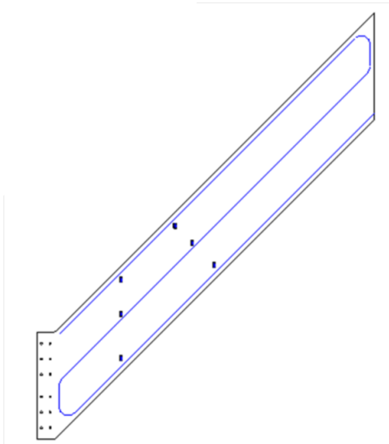

- 4 Interchangeable Test Articles
  - Planform shapes of wings
  - Aluminum plate (.190" thick)



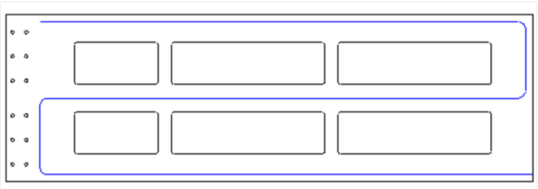
Rectangular Plate Test Article



Tapered Plate Test Article



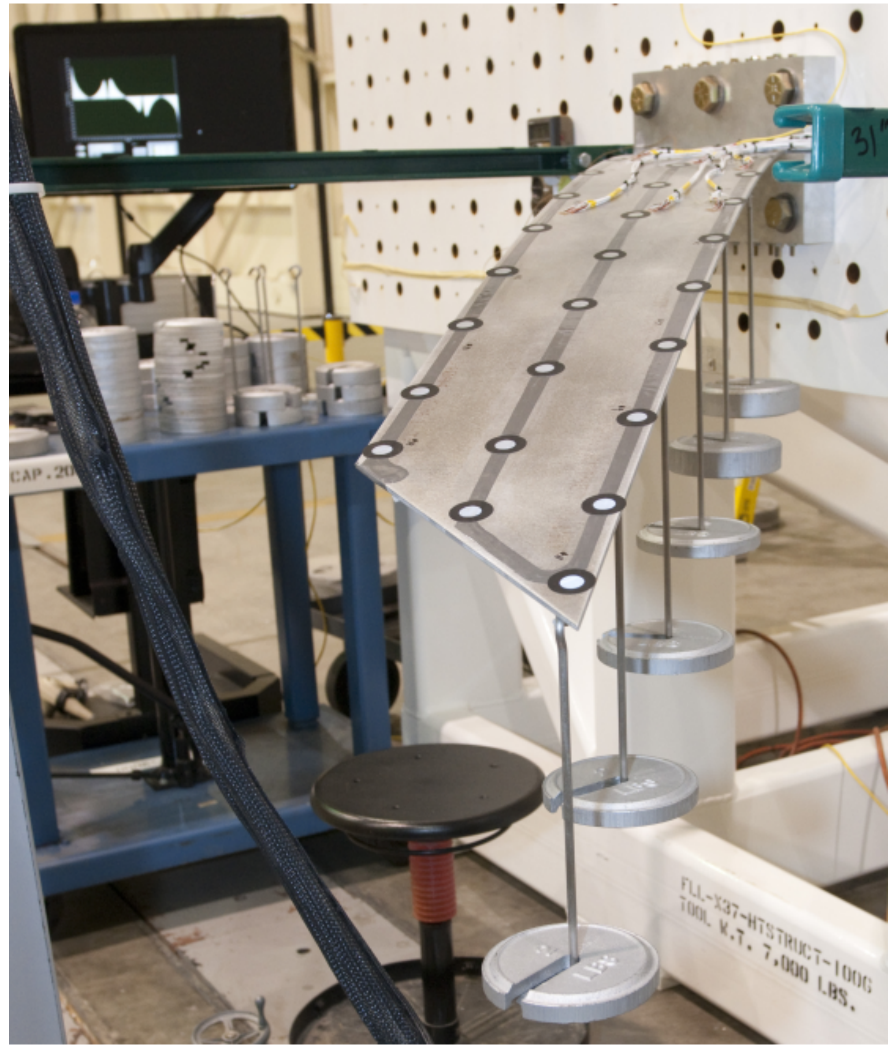
Swept Plate Test Article



Open Plate Test Article

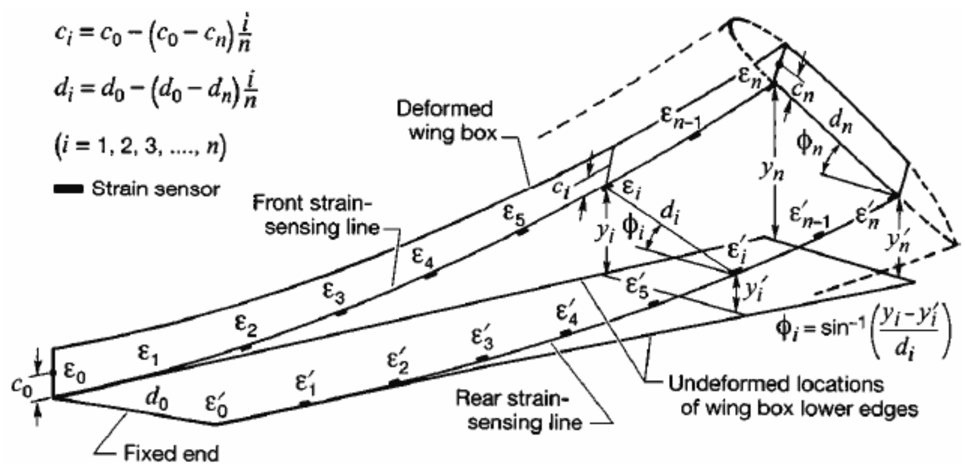
# Summary of Tests

- Multiple load cases applied to each test article
  - Uniform loading
  - Tip- and root-biased loading
  - Leading and trailing edge loading
  - Single-point loading
- Data
  - FOSS (fiber optic strain sensor)
