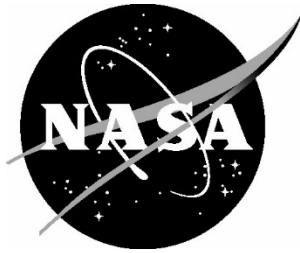


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Mock Truss-Braced Wing Loads Calibration Research Utilizing Fiber-Optic Sensors

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September 2024

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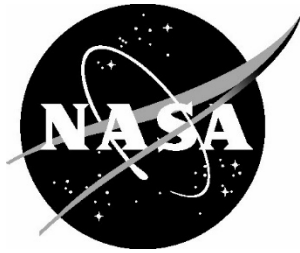
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Abstract

In support of the National Aeronautics and Space Administration Advanced Air Transonic Transport Truss-Braced Wing structural research, the Armstrong Flight Research Center Flight Loads Laboratory is performing pathfinder tests on a small, scaled test article (dubbed the mock Truss-Braced Wing) to study the application of a loads calibration on a truss-braced wing structure. The addition of a truss to the wing structure, as opposed to a purely cantilever beam setup, changes the strain-gage-based loads calibration techniques. In a truss-braced configuration, the internal shear and moments, inboard of the truss-wing connection, are not directly representative of the external aerodynamic loading as is the case for a traditional cantilever configuration. A 3-axis load cell was used at the wing-to-strut interface to estimate the load sharing between the two structural members. Crosstalk within the 3-axis load cell is added to the measurement uncertainties of the calibration effort, and the results, including crosstalk uncertainties, are presented. The calibration tests presented in this report are used as a pathfinder for developing an understanding how to perform loads calibration on a truss-braced wing structural configuration. The use of distributed fiber-optic strain sensors is leveraged to provide a near-full-span strain profile along the leading and trailing edge of the wing structure for strain-based loads calibration.

Nomenclature

AATT	Advanced Air Transonic Transport
AFRC	Armstrong Flight Research Center
CG	center of gravity
DTF	Displacement Transfer Function
FBG	fiber Bragg grating
FOSS	Fiber Optic Sensing System
OLEA	Operational Loads Estimation Algorithm
STA	wing structure station
tan	tangent
TRS	truss structure station
TBW	Truss-Braced Wing
NASA	National Aeronautics and Space Administration
d	distance, in
E	elastic modulus, $lbf - in^{-2}$
F	Force, lbf
h	distance between parallel optical fiber, in
I	second moment of area, in^4
lc	load cell
L	distance between sensing stations, in
M	bending moment, $in - lbf$
q	line load, $lbf - in^{-1}$
V	shear load, lbf
x	forward and aft in local aircraft coordinate frame, in
y	right and left in local aircraft coordinate frame, in
z	up and down in local aircraft coordinate frame, in

Greek symbols

Δ	difference
ε	normal strain, in/in
θ	wing twist angle, aircraft pitch angle, deg

σ	normal stress, $lbf - in^{-2}$
ϕ	wing slope angle, aircraft roll angle, deg
$\mu\epsilon$	microstrain
Σ	summation

Subscripts

f, a	reference to forward location and aft location
i	reference station indices
LC	reference to load cell reference station indices
M_x, M_z	reference derived from moment about x or z
n	reference number stations
u, l	reference to upper surface and lower surface
x, y, z	reference orthogonal orientations
xm, ym, zm	reference of the measured orthogonal orientations

Introduction

The National Aeronautics and Space Administration (NASA) Advanced Air Transonic Transport (AATT) Program has developed a proof-of-concept scaled model for the Truss-Braced Wing (TBW). The TBW consists of high-aspect-ratio swept wings with an incident truss supported by the fuselage. The performance of such a TBW aircraft is being investigated by NASA by studying the potential aerodynamic efficiency and structural concept of the aircraft. Multiple wind-tunnel tests have been performed by NASA (ref. 1), as shown in fig. 1. Using this truss-braced configuration with a high-aspect-ratio swept wing, we believe that significant fuel savings could be achieved while simultaneously reducing emissions.



Figure 1. Truss-Braced Wing wind-tunnel test at NASA Langley Research Center (Hampton, Virginia).

It is imperative that test facilities engaged in structural testing enhance their abilities to conduct both instrumentation and loads testing of future wing concepts. The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) (Edwards, California) has an extensive history of performing loads calibrations on aircraft structures. The standard method for calibrating strain gages on a structure makes use of the Skopinski and Aiken method (ref. 2). The Skopinski and Aiken approach to loads calibration requires a large collection of applied loads and strain-gage data. The typical loads measured on a wing include shear, bending moment, and torque loads about a measurement station on the wing. The procedure requires the collection of applied loads and strain-gage data. The intent is to collect data from multiple load cases that vary the center of pressure on the wing surface.

Aiding to the development of new loads calibration techniques is the application of distributed strain sensing utilizing fiber Bragg gratings. A Fiber Optic Sensing System (FOSS) can be used to interrogate optical fiber with a series (up to 1,000) of distributed fiber Bragg gratings (FBGs) to provide real-time strain data. During structural testing of the wing structure, the FOSS was able to simultaneously, and continuously, interrogate as many as eight 40-ft optical fibers with sensor locations spaced at 0.5-in intervals, providing nearly 8,000 strain sensor readings at a rate of 20 Hz (for more information regarding the FOSS technology and capabilities, see (ref. 3)). During testing of the mock TBW, there were a total of five fibers and approximately 1,500 unique strain sensors.

The FOSS provides 100 times the number of strain measurements at 1/100th the total sensor weight when compared to conventional electrical-resistance strain-gage implementations. The FOSS can operate in stand-alone mode (which is used for flight applications) or in remote-control mode (in which a laptop computer is connected to provide monitoring and control). A centralized software interface combines all functions into a suite of applications to fully utilize the FOSS.

Mock Truss-Braced Wing Description

The test article consists of a high-aspect-ratio rectangular planform with a 72-in half-span. The wing structure planform utilizes Z-shaped beams for forward and aft spars as well as rib stiffeners, and sheet metal for the upper and lower skins. The Z-shaped beams and the upper and lower skins are made of 1/16-in-thick 6061 aluminum. A cross-section view of the mock TBW is shown in fig. 2. The strut structure consists of a ladder truss with square and rectangular tubes that is swept laterally by 10 deg, as shown in fig. 3. The square and rectangular tubes are made of 1/16-in-thick 6061 aluminum. In addition, the truss is incident vertically by 11.7 deg into a swivel eyebolt at 35.8 in from the root, as shown in fig. 4. The mock AATT Truss-Braced Wing test article is mounted on a strongback to ensure the degree of freedom (DOF) at the planform root is as rigid as possible for the test. The framing plate is secured into the strongback with two steel L-beams. The test article was mounted upside down to facilitate hanging loads on the test article to simulate lift, as shown in fig. 5.

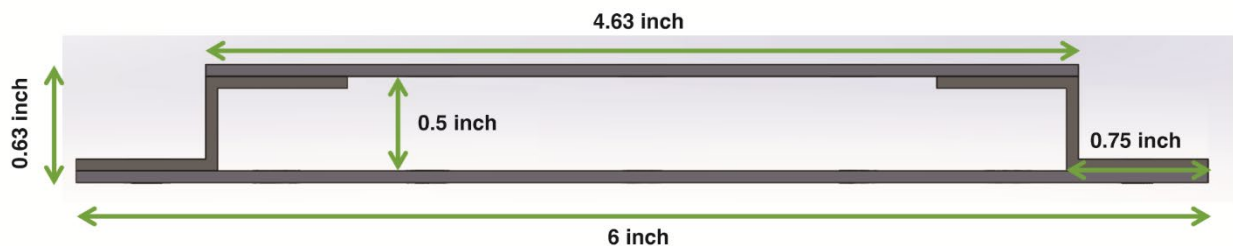


Figure 2. Mock Truss-Braced Wing cross-section view.

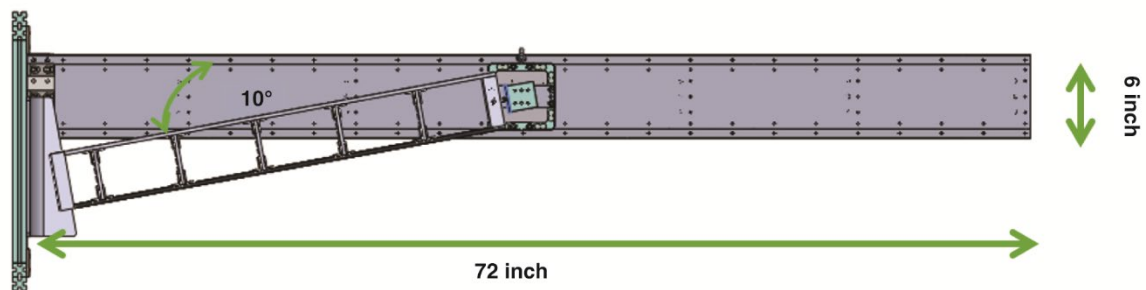


Figure 3. Mock Truss-Braced Wing (top view).

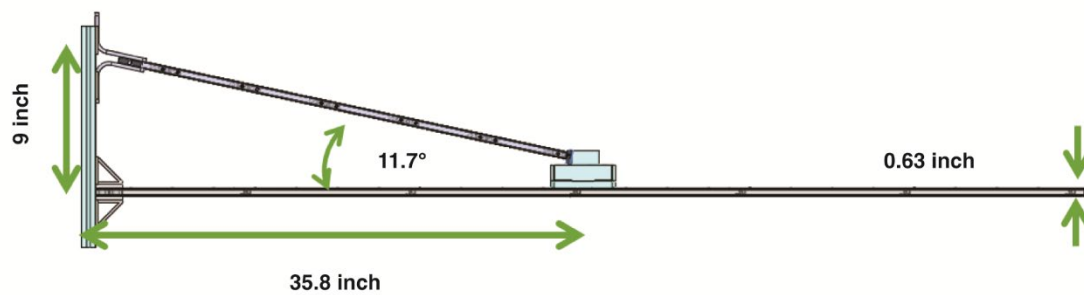


Figure 4. Mock Truss-Braced Wing (side view).



Figure 5. Mock Truss-Braced Wing on strongback.

Load Cases

A total of six load cases were applied during testing of the mock TBW structure, a root-biased load, mid-span-biased load, tip-biased load, uniformly distributed load, elliptical load and a 100-lb wingtip concentrated load. The total applied load over the full test series was limited to 200 lb of applied load for any given load case. Each load case utilized a combination of metallic slotted weights and shot bags. The wing structure was mounted upside down so that gravity would point in the lift direction. A sling system was used to hang the slotted weights underneath the wing structure, with clamps gripping the leading and trailing edge. Shot bags were placed on top of the ladder truss structure to simulate lift from the strut. The load case matrix containing the six applied load cases is shown in fig. 6, and the loading locations are shown in fig. 7. The application of the elliptical loading condition applied to the finite element model of the mock TBW structure is shown in fig. 8, and the remaining figures of the finite element model load cases can be found in Appendix A (figs. A1 to A5). An image of the mock TBW structure under test is shown in fig. 9. The maximum load of each load case was held for approximately 30 s before the loads were removed. All data provided in this report are from the average sensor response during the 30-s hold.

Load case	Amount of weight added											Weight on structure (lbf)
	STA1	TRS2	STA2	TRS3	STA3	TRS4	STA4	STA5	STA6	STA7	STA8	
Root-biased load	40	10	40	10	40	10	50					200
Mid-biased load					20	5	25	25	25			100
Tip-biased load								25	25	25	25	100
Elliptical load	26	4	26	4	24	4	28	26	24	20	14	200
Uniform load	20	5	20	5	20	5	25	25	25	25	25	200
Tip load											100	100

Figure 6. Load case matrix.

