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Validation Tests of Fiber Optic Strain-Based Operational Shape and Load Measurements

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Overview

- Motivation
- Strain-based measurements
  - Transfer functions
  - Fiber optic strain sensing
- Validation tests
  - Set-up
  - Execution
  - Results
- Conclusions

Motivation for Strain-Based Measurements

- Reduce structural weight
  - Benefits include:
    - Improved fuel efficiency
    - Increased performance
    - Reduced cost
  - Reduced weight leads to more flexible structures
    - Can be mitigated by intelligent sensing and control
- Strain-based structural measurements
  - Use strain measurements to determine global structural conditions
    - Shape (deflection and twist)
    - External loads
  - Many other applications (non-aerospace)
    - Maritime vessels
    - Civil structures
    - Biomedical devices

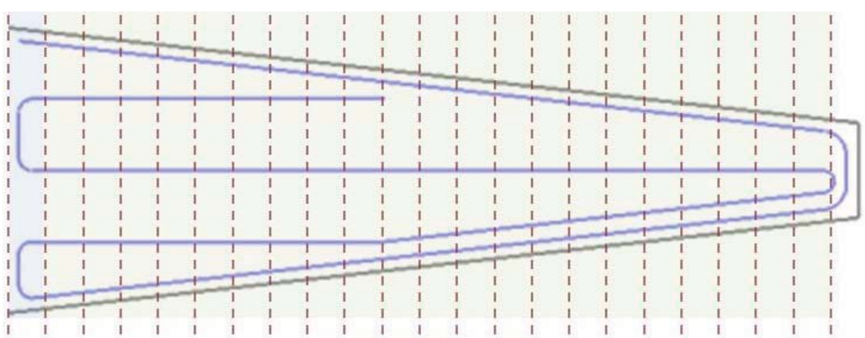
Method

Strain-based measurement has two parts:

- Strain transfer functions
  - Physics-based transfer functions have unique benefits
    - Deflection Transfer Functions (DTF)
    - Load Transfer Functions (LTF)
  - No a-priori knowledge of the structure required
  - Reduced calibration testing
  - Not effected by atmospheric conditions
- Strain measurement
  - Fiber optic strain sensing opens new possibilities
    - Dryden's Fiber Optic Strain Sensing (FOSS) technology
  - Lightweight and unobtrusive sensor
  - Distributed parameters
    - Conventional strain bridges render data only at specific span stations

Determination of Wing Deflection

- Formulated by integrating the curvature equation for deformed beam elastic curve
  - Structure divided into analysis domains
  - Strain described by a linear function in each domain
  - Curvature equation integrated to yield slope and deflection equations



Deflection of a Fiber:

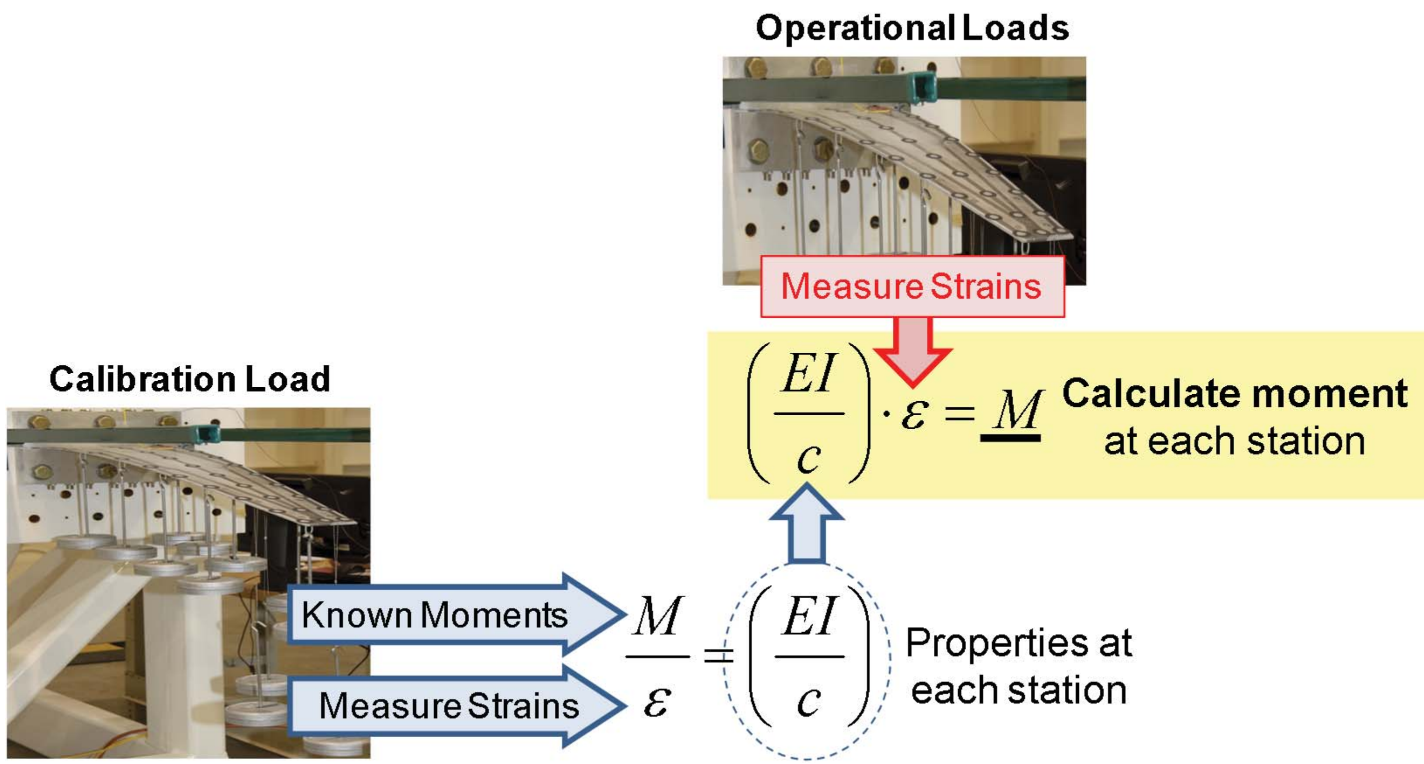
$$y_i = \frac{(\Delta l)_i^2}{6c_{i-1}}\left[\left(3 - \frac{c_i}{c_{i-1}}\right)\varepsilon_{i-1} + \varepsilon_i\right] + y_{i-1} + (\Delta l)_i \tan\theta_{i-1}$$