    - input to equations
  - Conventional strain gages
  - Photogrammetry
    - Displacement to verify results
  - Load
    - calibrated weights



# Deflection Calculation

# Determination of Wing Deflection




## Deflection of a Single Fiber:

$$y_i = \frac{(\Delta l)_i^2}{6c_{i-1}}\left[\left(3 - \frac{c_i}{c_{i-1}}\right)\varepsilon_{i-1} + \varepsilon_i\right] + y_{i-1} + (\Delta l)_i \tan\theta_{i-1}$$

**Slope:**

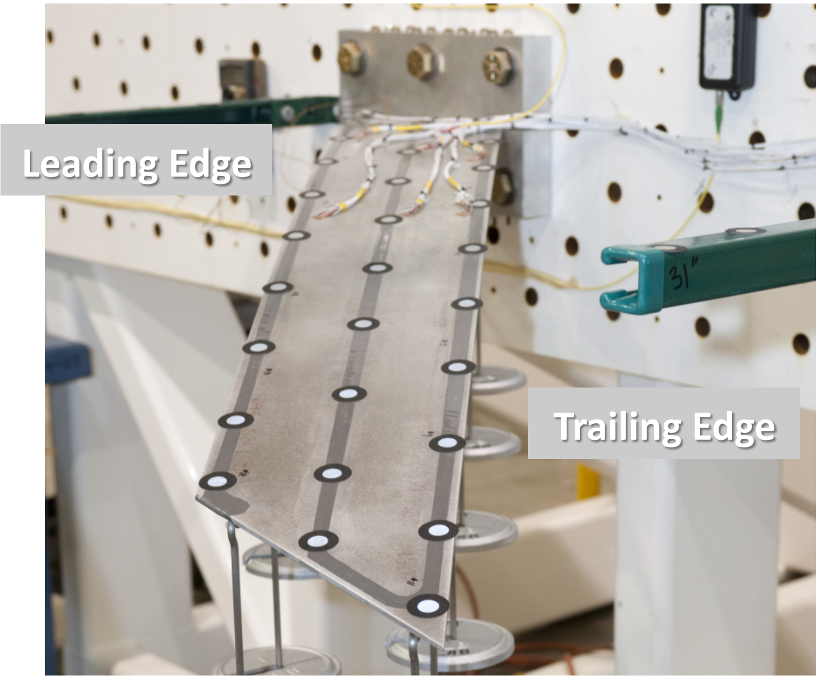
$$\tan\theta_i = \frac{(\Delta l)_i}{2c_{i-1}}\left[\left(2 - \frac{c_i}{c_{i-1}}\right)\varepsilon_{i-1} + \varepsilon_i\right] + \tan\theta_{i-1}$$