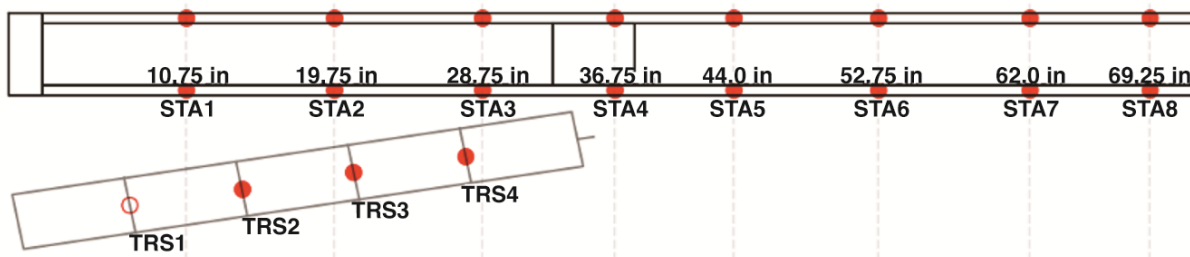


Figure 7. Loading stations.

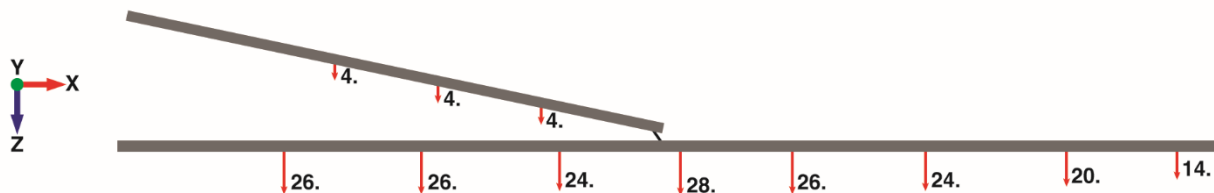


Figure 8. Finite element model of elliptical loading condition.

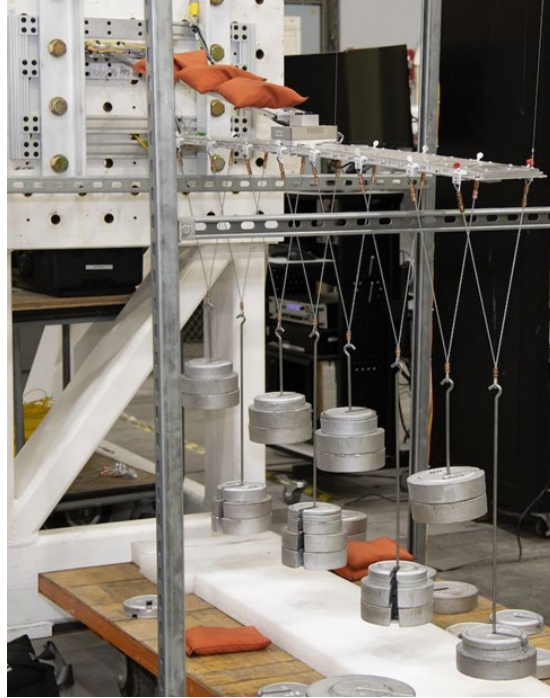


Figure 9. Elliptical loading condition.

Instrumentation

The mock TBW was instrumented with various types of instrumentation to characterize the structural response to applied load. Instrumentation included measurements of strain, displacement, angles, and internal structural load sharing at the wing-to-strut interface. A 3-axis load cell was installed between the main wing and strut interface, with an eyebolt utilized on the strut interface to release all rotational DOF, as shown in fig. 10. Wing displacement measurements were made utilizing string potentiometers at three span stations along the leading edge, outboard the strut. Wing-twist-angle and slope-angle measurements were made using dual-axis inclinometers. Distributed strain measurements were obtained by distributed fiber Bragg gratings (FBGs) and an AFRC in-house-developed Optical Frequency Domain Reflectometry (OFDR) interrogator, referred to as the Fiber Optic Sensing System (FOSS). A typical AFRC-developed FOSS unit can simultaneously and continuously interrogate eight 40-ft optical fibers at 0.5-in intervals, providing nearly 8,000 strain sensor readings per scan at a typical rate of 20 Hz.

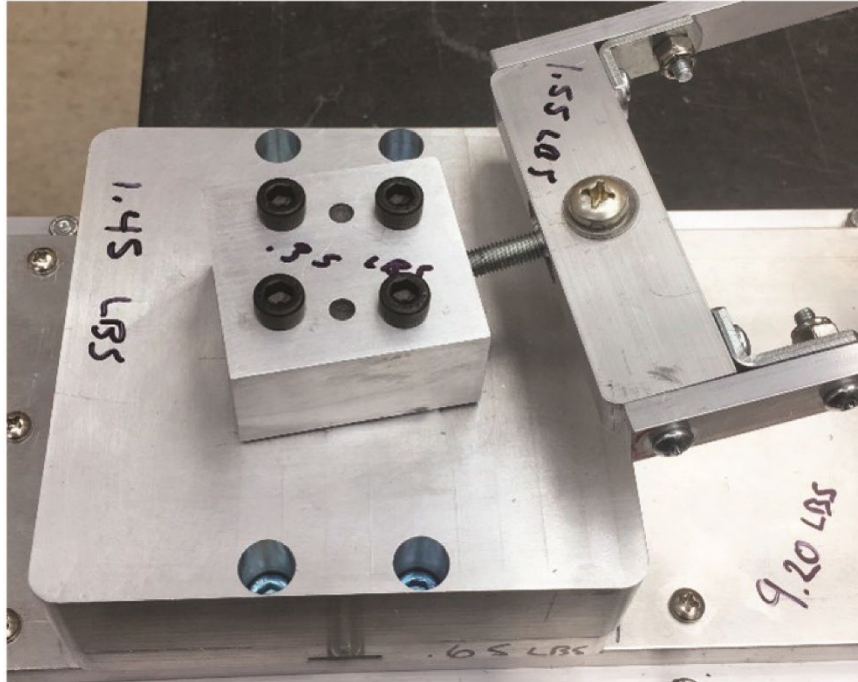


Figure 10. 3-axis load cell (dummy block) connecting wing structure to strut.

The FOSS was utilized as the only strain-sensing instrumentation. A 0.5-in-spaced distributed FBG on each fiber-optic channel was routed along the leading and trailing edge of the wing structure along with ± 45 deg patterns along the upper and lower surface. The FBGs routed in the ± 45 -deg directions are primarily sensitive to torsion. The FBGs routed along the leading and trailing edges are sensitive simultaneously to out-of-plane bending as well as in-plane bending. Due to the mounting of the load cell to the wing structure, the fiber-optic pattern on the lower surface was not continuous along the span but, instead, was split into an inboard and an outboard region. Distributed FBGs were also installed on the top and bottom of the strut structure. Figure 11 shows the FOSS layout pattern on the upper and lower surfaces.

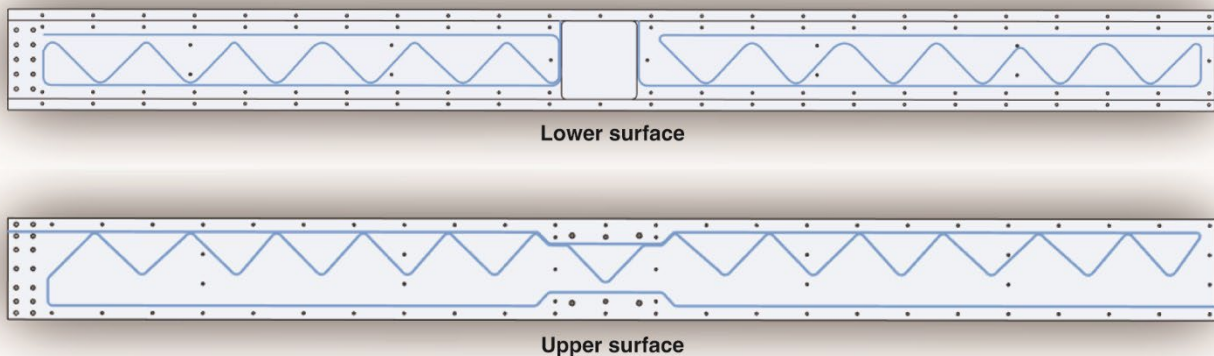


Figure 11. Fiber Optic Sensing System path on the mock Truss-Braced Wing (lower and upper surfaces).

The FOSS was also applied on the strut structure along the center of the forward and aft beam and on the upper and lower surface. Figure 12 shows the FOSS layout pattern on the strut structure.

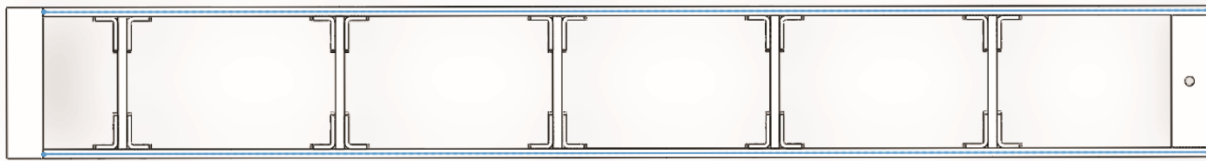


Figure 12. Fiber Optic Sensing System path on the mock Truss-Braced Wing, strut structure.

Operational Loads Estimation Algorithm

The ability to monitor hundreds or thousands of strains has led to the development of shape and load algorithms that leverage new technology. Previous work at AFRC by Dr. William L. Ko, et al. (refs. 4-6) has shown the benefits of using a displacement transfer function to calculate the deformed shape of a wing under external loading. A large-scale load test of the Global Observer wing (AeroVironment, Monrovia, California) validated the shape algorithms (ref. 7). Richards and Ko (refs. 8 and 9) have patented a method for calculating operational loads, but sensor-to-sensor measurement variations can make the method challenging to implement. Validation tests confirming the bending moment calibrations were demonstrated by utilizing distributed fiber-optic sensors and the method proposed by Richards and Ko (ref. 10). The Richards and Ko method relies on taking a numerical derivative of bending moments with respect to span to estimate shear load. Though the equations are mathematically correct, spatial measurement variations make the output less accurate. It is generally advisable to avoid numeric differentiation whenever possible (ref. 11) because small inaccuracies in measurements can produce large errors as the length domain converges to a small distance. An approach by Pak (ref. 12) uses the deformed shape from modal testing to calculate the accelerations and velocities. The modal deformed shapes are then used to estimate the loads on the wing.

This report describes an algorithm developed at AFRC that allows the calculation of shear and bending moment distribution along the wingspan, utilizing distributed strain measurements to compute wing bending shape and loading information. A brief formulation of the algorithm is described herein.

The typical local coordinate frame for an aircraft defines the local X-axis to be aligned forward and aft, and the rotation about the X-axis (referred to as the roll angle) is defined as ϕ . The change in slope of the aircraft wing structure due to structural deformation will also be defined as ϕ . Orthogonal to the local aircraft X-axis and on the horizontal plane of reference is the local aircraft Y-axis that is aligned left and right, and the rotation about the Y-axis is referred to as the pitch angle and is defined as θ . In this report, the change in pitch of the aircraft wing structure will also be referred to as twist angle and will also be defined as θ . The local aircraft Z-axis is aligned vertically in the up and down direction. An illustration of a typical aircraft local coordinate system frame is shown in fig. 13.