Slope:

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

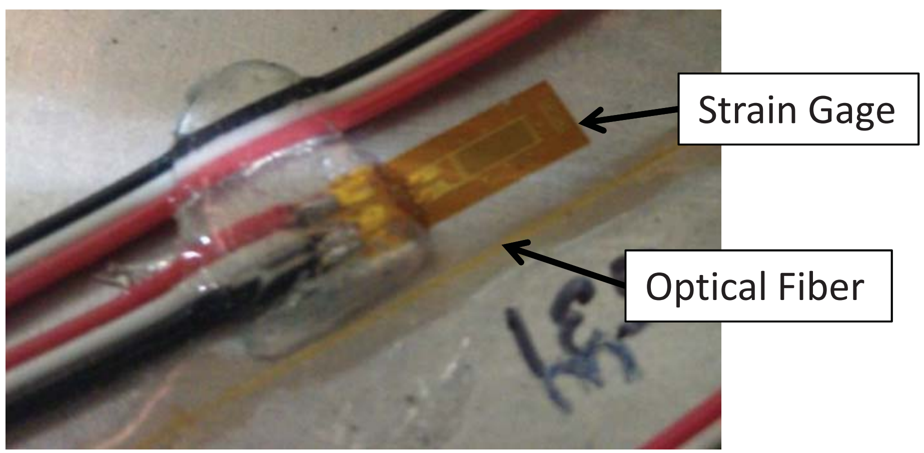
Load Calculation Process

- 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



Fiber Optic Strain Sensing (FOSS)

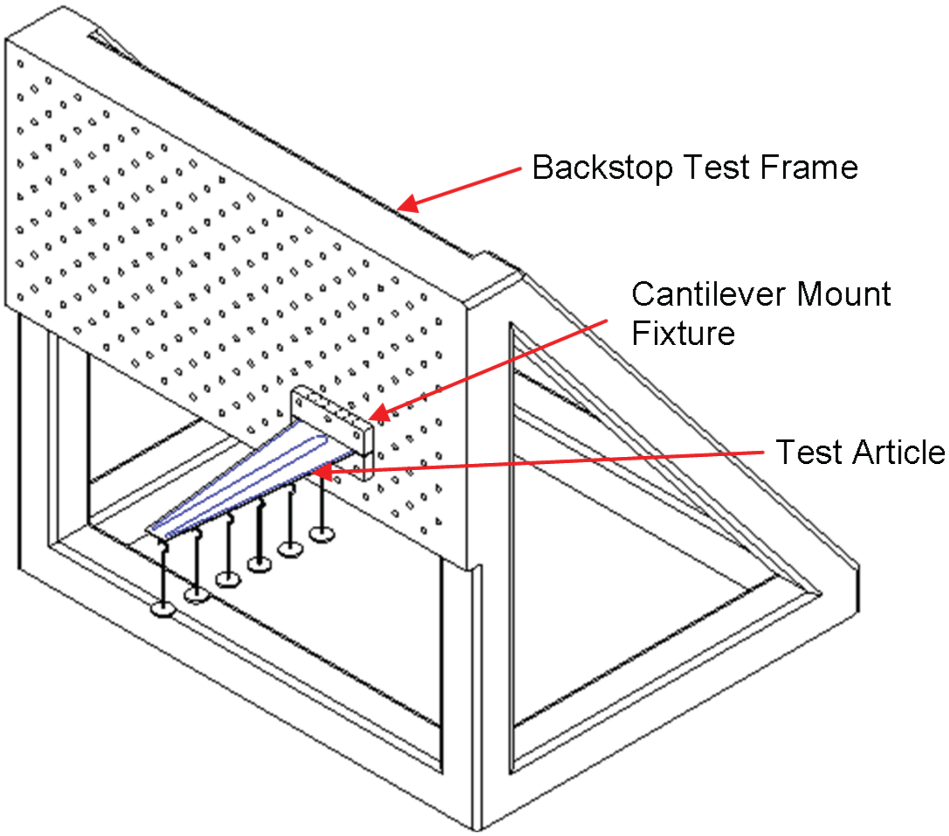
- FOSS allows nearly continuous strain measurements along a fiber
  - Measurements every half inch
  - Hundreds of measurements per channel
  - Flight-capable system
- FOSS offers several notable advantages to foil strain gages:
  - Lightweight sensor package (no copper leadwires)
  - Immune to EMI/radio-frequency interference and radiation
  - Fibers can be embedded within a composite part



Need for Validation Tests

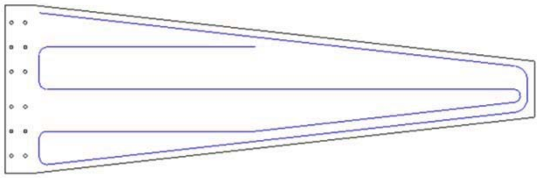
- Deflection and load equations had been analytically verified
  – Questions remained about practical implementation
- The capability is desired in order to improve aircraft design
  – Real-time shape and load measurement during flight enable:
    - Efficient, lightweight design
    - Maneuver/gust load alleviation
    - Structural feedback to control system
    - Structural health monitoring and damage detection
  – Benefits across speed regimes
- Validation tests a stepping stone to aircraft implementation