**Typically the first station is at the root:**

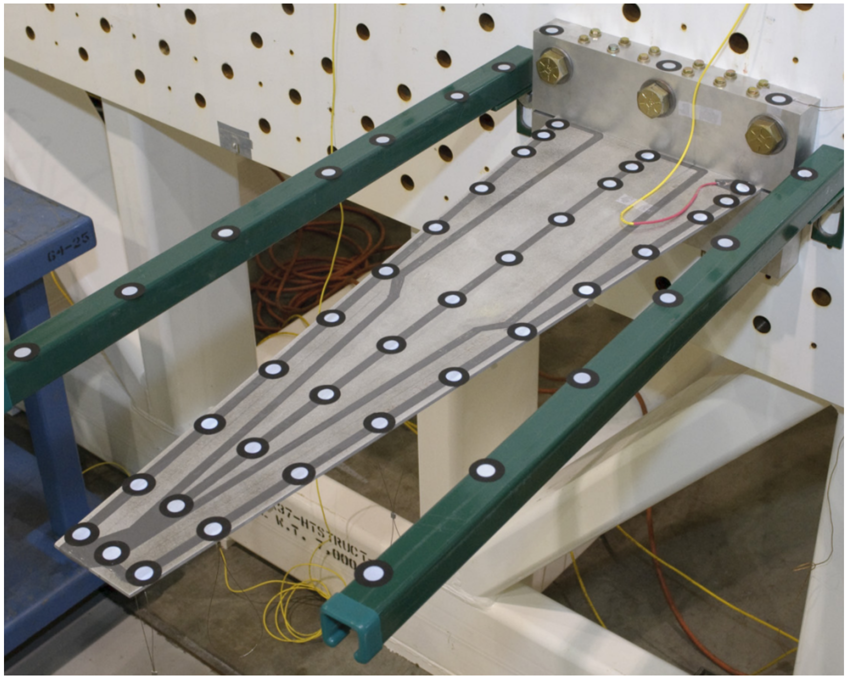
$$y_0 = \tan\theta_0 = 0$$

# Deflection Results

Swept Plate Test Article



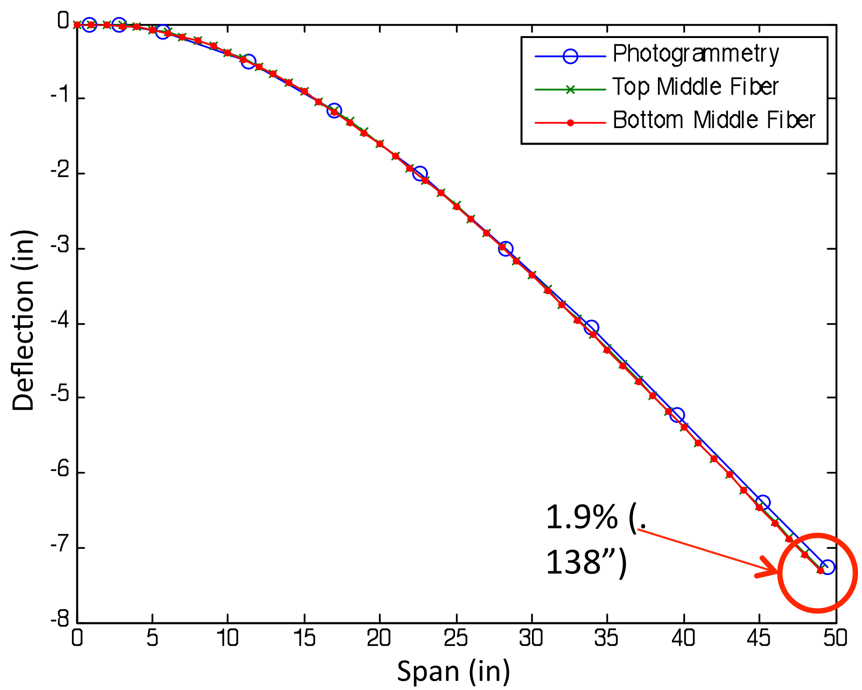

Tapered Plate Test Article



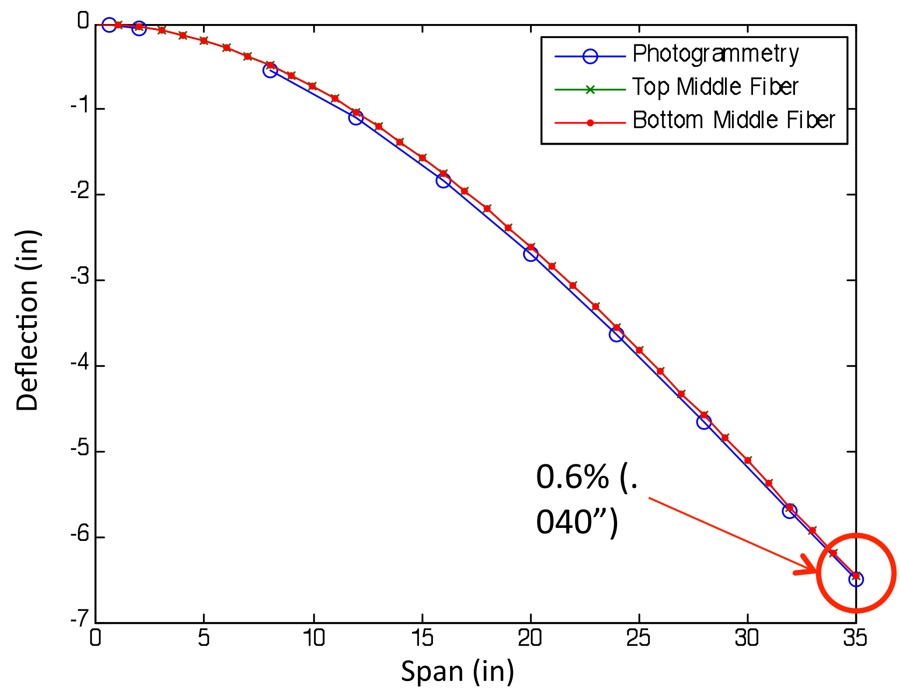
# Uniform Load Case Results

- Equal load applied to each of 12 load points