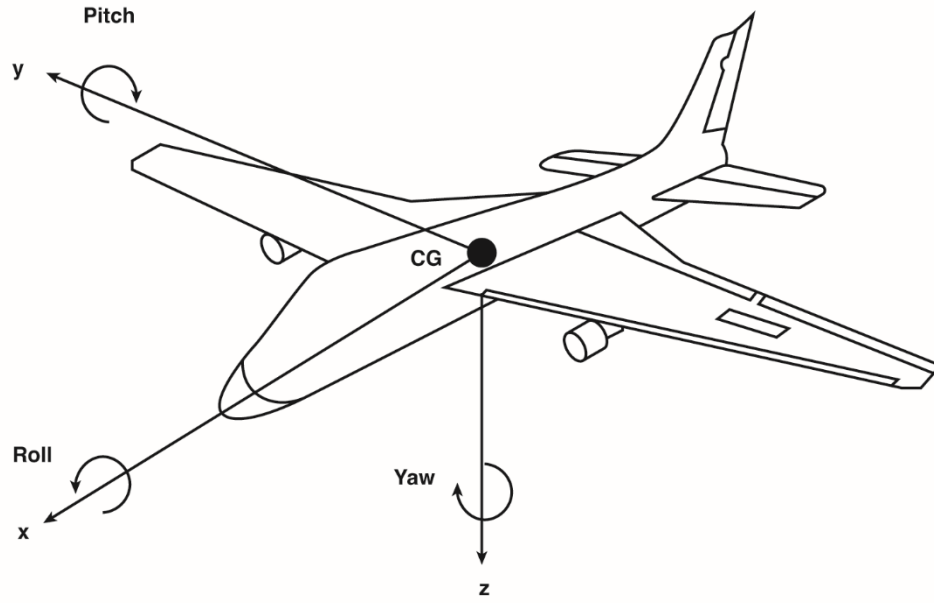


Figure 13. Aircraft local coordinate system frame.

The process of calibrating strain gages to map to bending moments requires determining the cross-sectional properties of this structure and is accomplished via structural testing. A calibration load case is applied to the test article with a known applied load, and the strain response is monitored. All strain measurements throughout this test series are generated from the FOSS. The strain-based load prediction algorithm, also known as the Operational Loads Estimation Algorithm (OLEA), is derived from the Classical Beam Theory (Euler-Bernoulli) for several beam configurations including cantilever beams, which are analogous to the wing spar structure of the aircraft. The Classical Beam Theory can be used to relate the loading of a structure to the theoretical curvature, slope, and deflection of a cantilever beam. The general differential equation that describes the relationship between a line loading function and the resulting shape of a beam is shown as eq. (1) (ref. 11):

$$\frac{d^4 z}{dy^4} = \frac{q}{EI_x} \quad (1)$$

where z is the vertical displacement of a beam as a function of distance from the root; q is the line loading function (load per unit length) analogous to the lift generated by the wing; E is the elastic modulus; and I_x (or I_z) is the second moment of area that is calculated from the centroidal axis perpendicular to the applied loading.

The general differential equation that describes the relationship between vertical shear and the resulting shape of the beam is shown as eq. (2) (ref. 11):

$$\frac{d^3 z}{dy^3} = \frac{V}{EI_x} \quad (2)$$

where the V is the vertical shear along the span of the structure. For cantilevered structures, the vertical shear is the summation of vertical applied load starting with zero load at the wingtip and resulting with maximum total applied load at the root.

For the purposes of implementing the strain-based OLEA, the equation of interest (shown as eq. (3)) is the moment-curvature relationship of the classical beam differential equation that states that the curvature, which is the second derivative of displacement (z) of a beam, is proportional to the applied bending moment (ref. 11).

$$\frac{d^2 z}{dy^2} = \frac{M_x}{EI_x} \quad (3)$$

Since the bending moment cannot be measured directly, strain sensors are placed on the upper and lower surfaces to quantify the bending moments. For out-of-plane bending or bending strain due to bending moment about the global X-axis, the bending strain (ε_{Mx}) is defined as the upper surface strain (ε_u) subtracted by the lower surface strains (ε_l), as shown in eq. (4). For in-plane bending or bending strain due to bending moment about the global Z-axis, the bending strain (ε_{Mz}) is defined as the forward surface strain (ε_f) subtracted by the aft surface strains (ε_a), as shown in eq. (5). The rest of this section will focus on out-of-plane bending and shear; however, applications to in-plane bending can be used. An illustration of out-of-plane bending is shown in fig. 14, and an illustration of in-plane bending is shown in fig. 15.

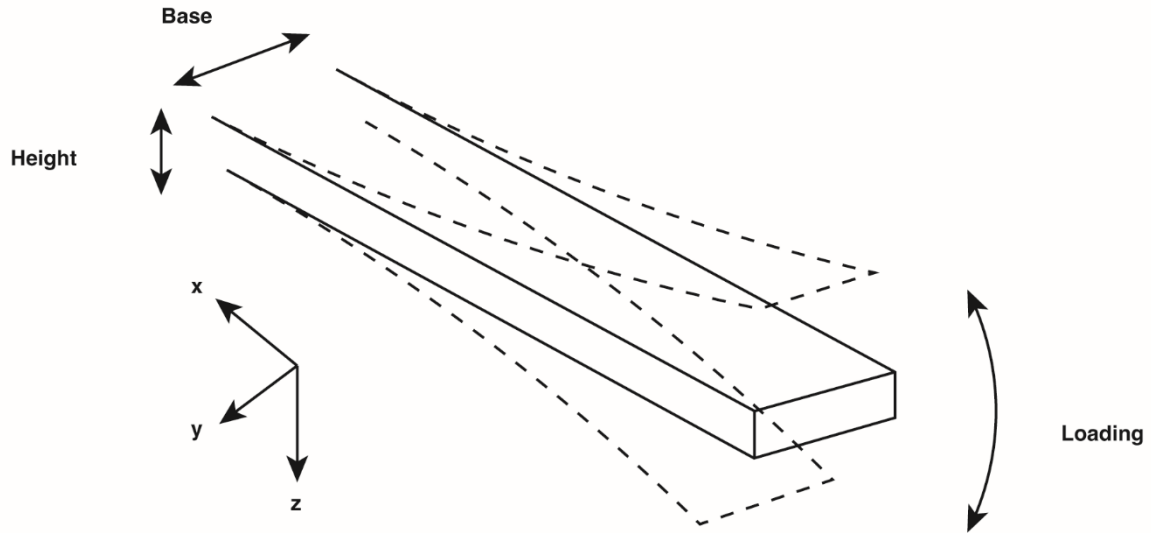


Figure 14. Out-of-plane bending.

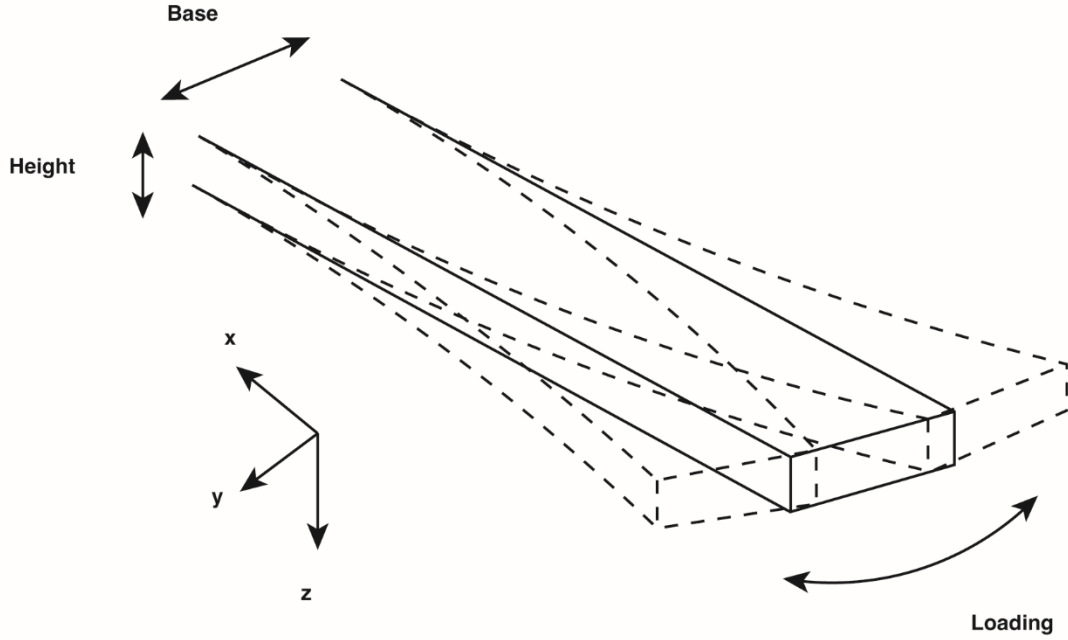


Figure 15. In-plane bending.

The technique of relating bending moments to the difference in axial strain between different surfaces is similar to the process of utilizing a four-active-arm Wheatstone Bridge Circuit (full-bridge circuit) set-up in a moment bridge configuration, where two foil gages are placed on one surface, and the other two foil gages are placed on a separate surface (ref. 2). The bending strain equations about the X- and Z-axis is provided in eqs. (4) and (5).

$$\varepsilon_{Mx} = \varepsilon_u - \varepsilon_l \quad (4)$$

$$\varepsilon_{Mz} = \varepsilon_f - \varepsilon_a \quad (5)$$

The differential bending stresses (σ_x and σ_z) are defined as the bending moment multiplied by the distance between paired strain sensors (h_1 or h_2) relative to the bending plane of interest, divided by the second moment of area (I_x or I_z) about the axis of interest (ref. 11). The bending stress is also related to bending strain by multiplying the elastic modulus (E), as shown in eqs. (6) and (7).

$$\sigma_{Mx} = \frac{M_x h_1}{I_x} = E (\varepsilon_u - \varepsilon_l) \quad (6)$$

$$\sigma_{Mz} = \frac{M_z h_2}{I_z} = E (\varepsilon_f - \varepsilon_a) \quad (7)$$

By rearranging the terms in eqs. (3), (4) and (5) we see that the bending moment can be related to bending strains, as shown in eqs. (8) and (9), where the elastic modulus (E); second moment of area (I_x and I_z); and distance between strain sensors (h_1 and h_2) are all constants. The individual constants do not need to be solved independently but, rather, are calculated as a

combined value carried forward to map bending strains to bending moments. The process of mapping bending strain to bending moments is referred to as the load transfer function (refs. 8-10), shown in figure 16.

$$M_x = \varepsilon_{Mx} \left(\frac{EI_x}{h_1} \right) \quad (8)$$

$$M_z = \varepsilon_{Mz} \left(\frac{EI_z}{h_2} \right) \quad (9)$$

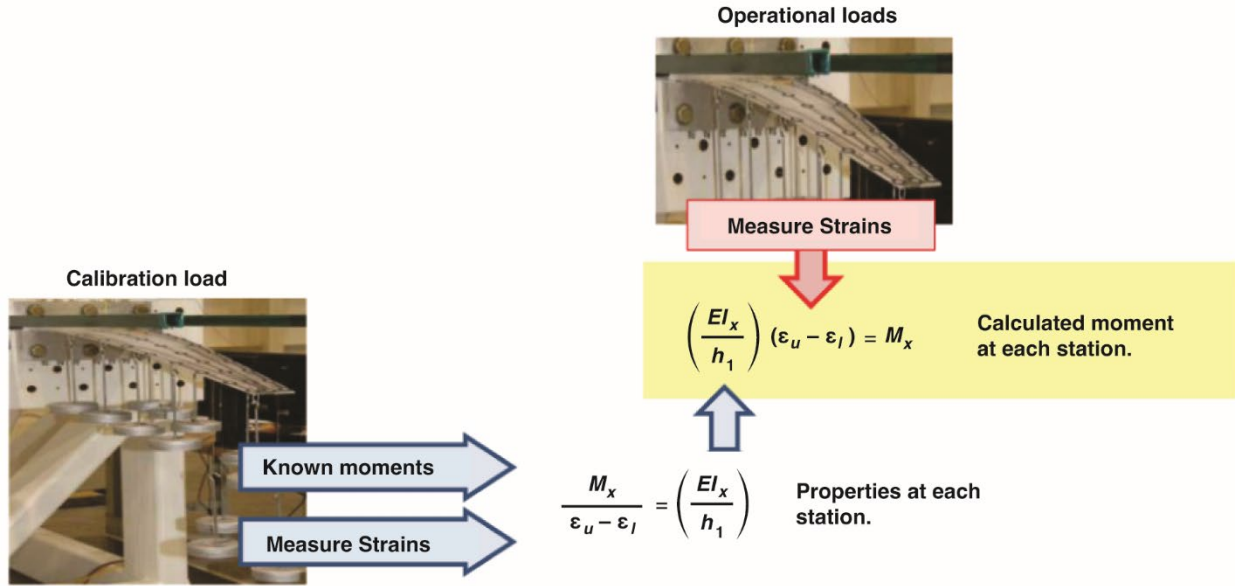


Figure 16. Load transfer function implementation process (ref. 10).