Validation Test Setup

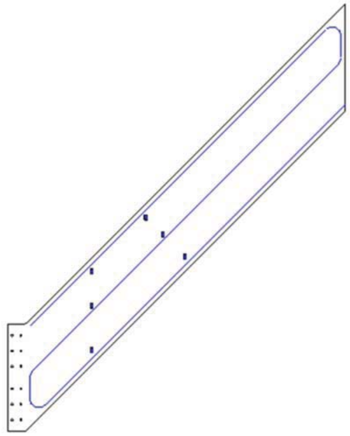


- 4 Interchangeable Test Articles
  - Planform shapes of wings
  - 6061 Aluminum plate (.190” thick)

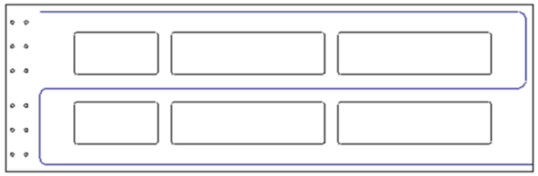
Rectangular Plate Test Article



Tapered Plate Test Article



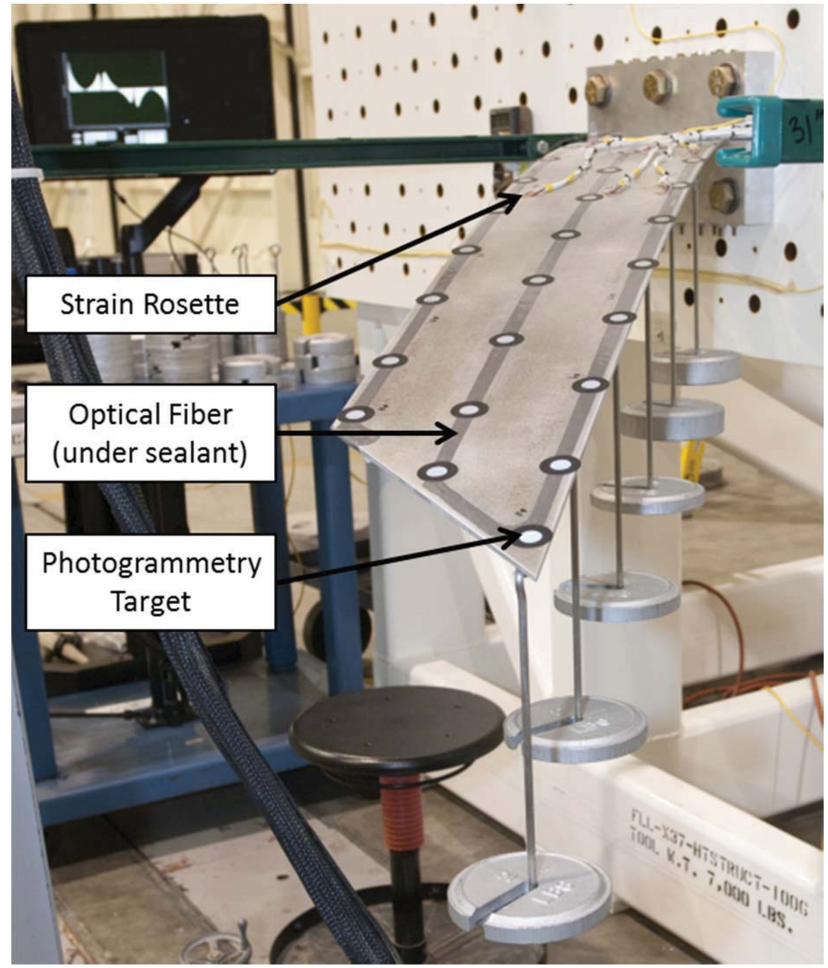
Swept Plate Test Article



Open Plate Test Article

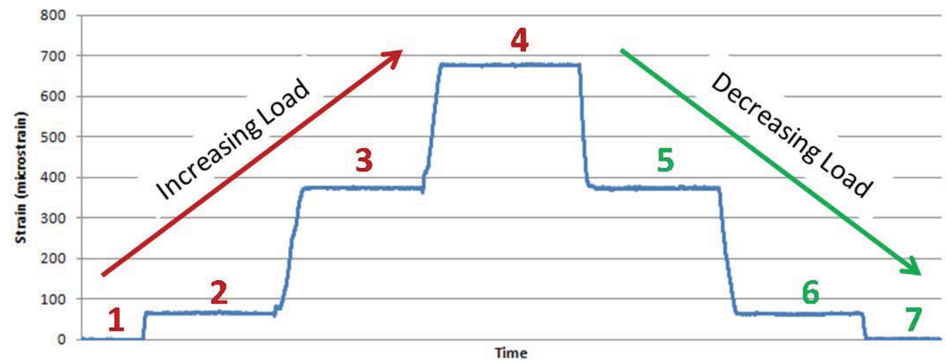
Summary of Tests

- 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



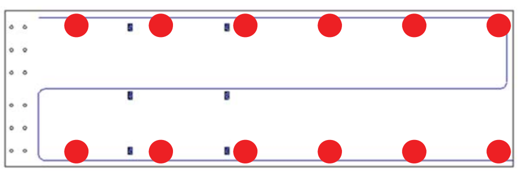
Load Cases

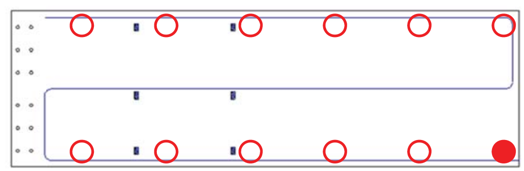
- 12 load points
  - All loads applied downward (gravity)
- Each load case broken into 7 load steps