- Deflection measured along middle fiber

## Swept Plate Test Article




## Tapered Plate Test Article

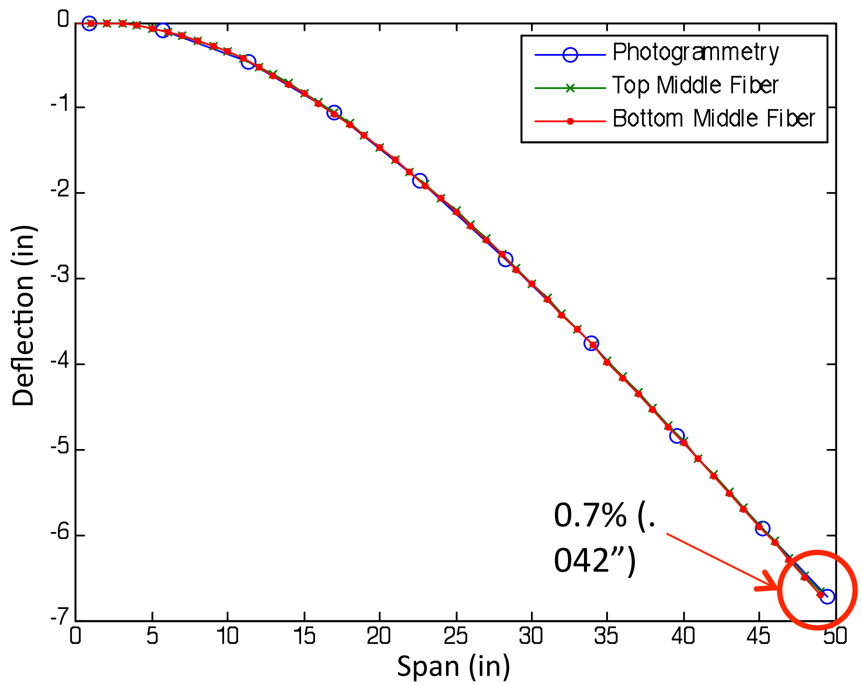



- 1800 microstrain at root
- 1620 microstrain at root

# Trailing Edge Load Case Results

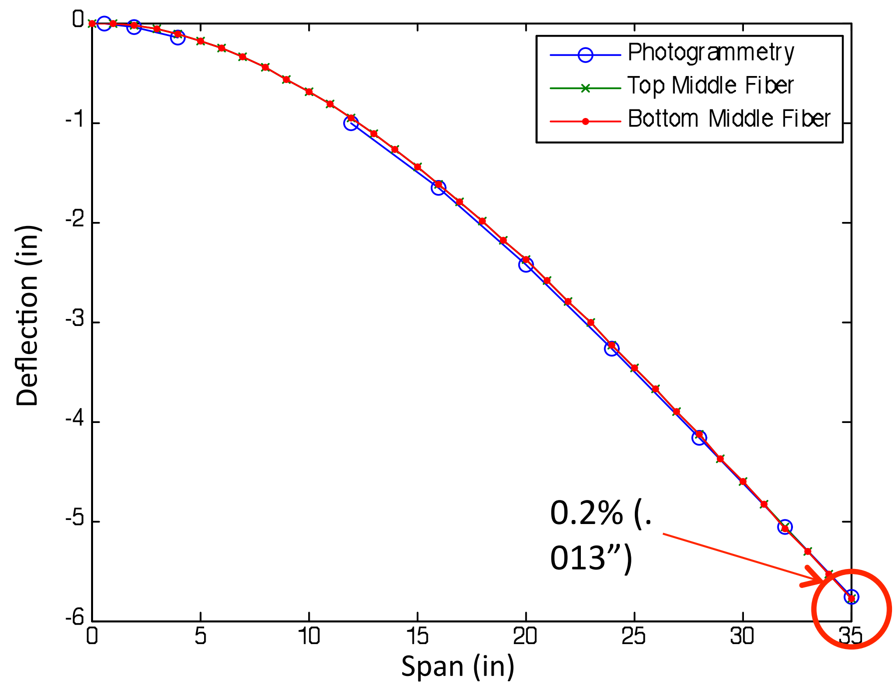
- Load applied to points along trailing edge
- Deflection measured along middle fiber