Since the FOSS strain measurements are comprised of discrete sensors, it is possible to numerically integrate the curvature in eq. (3) utilizing the trapezoidal rule. The distributed slope (ϕ) of the structure can be estimated by eq. (10):

$$\frac{dz}{dy} = \tan(\phi) \approx \phi_n = \phi_0 + \sum_{i=1}^{n-1} \left(\left(\frac{M}{EI_x} \right)_i + \left(\frac{M}{EI_x} \right)_{i+1} \right) \frac{\Delta L_i}{2} \quad (10)$$

where $\tan(\phi) \approx \phi$ for small angles, ϕ_i is the slope angle in the roll orientation at the i th sensing element, with the n th station representing the last sensing station at the tip, ϕ_0 is the root slope, and ΔL_i is the distance between the sensor stations. The small angle approximation for the tangent function produces a relative error of less than 1 percent for angles less than 10 deg (0.175 rad), and less than a 1-percent error for the sine function with less than 14 deg (0.244 rad). The small angle approximation also linearizes the relationship between loads and displacement. The vertical displacement (Z_n) at each sensing station can be approximated by integrating the slope equation. The process of determining the vertical displacement at any sensing station is called the Displacement Transfer Function (DTF) and can be determined by eq. (11).

$$z_n = z_0 + \sum_{i=1}^n \sin(\phi_i) \Delta L_i \quad (11)$$

Using small angle approximation $\sin(\phi) \approx \phi$, the calculation for vertical displacement becomes eq. (12).

$$z_n = z_0 + \sum_{i=1}^n \phi_i \Delta L_i \quad (12)$$

An illustration of the OLEA flowchart is shown in fig. 17. The OLEA utilizes the estimated shape (Z_n) from eq. (12); the calibrated section properties (EL_x) from eq. (8); and an initial guess of the shear loads as input. For the first iteration of OLEA, a small-magnitude uniform shear load is recommended. The guess shear load is then assigned to a temporary shear load variable for further processing. The shear load variable divided by the calibrated section properties are then integrated twice with respect to span to obtain a variable mathematical model of the deflection. The model deflection and the DTF deflections are then compared with one another to determine the error between the two distributed shapes. If the deflection error is not within a specified tolerance, the shear load estimate is updated proportionally to the amount of spanwise deflection error. The updated shear load variable is checked to ensure that the results are consistent with a cantilever configuration. The cantilever check ensures the shear load at the tip is set to zero and that each shear load sensing station ordered from root to tip is greater than or equal to the next sensing station. The resulting shear load estimate is then sent in a loop for further reprocessing to obtain an updated model deflection. This processing loop continues until the deflection error is within a specified tolerance or until a specified number of iterations are completed. Once the deflection error is within tolerance, the shear load estimate is further processed to obtain an estimate for bending moment. The output of the OLEA is the estimated spanwise shear load and bending moment. For sequentially timed calculations of load, we recommended that the output results from the previous time frame ($time_{j-1}$) be fed to the current initial estimate for shear load to reduce the computation time, enabling near-real-time calculation. The results presented in this report, however, represent the average response of each sensor during maximum loading, so no time optimization was applied.

Due to the interaction between the truss to the main wing section, the OLEA process is split into two sections: one section outboard of the load cell and another section inboard of the load cell. The outboard process was unmodified. The inboard section was processed as a cantilevered structure and assumed zero shear up to the load cell. After the OLEA processing of the inboard section was completed, an additional offset was included to account for the shear calculated from the outboard section and to account for the load cell output.

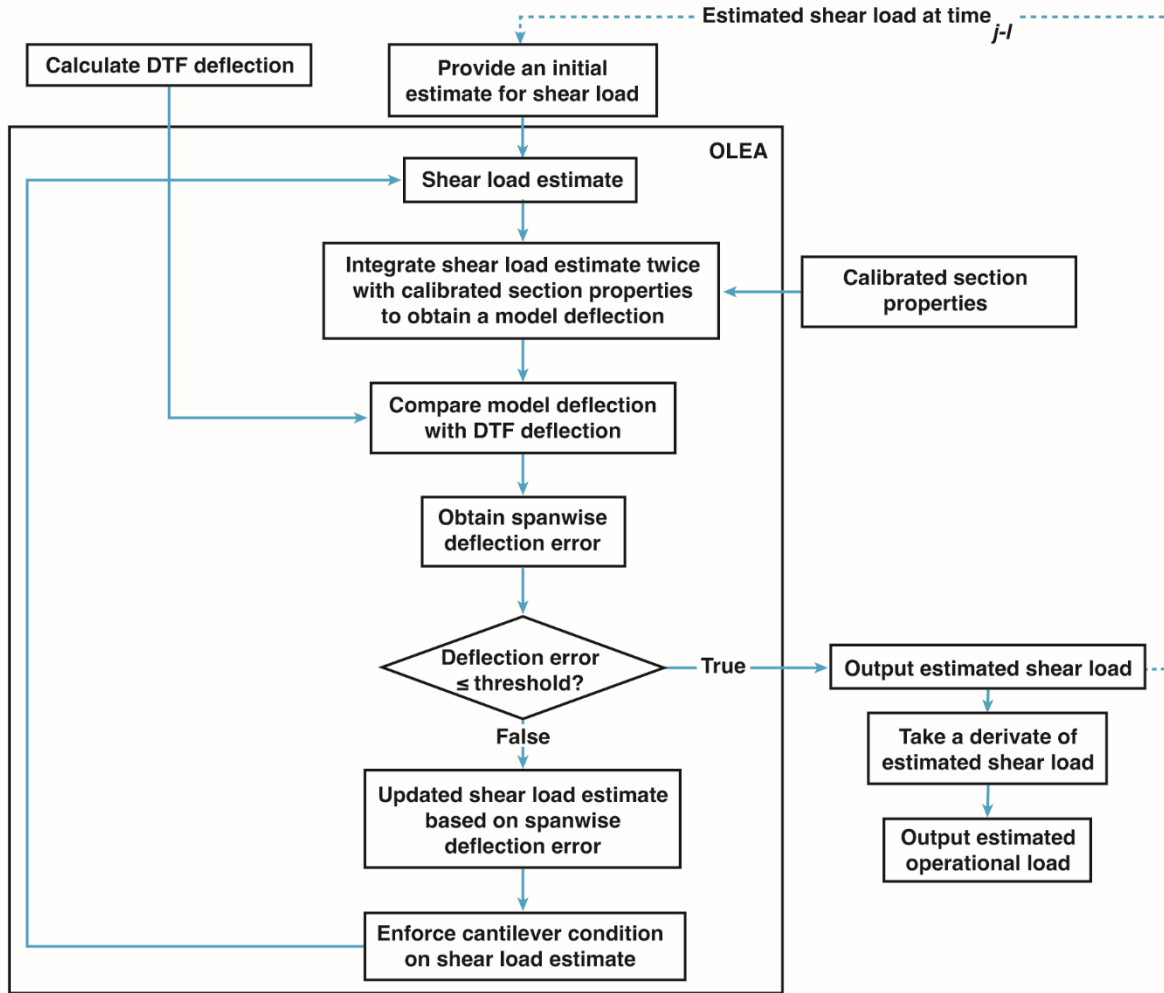


Figure 17. Operational Loads Estimation Algorithm flowchart.

Loads Calibration

The focus of this report is on the calibration of the wing structure; therefore, all the calibrations shown in this report have focused on the wing structure and not the strut. A similar analysis, however, may be performed on the strut using the same techniques described in this report.

Out-of-plane Calibration

To develop a free-body diagram for the mock TBW, measurements from the load cell that connect the wing structure to the strut must be taken into account. The load cell was installed off-center of the neutral axis (dy and dz) of the wing structure. As a result, bending moments that are caused by the load cell offset (M_{LC}) need to be accounted for in addition to the load cell force-measurement output. The equation for the bending moments caused by the load cell offset is provided in eq. 13. Figure 18 shows the free-body diagram and the bending moment caused by the load cell offset, where F_z and F_y are the load cell outputs.

$$M_{LC} = dzF_y - dyF_z \quad (13)$$

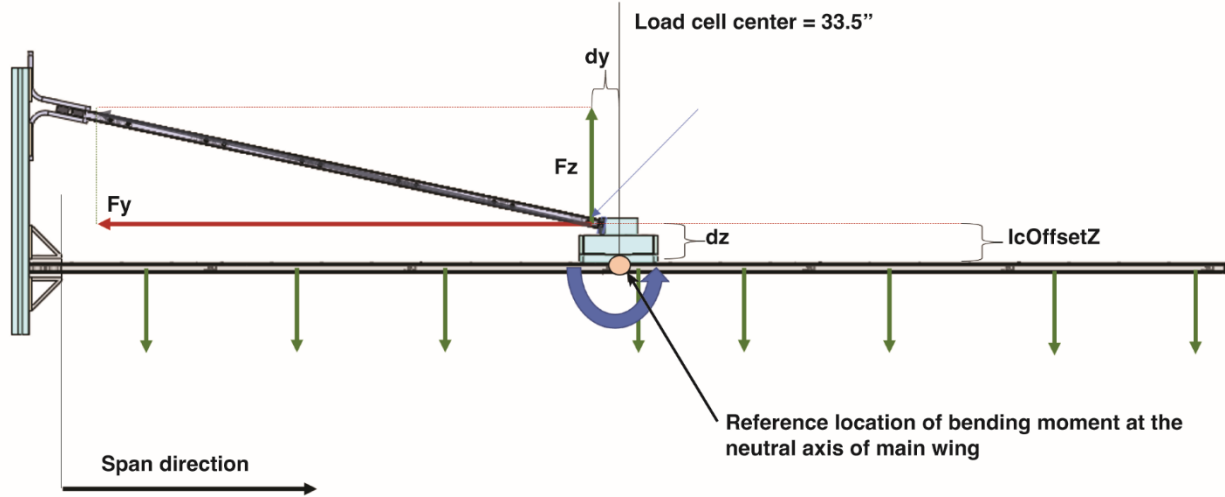


Figure 18. Mock Truss-Braced Wing free-body diagram for out-of-plane bending, with the structure mounted upside down to facilitate hanging weights to simulate lift loads.

An important property of the load cell that needs to be monitored is the crosstalk along the perpendicular sensing axis. The load cell used in the testing of the mock TBW test series had a stated 2-percent crosstalk effect on F_x and F_z due to loads generated in F_y ; therefore, F_z is based on the measurements (F_{ym} and F_{zm}) plus a 2-percent uncertainty of the perpendicular measurement. The calculated forces in the X- and Z-axis is presented in eqs. (14) and (15). For out-of-plane bending, the measurements in the forward and aft direction (F_x) are omitted.

$$F_z = F_{zm} \pm 0.02(F_{ym}) \quad (14)$$

$$F_y = F_{ym} \pm 0.02(F_{zm}) \quad (15)$$

Due to the shallow angle of the strut relative to the wing structure, F_y is on the order of five times larger than F_z . The crosstalk between F_y and F_z cause a measurement uncertainty of ± 10 percent in F_z , while F_y had an uncertainty of 0.4 percent due to the crosstalk. The uncertainty in F_z is included in the out-of-plane bending moment diagrams since the uncertainty produces a wide range of possible bending moments inboard of the load cell. The outboard section of the wing, therefore, was used to determine the calibration parameters, and the calibration parameters were carried over to the inboard section since the wing cross section was uniform along the entire length. We recommend, whenever possible, to calibrate the wing and strut independently to avoid errors due to measurement uncertainties introduced when testing the structure as an assembly.