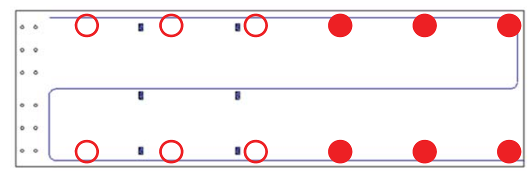


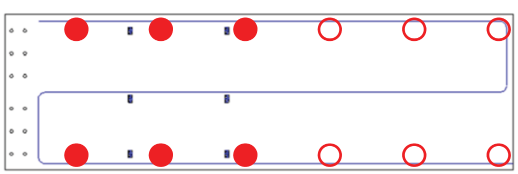
Load Steps

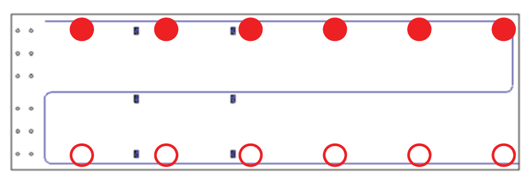
Load Cases

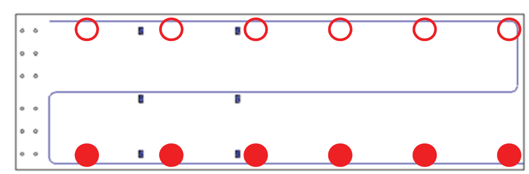

Uniform Load Case


Single Point Load Case


Tip-Biased Load Case


Root-Biased Load Case

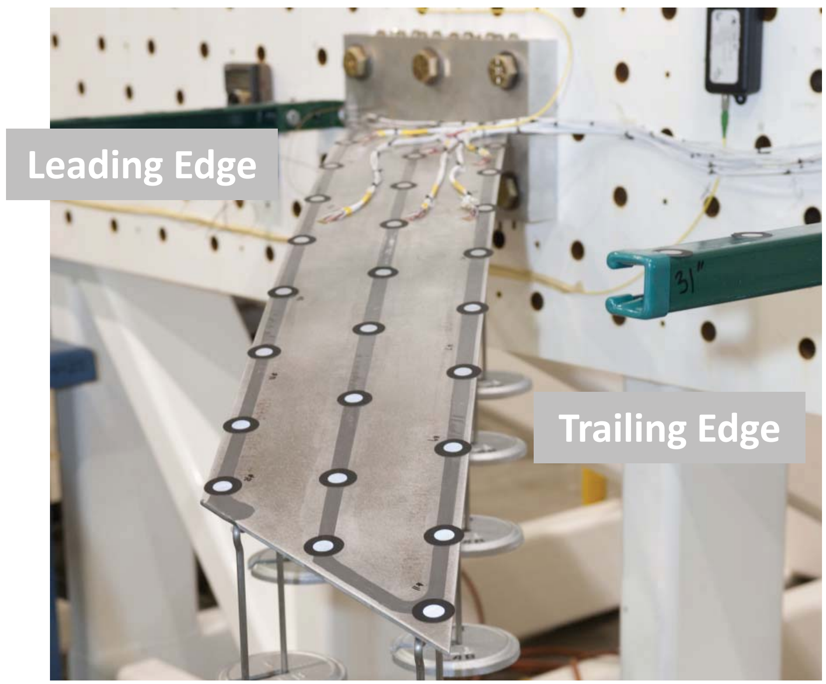

Leading Edge Load Case

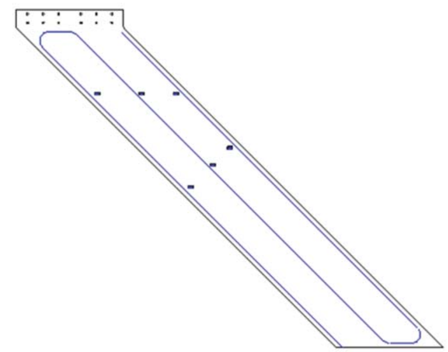

Trailing Edge Load Case

Testing – Deflection Results

- Results from the Swept Plate test article will be shown
  - Most interesting of the test articles
  - The other test articles, in general, were more accurate