Swept Plate Test Article




- 1880 microstrain at root

Tapered Plate Test Article




- 1650 microstrain at root

# Angle of Twist

$$\phi = \sin^{-1}\left(\frac{y_{LE} - y_{TE}}{d}\right)$$

- Angle measurement requires difference between two similar deflection values
  - Small error in deflections equates to large error in angle of twist
- Tapered Plate
  - Leading Edge:
    - Calculated: 2.78 degrees
    - Photogrammetry: 1.43 degrees
  - Uniform:
    - Calculated: 1.63 degrees
    - Photogrammetry: 0.25 degrees

# Load Calculation

# Load Calculation Process

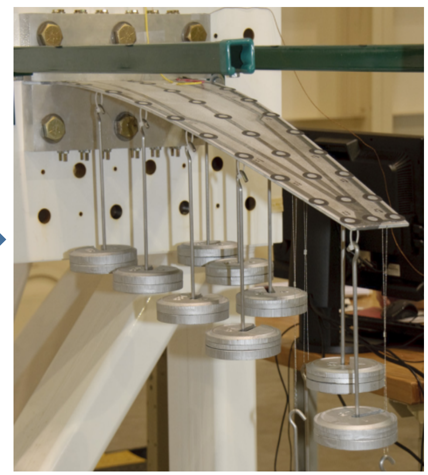
- Bending moment calculated at each analysis station
- Cross-sectional properties calculated by applying known load
  - EI/c term backed out at each evaluation station
- With properties known, strain can be directly related to bending moment