The out-of-plane bending moment calibration load case was based on the wingtip concentrated load case. In this load case, 100 lb was applied at the outboard loading station. The strain response from the wingtip concentrated load case is shown in fig. 19 and shows that

the strain along the top and bottom surfaces are plotted against the span. There were approximately 142 unique strain-measurement stations on both the upper and lower sensing fiber. The measured strain distribution along the bottom surface was discontinuous at the load cell interface due to the footprint of the load cell and how it was bolted flush to the wing surface; therefore, bending strain is not obtainable along the footprint of the load cell. Vertical-dash lines are shown in fig. 19 to show the load cell location relative to span.

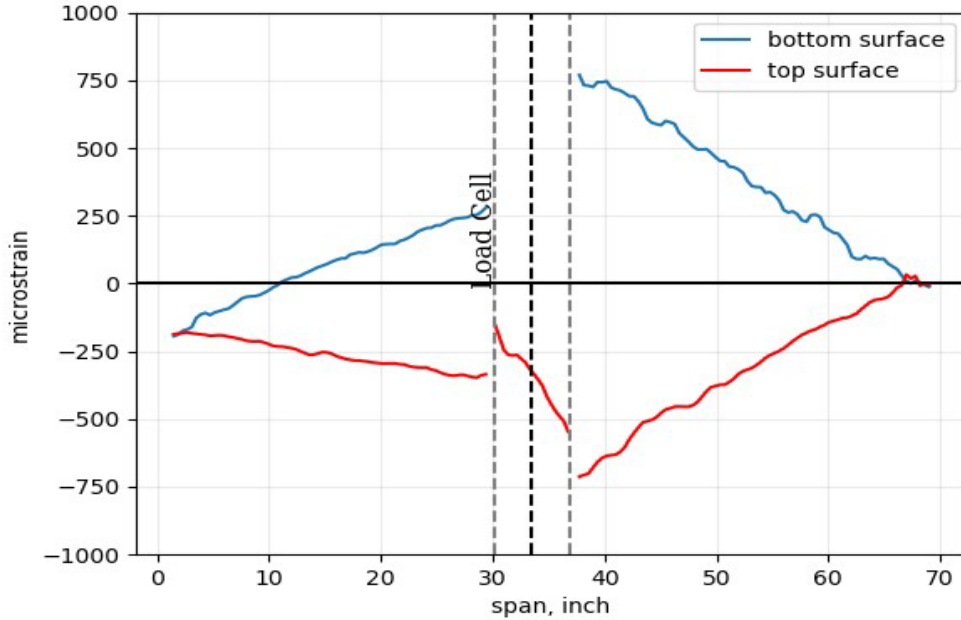


Figure 19. Fiber Optic Sensing System strain response to a concentrated wingtip load.

An example mapping between the applied bending moment and the unprocessed bending strain ε_{Mx} (see eq. (4)) response is shown in fig. 20. Within fig. 20, the left-vertical axis is the bending strain response (blue curve) in microstrain, and the right-vertical axis is the bending moment put into the test article in in-lbf (red curve). The results for the additional ± 2 -percent crosstalk are also shown in fig. 20, with the orange-shaded region representing the range of values. The vertical-dash lines represent the load cell footprint where the bending strains were not obtained.

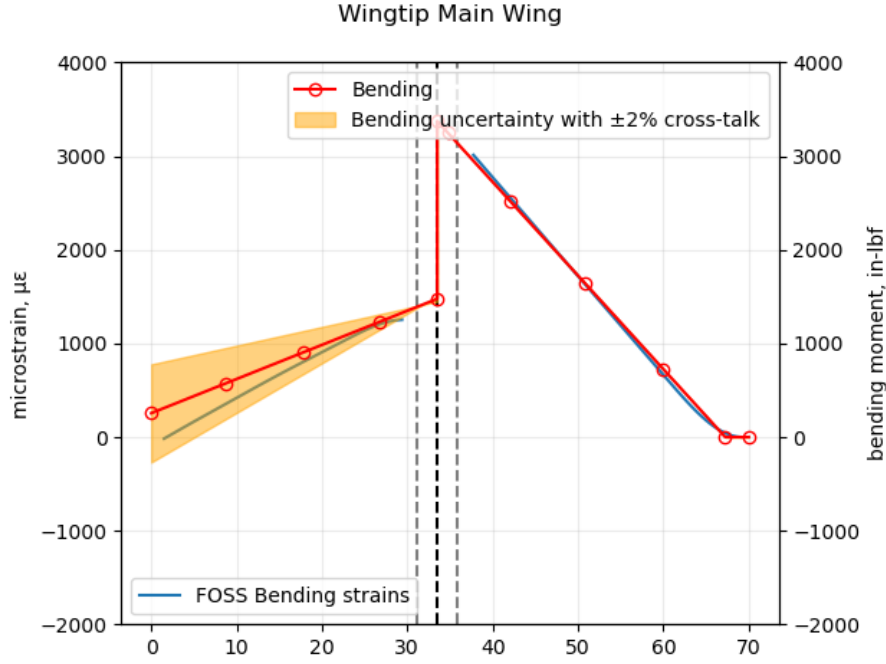


Figure 20. Out-of-plane bending moment diagram for concentrated wingtip load case.

Figure 20 shows that the bending strain response and the applied bending moment align well along the outboard portion of the wing beyond the load cell. The bending strain measurements inboard of the load cell are within the tolerance of the output of the 3-axis load cell. The strain measurements and bending moments outboard of the load cell are used for calibration of the operational loads estimation algorithm, since the inboard portion has some uncertainties due to crosstalk between the sensing axes. The average calibration value that maps the bending strain to bending moment is approximately $El_x/h_1 = 2.02$ in-lbf per microstrain.

In-plane Calibration

Due to the interaction between the wing and the swept strut structure, there exists an in-plane bending moment even though there were no external loads applied in the fore or aft direction. The in-plane bending moment is determined by the fore or aft output of the 3-axis load cell measurement (F_{xm}). As mentioned in the previous section, “In-plane Calibration,” the crosstalk between forces in the fore or aft direction, and the inboard or outboard direction need to be accounted for. The measurement uncertainty utilized to determine F_x are provided in eq. (16).

$$F_x = F_{xm} \pm 0.02(F_{ym}) \quad (16)$$

The strain response from the FBGs on the forward and aft fibers routed on the upper surface is utilized in determining the in-plane bending strains, ε_{Mz} , in eq. (5) and is shown in fig. 21. Figure 21 shows the vertical axis is the measured strain from the FOSS, and the horizontal axis is the span distance. There were approximately 142 unique strain measurement stations on both the forward and aft sensing fiber. As mentioned in the previous section, “In-plane Calibration,” the measured strain distribution along the span was discontinuous at the load cell interface due to the footprint of the load cell and how it was bolted flush to the wing surface.

Bending strain, therefore, is not obtainable along the footprint of the load cell. Vertical-dash lines are shown in fig. 21 and represent the load cell location relative to span.

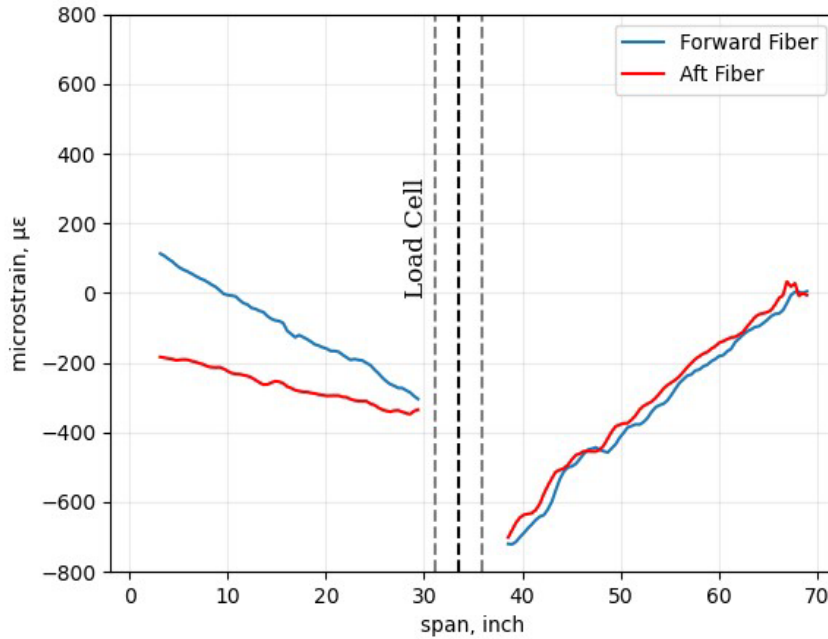


Figure 21. In-plane Fiber Optic Sensing System strain response for concentrated wingtip load case.

An example mapping between the applied bending moment and the unprocessed bending strain ε_{Mz} (see eq. (5)) response is shown in fig. 22. Within fig. 22, the left-vertical axis is the bending strain response (blue curve) in microstrain, and the right-vertical axis is the in-plane bending moment put into the test article in in-lbf (red curve). The results for the additional ± 2 -percent crosstalk are also shown in fig. 22, with the orange-shaded region representing the range of values. The vertical-dash lines represent the load cell footprint where the bending strains were not obtained. The focus of fig. 22 is on the bending moments inboard of the load cell since there is no external loading outboard of the load cell. The average calibration value that maps the bending strain to bending moment is approximately $El_z/h_2 = 11.6$ in-lbf per microstrain. It is noted that the strain output in the in-plane direction has relatively low output when compared to the out-of-plane loading due to the much larger second moment of area of the structure in the in-plane direction, causing the structure to be much stiffer in this loading direction. The strain output appears much noisier in the in-plane direction.

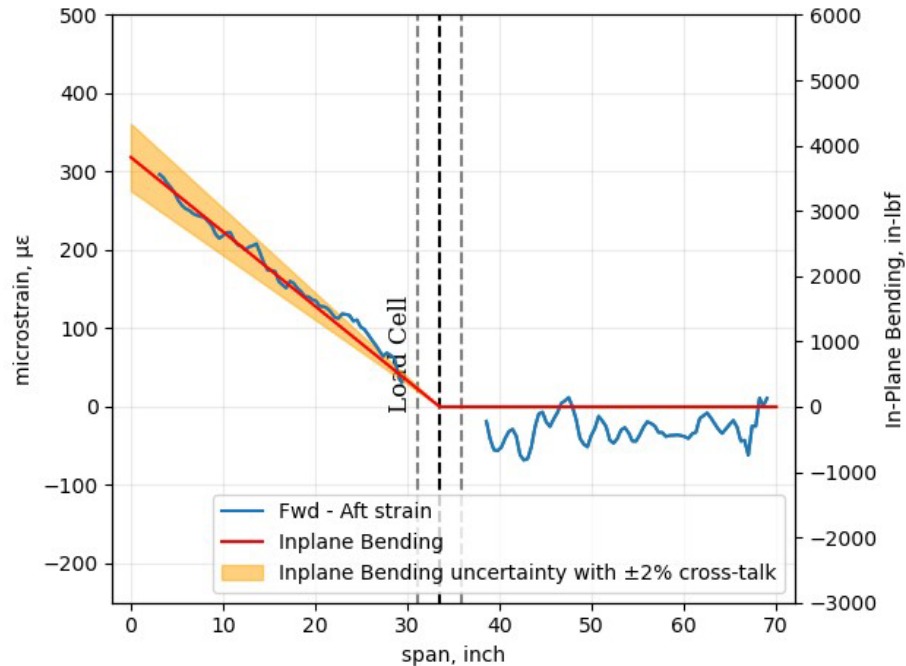


Figure 22. In-plane bending moment diagram for concentrated wingtip load case.