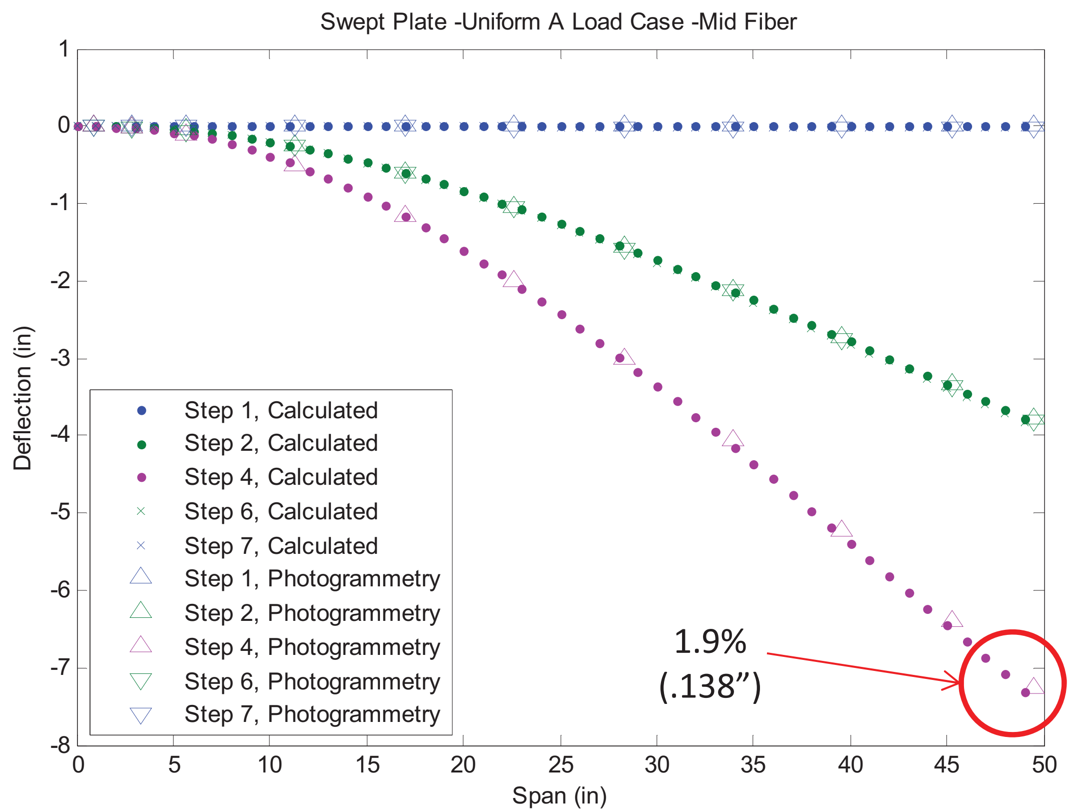
Swept Plate Test Article





Uniform Load Case Results

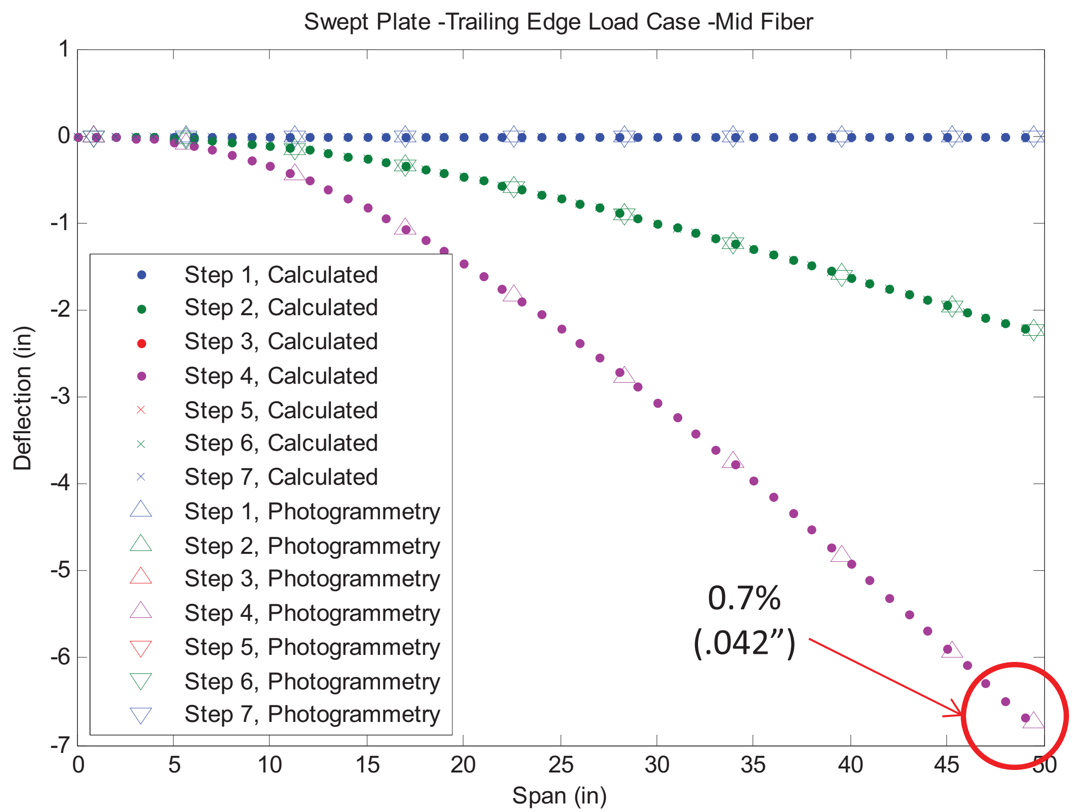
- Equal load applied to each of 12 load points
- Deflection measured along middle fiber



- 1800 microstrain at root

Trailing Edge Load Case Results

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



- 1880 microstrain at root

Deflection Results Summary

- Results were quite accurate
  - Less than 4% error was typical
- Trailing edge fiber consistently had greater error (Swept Plate)
  - Not seen in any of the other test articles
  - Thought to be caused by change in principle direction at root

	Swept Plate Deflection at Wingtip											
	Trailing Edge				Middle				Leading Edge			
Load Case	Calc (in)	Ref (in)	Ref - Calc (in)	*Error (%)*	Calc (in)	Ref (in)	Ref - Calc (in)	*Error (%)*	Calc (in)	Ref (in)	Ref - Calc (in)	*Error (%)*
Uniform A	-7.361	-7.661	-0.300	*3.9*	-7.088	-6.953	0.134	*-1.9*	-6.229	-6.233	-0.005	*0.1*
Uniform B	-7.361	-7.655	-0.294	*3.8*	-6.981	-6.944	0.037	*-0.5*	-6.172	-6.219	-0.046	*0.7*
Uniform C	-7.358	-7.658	-0.300	*3.9*	-7.082	-6.949	0.132	*-1.9*	-6.244	-6.225	0.019	*-0.3*
Single Point	-8.601	-8.669	-0.068	*0.8*	-7.876	-7.695	0.180	*-2.3*	-6.747	-6.711	0.036	*-0.5*
Tip Biased	-6.409	-6.576	-0.167	*2.5*	-6.034	-5.925	0.110	*-1.9*	-5.259	-5.255	0.004	*-0.1*
Root Biased	-2.059	-2.310	-0.251	*10.9*	-2.167	-2.145	0.022	*-1.0*	-1.919	-1.976	-0.057	*2.9*
Leading Edge	-4.868	-5.096	-0.228	4.5	-4.745	-4.714	0.031	-0.7	-4.294	-4.320	-0.026	0.6
Trailing Edge	-6.877	-7.189	-0.312	4.3	-6.481	-6.447	0.034	-0.5	-5.635	-5.688	-0.052	0.9