Known moment

Measure strains

$$\frac{M}{\varepsilon} = \left(\frac{EI}{c}\right)$$

Get properties at each station



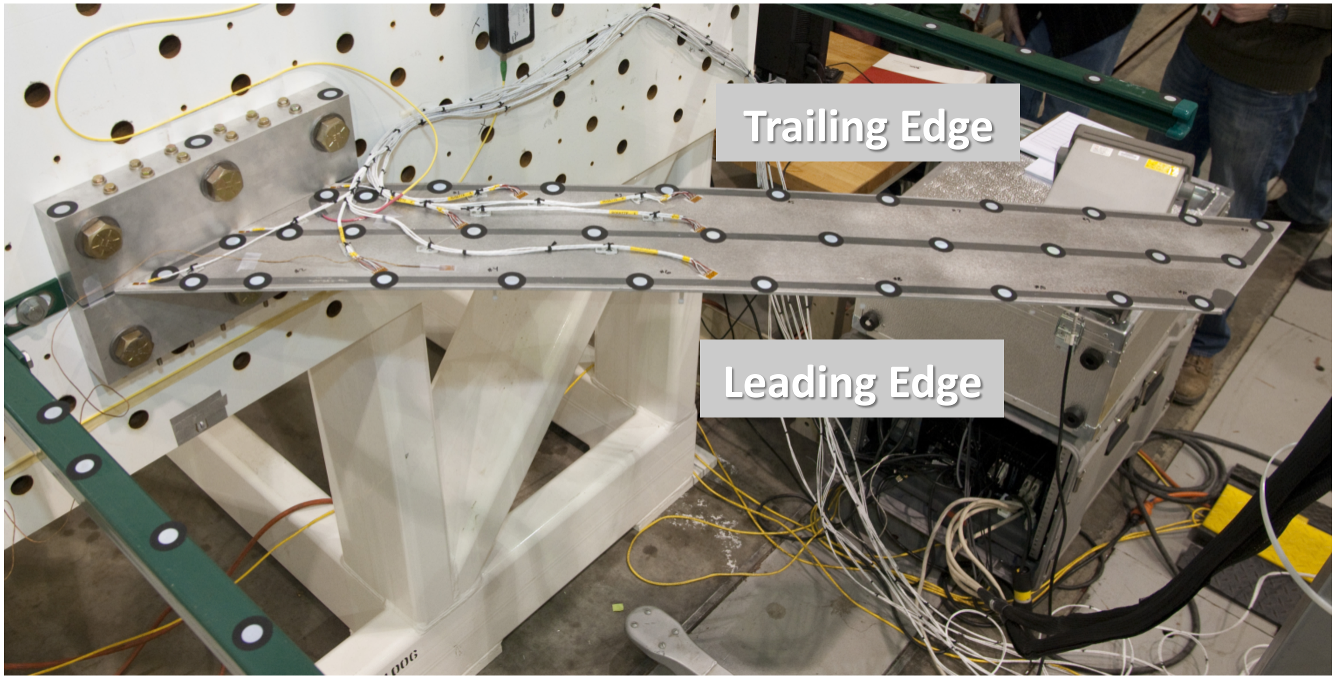
Unknown moment

Measure strains

$$\left(\frac{EI}{c}\right) \cdot \varepsilon = M$$

**Calculate moment** at each station

# Swept Plate Load Results

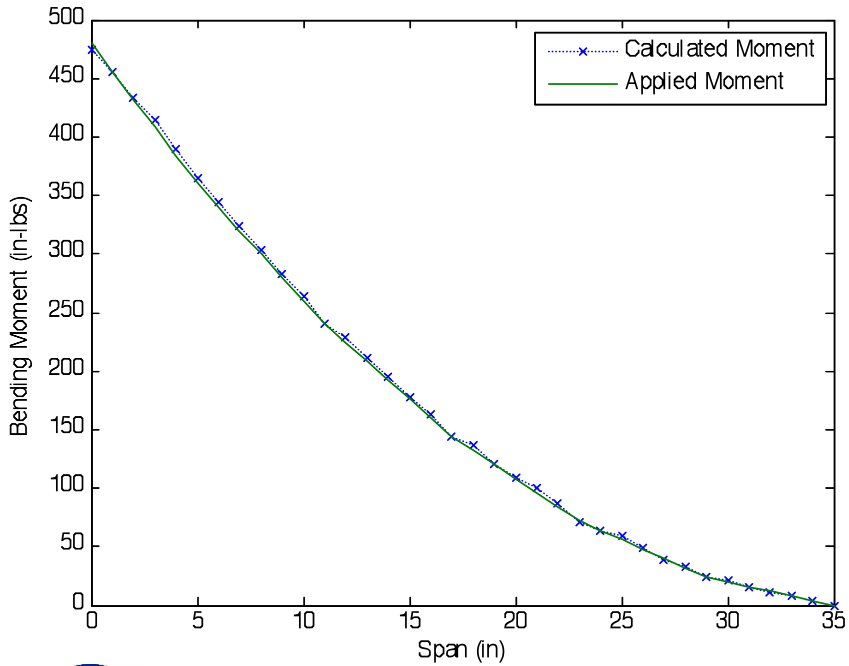


# Swept Plate Load

## Cross-sectional properties calculated using ‘Uniform A’ load case

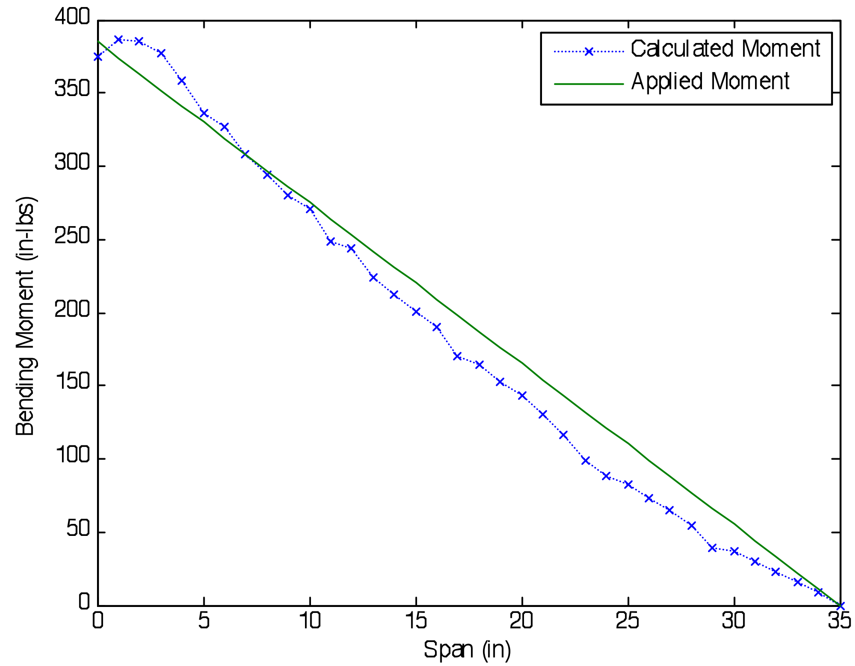
**Uniform B Load Case**

$$M = \left(\frac{EI}{c}\right)_{UniformA} \cdot \varepsilon_{UniformB}$$




**Single Point Load Case**

$$M = \left(\frac{EI}{c}\right)_{UniformA} \cdot \varepsilon_{SinglePt}$$

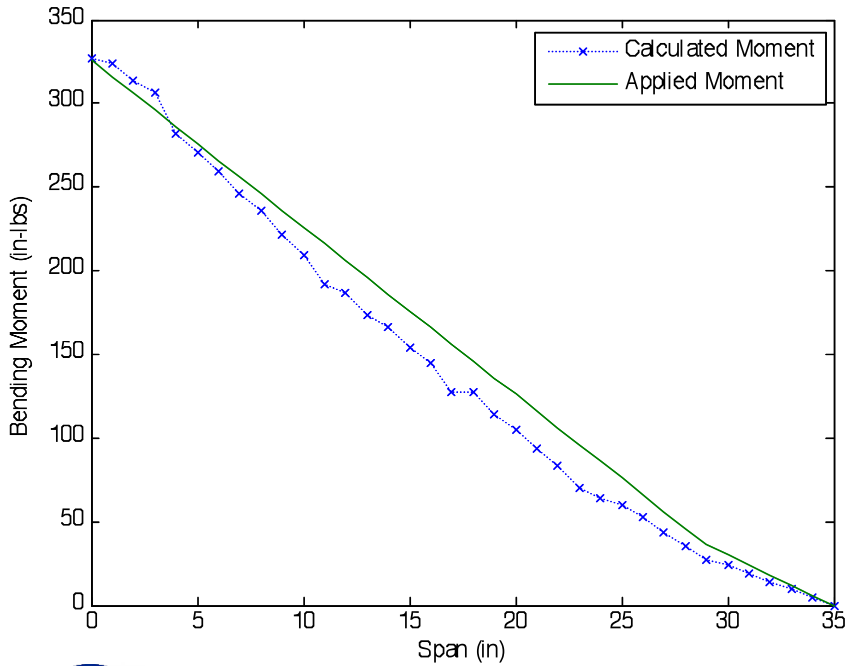


# Swept Plate Load (cont.)

Cross-sectional properties calculated using ‘Uniform A’ load case