Shear and Bending Loads Estimations

Out-of-plane

The FOSS out-of-plane bending strains (eq. (4)) were then processed into a linearized deflection profile using eqs. (10) and (12). The linearized deflection along with section properties (EI_x) were processed using OLEA (fig. 17). The output of OLEA provides a qualitative estimate of the shear loads and bending moments. The bending moment component of the OLEA process for the elliptical load case is shown in fig. 23 and shows that the blue curve is the spanwise FOSS-derived OLEA bending moment estimation, the red curve is the load-cell-derived bending moment, and the ± 2 -percent crosstalk of the load cell is shown as the orange-shaded region representing the range of values. The OLEA out-of-plane bending results for the remaining five load cases are provided in Appendix B (figs. B1 to B5).

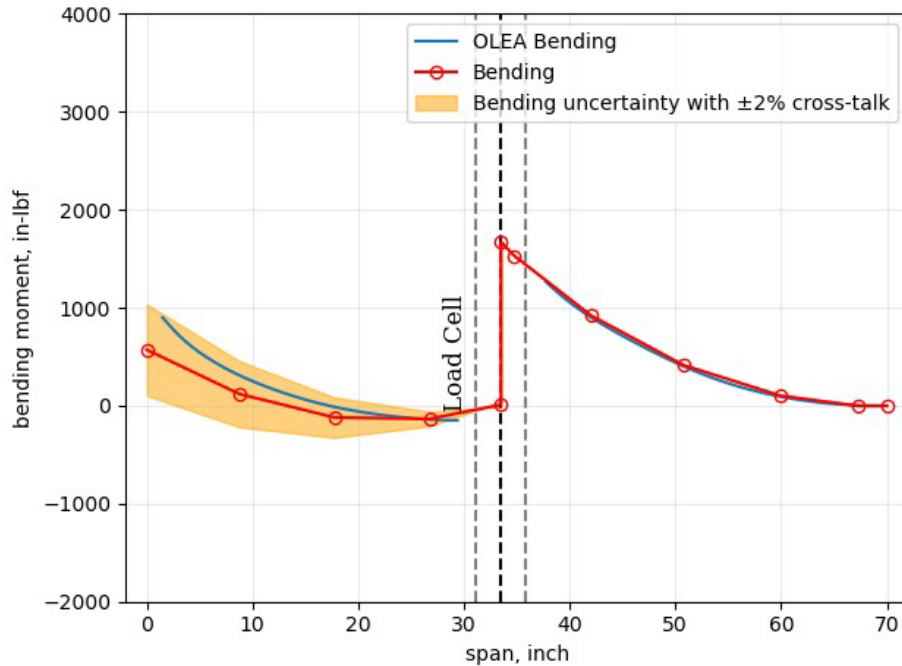


Figure 23. Out-of-plane bending moment diagram for elliptical load case.

The shear component of the OLEA process is shown in fig. 24, where the blue curve is the spanwise FOSS-derived OLEA shear estimation, the red curve is the load-cell-derived shear, and the ± 2 -percent crosstalk of the load cell is shown as the orange-shaded region representing the range of values. Figure 24 shows that the qualitative profile of the shear load is captured by the OLEA. It is also apparent that the OLEA technique is not able to provide the piecewise linear curves that satisfy the true applied shear load curve calculated from the load cells, as shown in fig. 24. This result is because vertical deflection is used as the optimization parameter for convergence in the OLEA feedback loop. The vertical deflection is a smooth, continuous curve, and by utilizing the spanwise error calculations of a smooth curve to update the shear loads, a smooth shear load curve is produced. The inability of the OLEA to predict sharp, piecewise linear curves, produces comparatively large errors at kinked locations for the load cell shear calculations. It is believed that the OLEA calculations would produce reduced errors for shear estimates in a flight environment in which the applied loads are distributed pressure loads versus discrete span locations with hanging weights. The OLEA out-of-plane shear results for the remaining five load cases are provided in Appendix C (figs, C1 to C5).

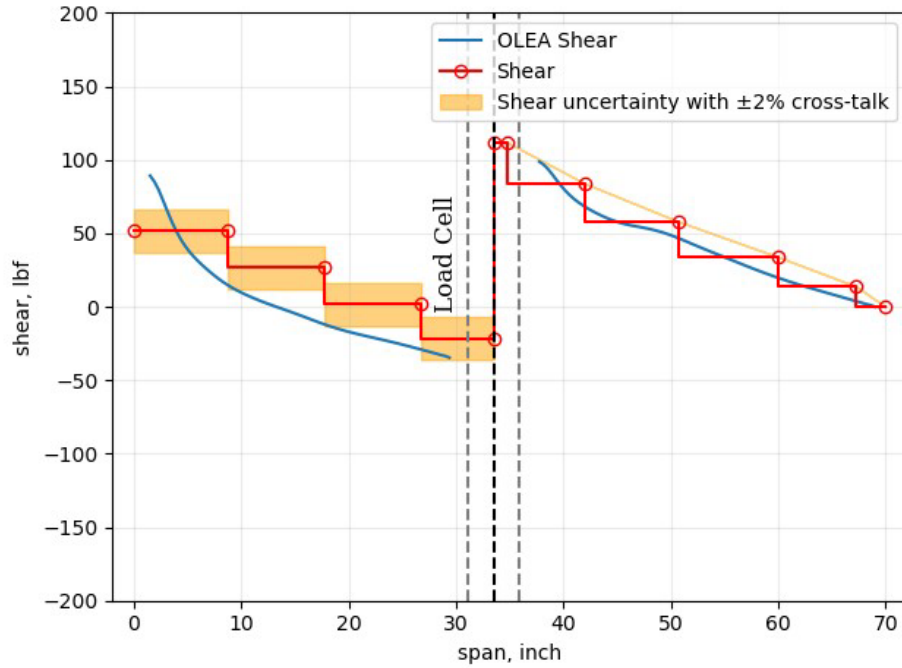


Figure 24. Operational Loads Estimation Algorithm out-of-plane shear diagram for elliptical load case.

In-Plane

The FOSS in-plane bending strains (eq. (5)) were then processed into a linearized deflection profile using eqs. (10) and (12). The linearized deflection along with section properties (EI_z) were processed using the OLEA (fig. 17). The bending moment component of the OLEA process for the elliptical load case is shown in fig. 25, where the blue curve is the spanwise FOSS-derived OLEA bending moment estimation, the red curve is the load-cell-derived bending moment, and the ± 2 -percent crosstalk of the load cell is shown as the orange-shaded region representing the range of values. The OLEA in-plane bending results for the remaining five load cases are provided in Appendix D (figs. D1 to D5).

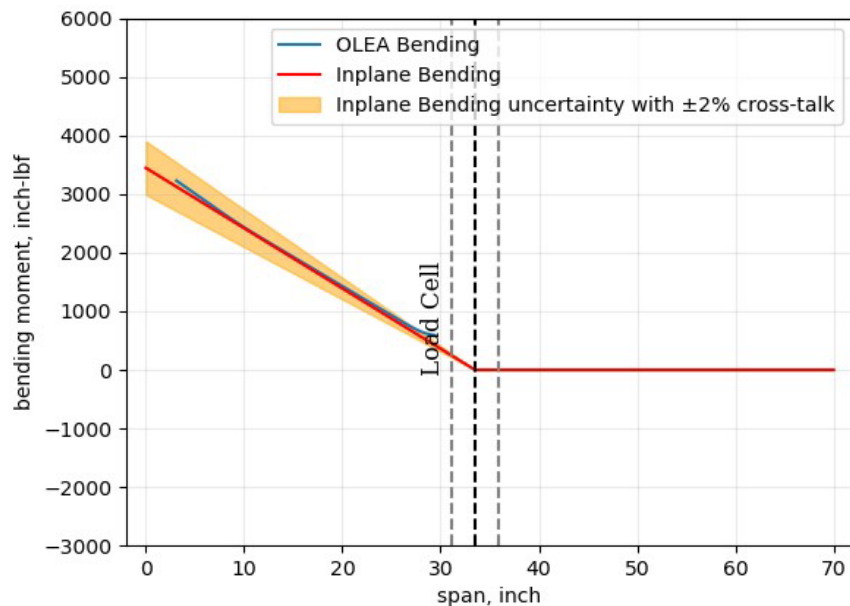


Figure 25. Operational Loads Estimation Algorithm in-plane moment diagram for elliptical load case.

The shear component of the OLEA process is shown in fig. 26, where the blue curve is the spanwise FOSS-derived OLEA shear estimation, the red curve is the load-cell-derived shear, and the ± 2 -percent crosstalk of the load cell is shown as the orange-shaded region representing the range of values. Figure 26 shows that the qualitative profile of the shear load is captured by the OLEA. The OLEA in-plane shear results for the remaining five load cases are provided in Appendix E (figs. E1 to E5).

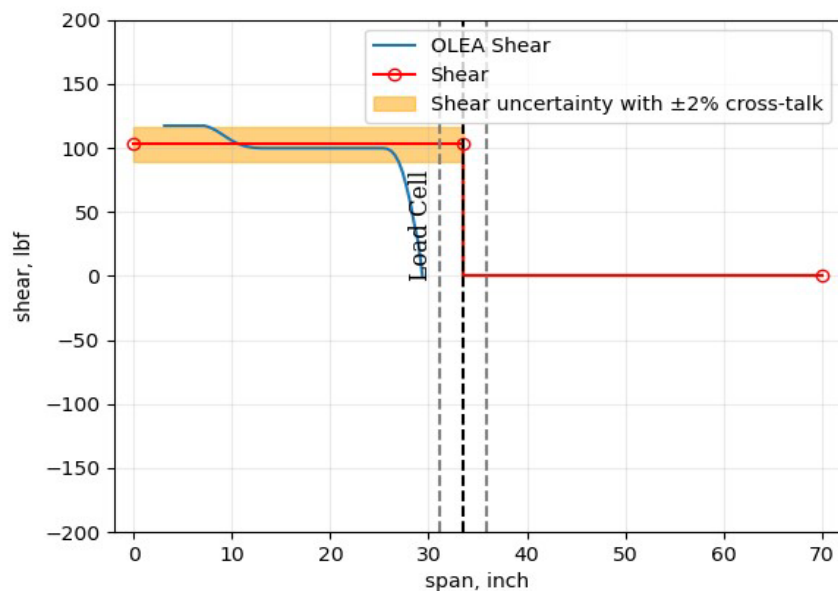


Figure 26. Operational Loads Estimation Algorithm in-plane shear diagram for elliptical load case.

Out-of-plane Bending Shape Estimation

The FOSS strain data along the upper and lower surfaces were processed to estimate the out-of-plane displacement using eqs. (6), (10), and (11) for all load cases. The FOSS strain distribution utilized in the shape estimate is shown in fig. 27. The shape estimate for the elliptical load distribution case is shown in fig. 28. Within fig. 28, the blue curve represents the FOSS displacement outputs, and the red circles represent co-located string potentiometers. As mentioned throughout the report, the strain information under the load cell region was discontinuous, causing some deviations in the shape output when compared to the string potentiometers. To compensate, a ramp function was used to bridge the strain distribution from the inboard section to outboard section under the load cell. In general, if accurate shape is desired, continuous distributed strain measurements from the root to the tip of the structure of interest is advised. The displacement estimates for the remaining load cases are provided in Appendix F (figs. F1 to F5).