Calc: Calculated value, using DTF and FOSS Strain

Ref: Reference value, using photogrammetry data

Ref-Calc: Difference between reference and calculated

Error: (Ref-Calc)/Ref

Angle of Twist

$$\phi = \sin^{-1}\left(\frac{y_{LeadingEdge} - y_{TrailingEdge}}{\Delta_{Chord}}\right)$$

- Angle calculated using leading and trailing edge deflections
  - Difference between two similar deflection values
  - Small error in deflections equates to large error in angle of twist

Swept Plate Twist at Wingtip (degrees)

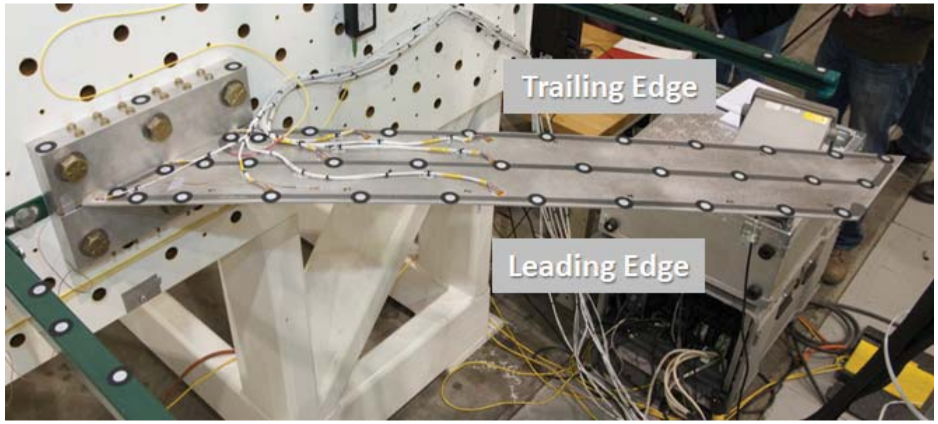
Load Case	Calc	Ref	*Ref - Calc*	
Uniform A	-5.91	-7.47	*-1.56*	-21%
Uniform B	-6.20	-7.51	*-1.31*	-17%
Uniform C	-5.82	-7.50	*-1.69*	-23%
Single Point	-9.71	-10.32	*-0.62*	-6%
Tip Biased	-6.00	-6.91	*-0.91*	-13%
Root Biased	-0.73	-1.74	*-1.01*	-58%
Leading Edge	-2.99	-4.04	*-1.04*	-26%
Trailing Edge	-6.48	-7.85	*-1.37*	-17%

Calc: Calculated value, using DTF and FOSS Strain

Ref: Reference value, using photogrammetry data

Ref-Calc: Difference between reference and calculated

Load Transfer Function Results

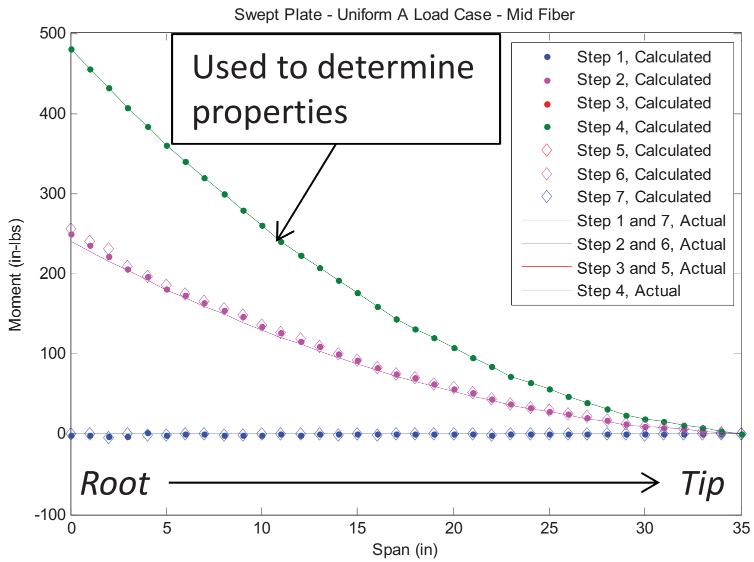


- Cross-sectional properties resolved at each analysis domain
  - Uniform A (step 4) used
  - Determined at middle fiber
  - Values remained fixed throughout the analysis
- Strain values from subsequent load cased applied to analysis

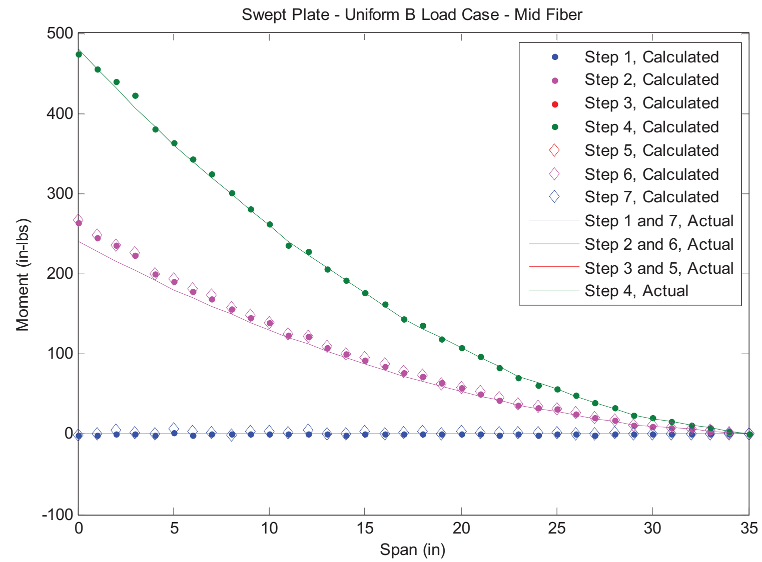
$$M_{LoadCase} = \left(\frac{EI}{c}\right)_{UniformA} \cdot \varepsilon_{LoadCase}$$

Load Transfer Function Results (cont.)