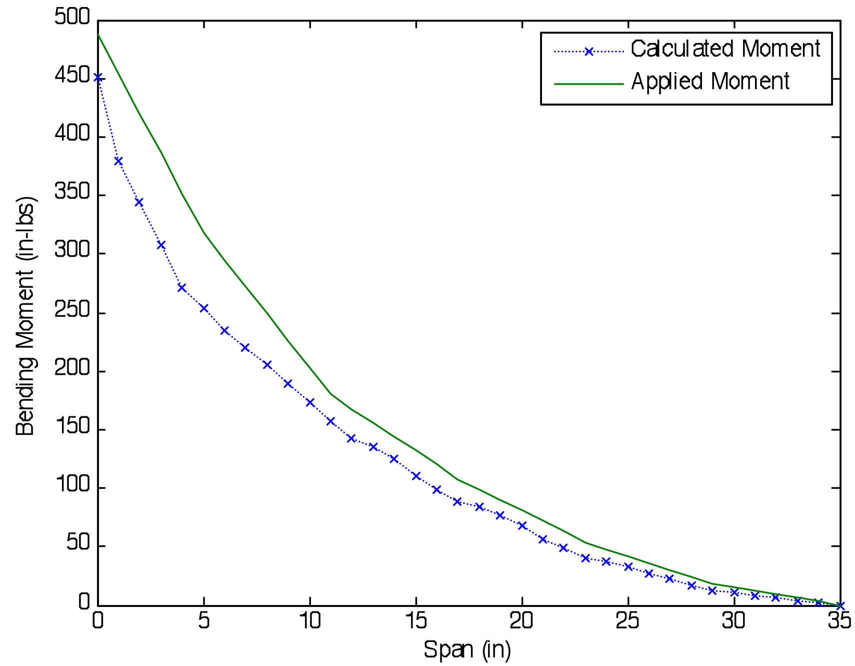
**Tip-Biased Load Case**

$$M = \left(\frac{EI}{c}\right)_{UniformA} \cdot \varepsilon_{TipBiased}$$




**Leading Edge Load Case**

$$M = \left(\frac{EI}{c}\right)_{UniformA} \cdot \varepsilon_{LeadingEdge}$$



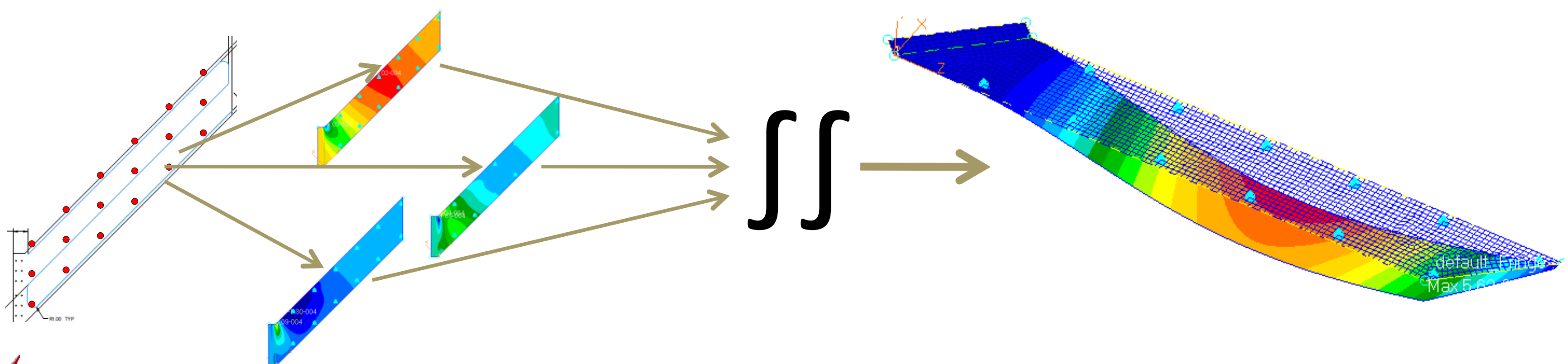
# Shape and Load Calculation Conclusions

- Deflection calculations are accurate (within ~5%)
  - Different test articles
  - Different load cases
  - Different load magnitudes
- Load results will be improved
  - Least-squares method
- Developing methods to further use FOSS measurements
  - Angle-of-twist
  - Improved deflection and load
  - Torque

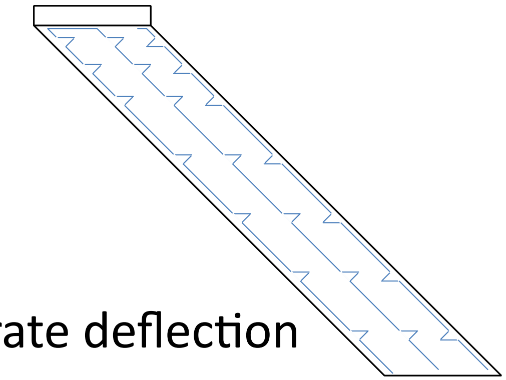
# Shape Measurement – Future Testing

- Working to create new method for determining **wing twist**