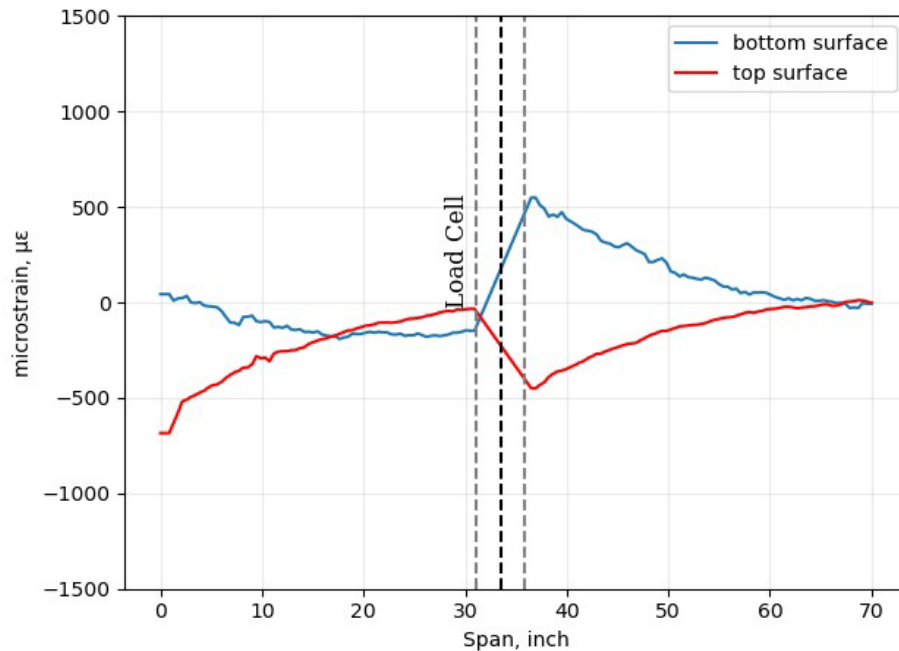


Figure 27. Fiber Optic Sensing System strain distribution for elliptical load case.

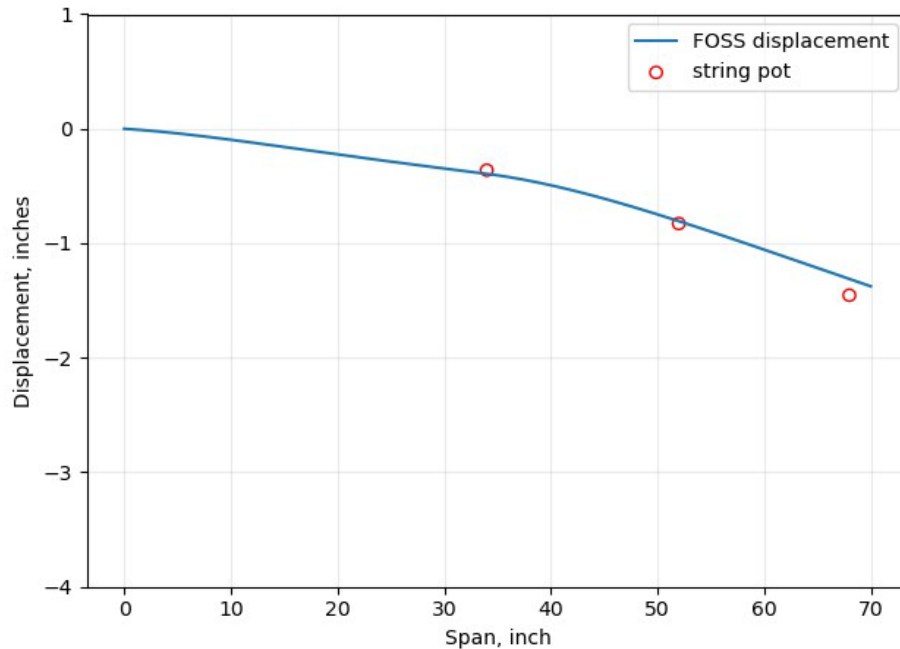


Figure 28. Out-of-plane displacement for elliptical load case.

Conclusion

The loads calibration research performed on the mock Truss-Braced Wing test article highlights the usefulness of utilizing distributed strain sensing technology, such as the National Aeronautics and Space Administration Armstrong Flight Research Center Fiber Optic Sensing System. Distributed surface strain measurements can be utilized with the Fiber Optic Sensing System to estimate the stiffness characteristics of a wing without using a finite element model. These distributed strain measurements can, in turn, provide a fully defined bending moment and an estimate of the shear load diagrams. Due to the measurement uncertainties of the selected 3-axis load cell used in these test series to monitor the load sharing between the wing and strut, the accuracy of the bending and shear diagrams cannot be reported for this test series.

Though the applied operational loading information provided in this report was shown to be more qualitative than quantitative, the distributed load sensing measurement can continue to improve with advancements in sensing technology, increased computer performance, and the potential incorporation of improved algorithms or machine-learning algorithms. The use of a 3-axis load cell with crosstalk makes the determination of the true internal loads difficult to obtain; therefore, estimates related to accuracy of the FOSS-derived loads is qualitative. The development of smart adaptive structures could lead to lighter-weight structures and, thus, improved structural safety and fuel efficiency.

References

- [1] Viken, Sally A., Craig A. Hunter, S. Naomi McMillin, Gregory M. Gatlin, Daniel Maldonado, Jefferey A. Housman, Jared C. Duensing, James C. Jensen, and Cetin C. Kiris, "Comparison of Computational Predictions of the Mach 0.80 Transonic Truss-Braced Wing Configuration with Experimental Data," NASA/TM-20205007879, June 2022.

- [2] Skopinski, T. H., William S. Aiken, Jr., and Wilber B. Huston, "Calibration of Strain-Gage Installations in Aircraft Structures for the Measurement of Flight Loads," NACA TR-1178, 1954.
- [3] Richards, W. Lance, Allen R. Parker, Jr., William L. Ko, Anthony Piazza, and Patrick Chan, "Application of Fiber Optic Instrumentation," NATO, RTO AGARDograph 160, Flight Test Instrumentation Series – Volume 22, SCI-228, 2012.
- [4] Ko, William L., W. L. Richards, and Van T. Tran, "Displacement Theories for In-Flight Deformed Shape Predictions of Aerospace Structures," NASA/TP-2007-214612, January 2007.
- [5] Ko, William L., "Further Development of Ko Displacement Theory for Deformed Shape Predictions of Nonuniform Aerospace Structures," NASA/TP-2007-214643, 2007.
- [6] Ko, William L., W. Lance Richards, and Van Tran Fleischer, "Applications of Ko Displacement Theory to the Deformed Shape Predictions of the Doubly-Tapered Ikhana Wing," NASA/TP-2009-214652, 2009.
- [7] Jutte, Christine V., William L. Ko, Craig A. Stephens, John A. Bakalyar, W. Lance Richards, and Allen R. Parker, "Deformed Shape Calculation of a Full-Scale Wing Using Fiber Optic Strain Data from a Ground Loads Test," NASA/TP-2011-215975, 2011.
- [8] Richards, W. L., and Ko, William L., Process for Using Surface Strain Measurements to Obtain Operational Loads for Complex Structures, United States Patent No. US 7,715,994, issued May 11, 2010.
- [9] Ko, William L., and Van Tran Fleischer, "Method for Estimating Operational Loads on Aerospace Structures Using Span-wisely Distributed Surface Strains," NASA/TP-2013-216518, 2013.
- [10] Bakalyar, J., and Jutte, C., "Validation Tests of Fiber Optic Strain-Based Operational Shape and Load Measurements," 53rd AIAA/ASME/ASCE/AHS/ASC Structure, Structural Dynamics and Materials Conference, Honolulu, HI, AIAA Paper 2012-1904,, pp. 1-81.
- [11] Budynas Richard. G., and Nisbett, J. Keith, Shigley's Mechanical Engineering Design, Eighth Edition, ISBN 978-0-07-312193-2, MHID 0-07-312193-2, McGraw-Hill, 2008.
- [12] Pak, Chan-gi, "Unsteady Aerodynamic Force Sensing from Strain Data," Journal of Aircraft, Vol. 54, No. 4, July 2017.

Appendix A: Load Cases

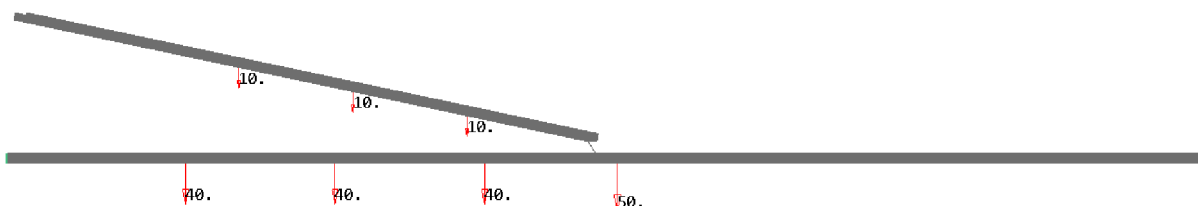


Figure A1. Finite element model of root-biased loading condition.

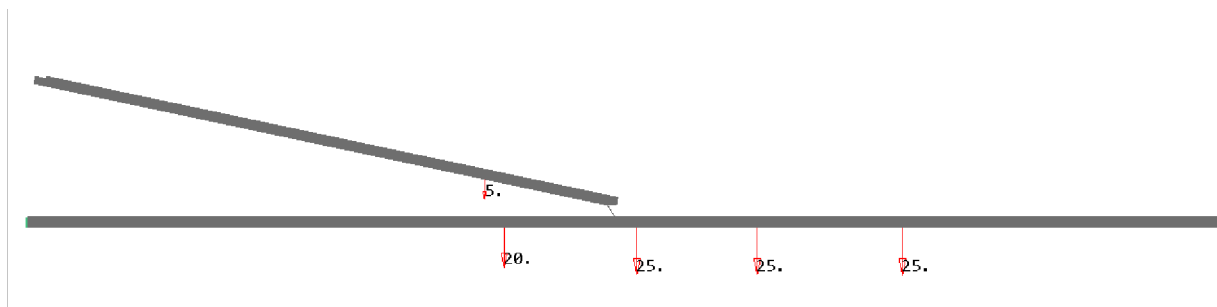


Figure A2. Finite element model of mid-span-biased loading condition.

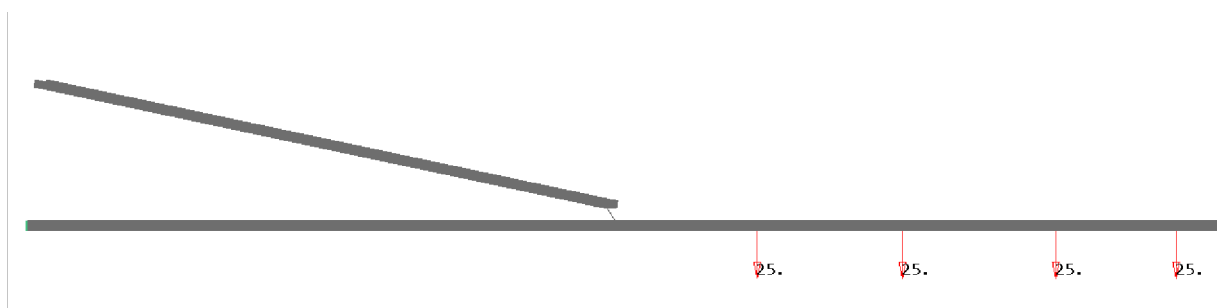


Figure A3. Finite element model of tip-biased loading condition.

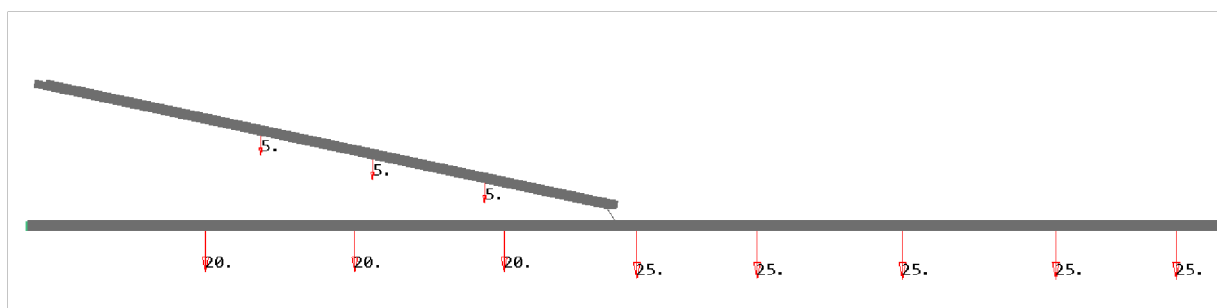


Figure A4. Finite element model of uniform loading condition.