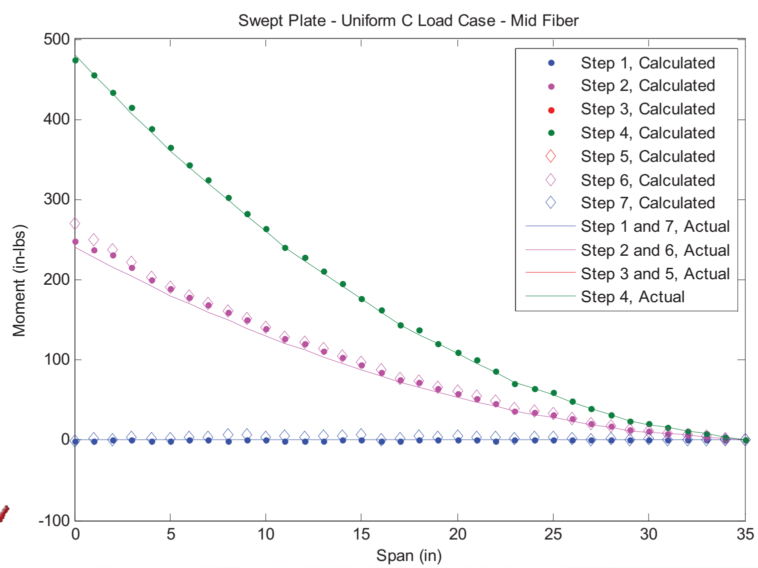
Uniform A



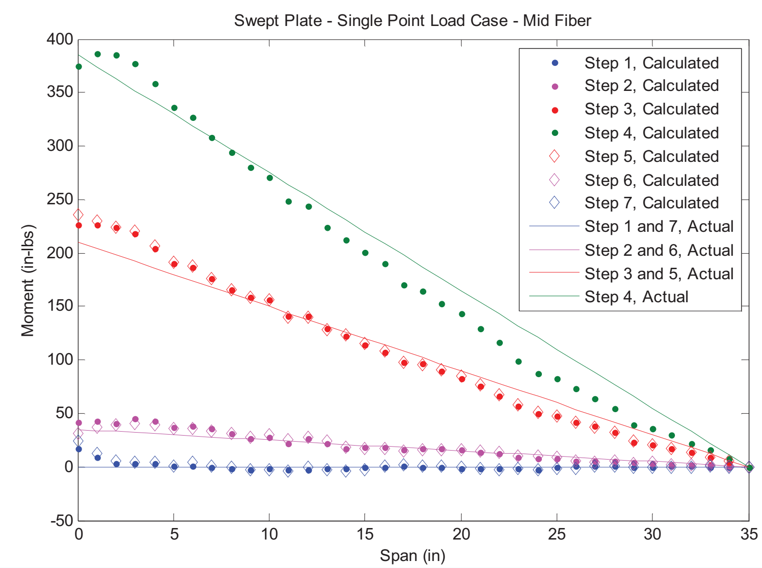
Uniform B



Uniform C

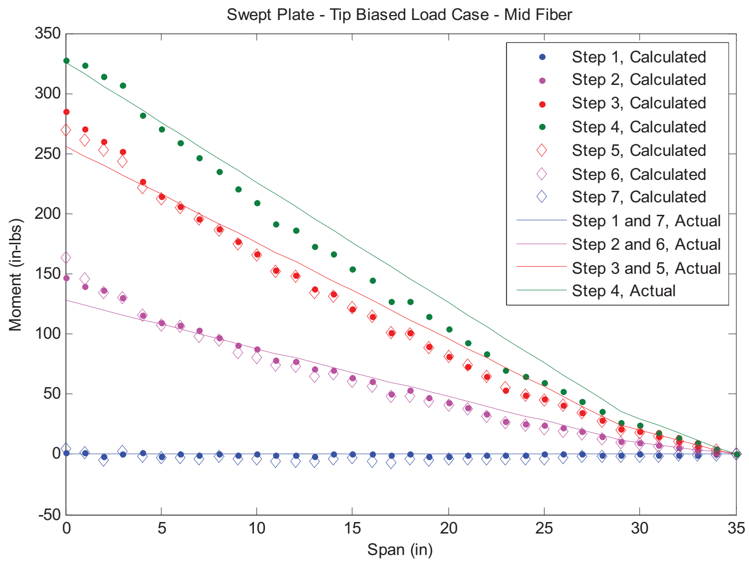


Single Point

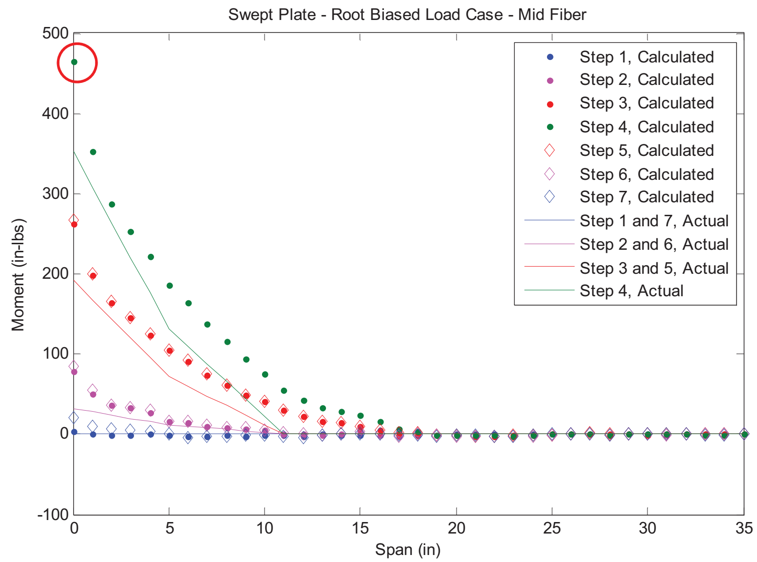


Load Transfer Function Results (cont.)