  - New fiber routing being explored
  - Measure entire strain state ($\varepsilon_{xx}$, $\varepsilon_{yy}$, and $\gamma_{xy}$)


  - Map/spline strain components to get strain fields over test article
  - Integrate to determine deflections

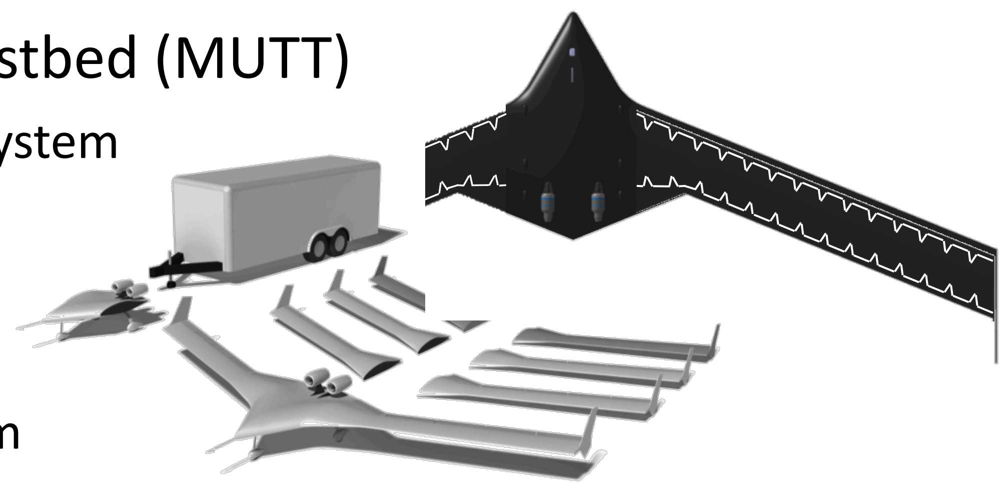


# Future Testing (continued)



- Fiber routing ground tests
  - Will test new fiber routing methods
  - Aimed at twist measurement and more accurate deflection
  - More complex load cases
- NASA F/A-18 N853
  - Fiber will be installed on wings
  - Ground tests will be performed
  - FOSS data will be sent through control system and telemetered

- Multi-Utility Technology Testbed (MUTT)
  - Unique opportunity to use system
    - Ground tests
    - Flight tests
  - Very flexible wings
  - Versatile flight control system



# Questions?