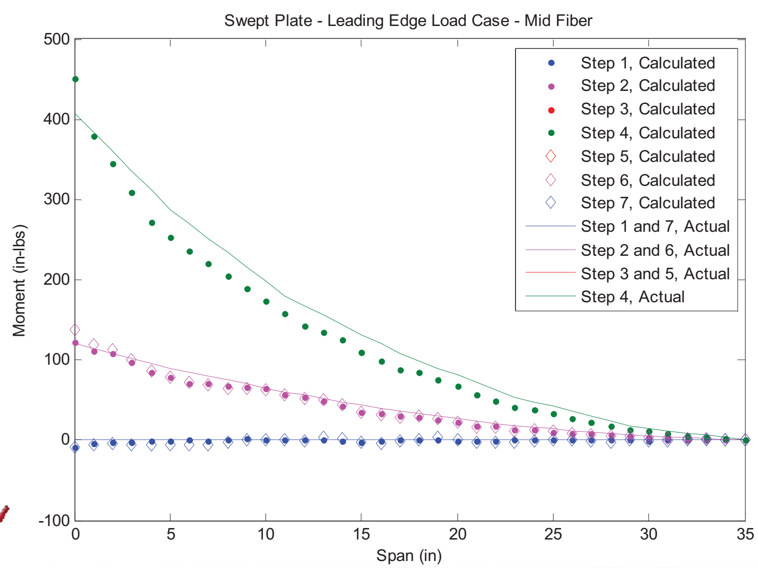
Tip Biased



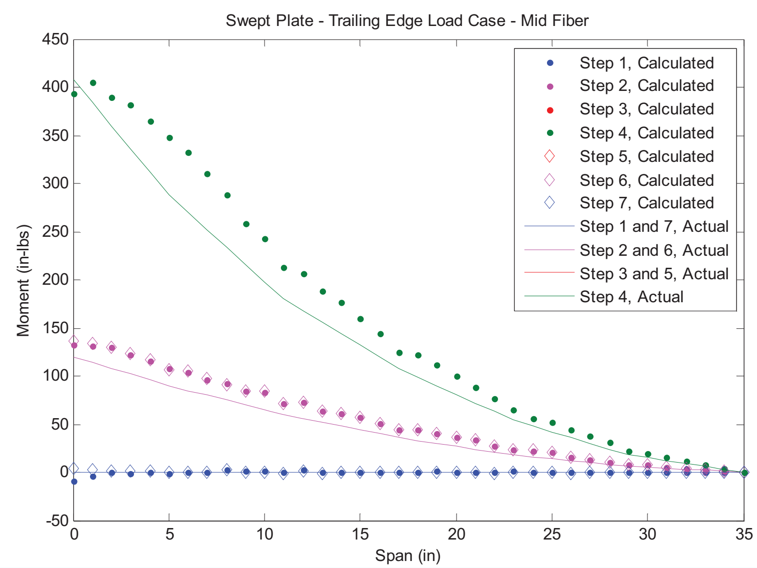
Root Biased



Leading Edge



Trailing Edge



Load Transfer Function Results Summary

- Results are encouraging
  - A single calibration load yielded good results for *most* load cases
    - Loads similar in distribution to calibration load were measured well
    - The root biased load had a notably different distribution
      - Least accurate measurements
      - Difference in load distribution apparent

Swept Plate Bending Moment at Root (in-lbs)				
Load Case	**Calc**	**Ref**	**Ref - Calc**	***Error (%)***
Uniform A	480.0	480.0	0.0	*0.0*
Uniform B	474.0	480.0	6.0	*1.2*
Uniform C	474.9	480.0	5.1	*1.1*
Single Point	374.5	385.0	10.5	*2.7*
Tip Biased	327.4	326.0	-1.4	*-0.4*
Root Biased	465.1	352.0	-113.1	*-32.1*
Leading Edge	451.0	408.0	-43.0	*-10.5*
Trailing Edge	393.0	408.0	15.0	*3.7*

Calc: Calculated value, using LTF and FOSS Strain

Ref: Actual value

Ref-Calc: Difference between reference and calculated

Error: (Ref-Calc)/Ref

Sensitivity

- A sensitivity analysis was performed to determine how measurement errors effect results
  - Deflection
    - Change due to possible error in strain values: 2%
    - Change due to possible error in thickness: 8%
    - Change in reference due to photogrammetry error: 0.2%
  - Twist
    - Change due to 2% error in deflection values: 49%
  - Load
    - Change due to error in strain & calibrated load values: 7%

Shape and Load Calculation Conclusions

- DTF deflection calculations are accurate (within ~4%)
  - Different test articles
  - Different load cases
  - Different load magnitudes
- Twist calculations had undesirably high error
  - Highly sensitive to small error in deflection measurement
- LTF load calculations were encouraging
  - Single calibration load used
  - Most useful when operation load distributions are understood
    - Could be factored into calibration load
  - May be possible to improve cross-sectional property estimates
- Investigating opportunities to further demonstrate the capability in flight

Questions?