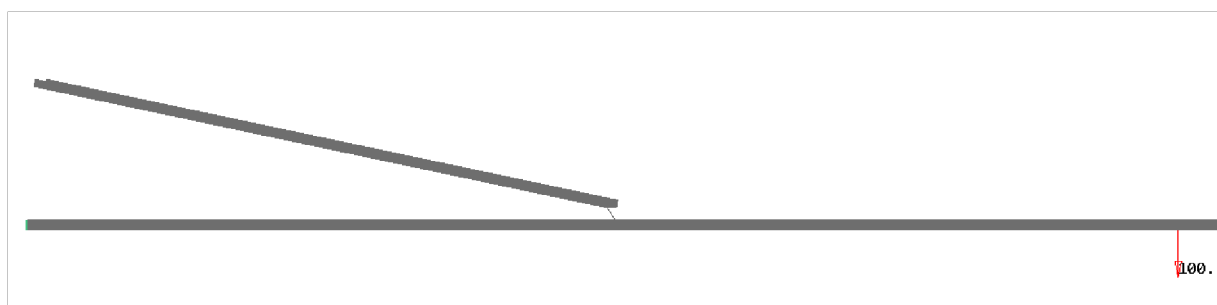


Figure A5. Finite element model of tip loaded condition.

Appendix B: Out-of-plane Bending Diagrams

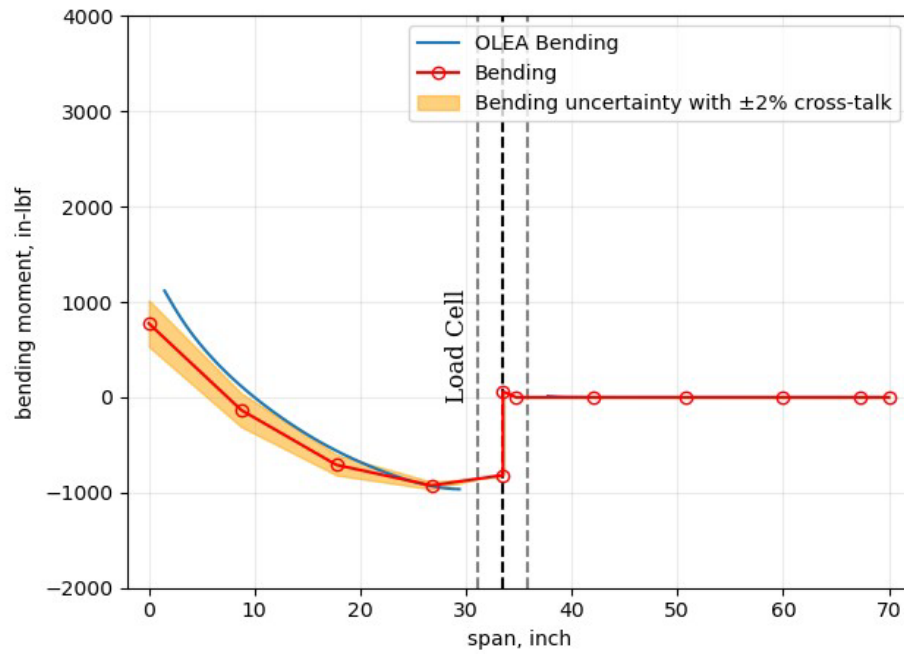


Figure B1. Out-of-plane bending moment diagram for root-biased load case.

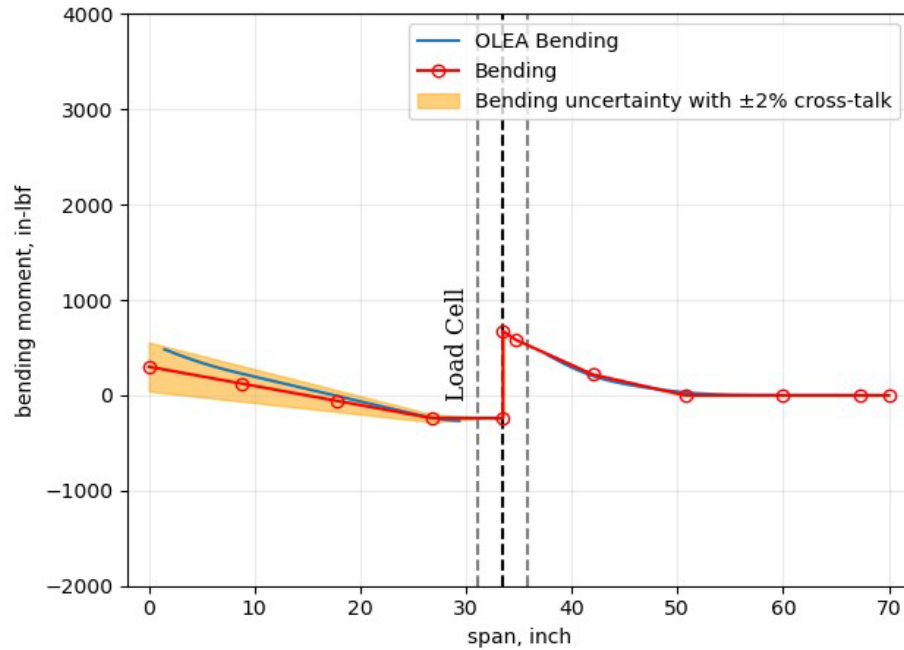


Figure B2. Out-of-plane bending moment diagram for mid-span-biased load case.

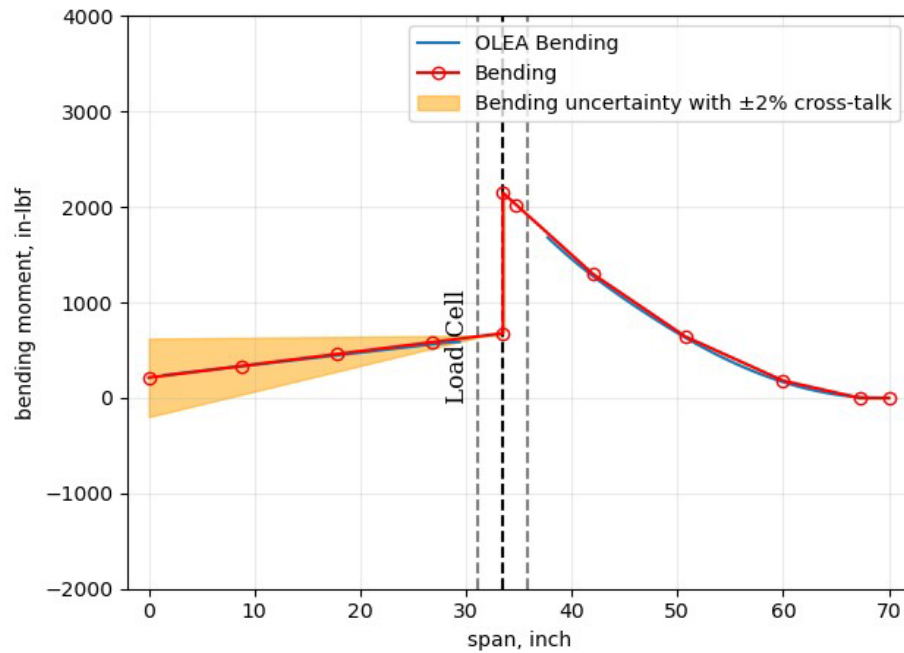


Figure B3. Out-of-plane bending moment diagram for wingtip-biased load case.

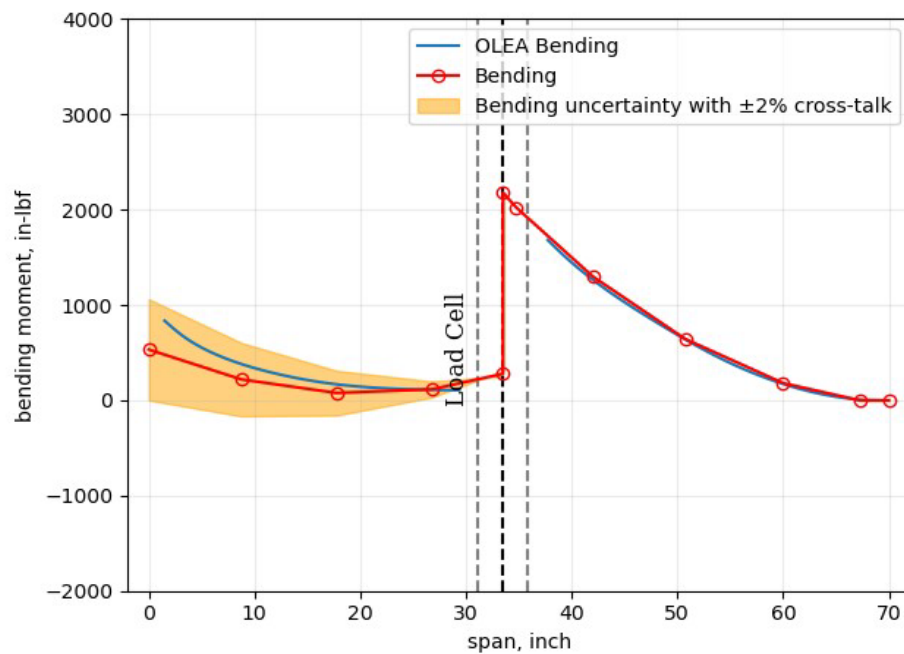


Figure B4. Out-of-plane bending moment diagram for uniform load case.

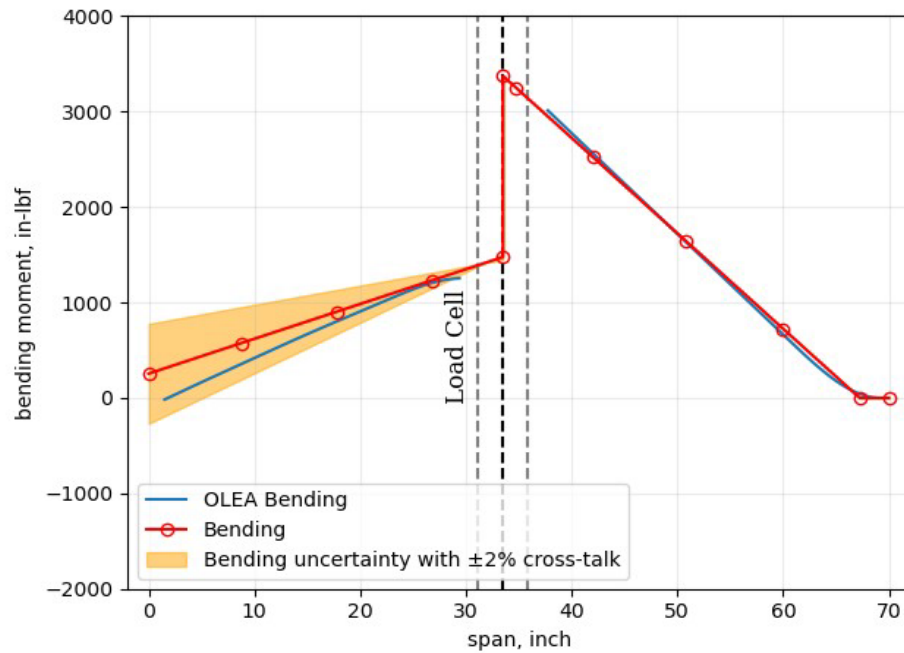


Figure B5. Operational Loads Estimation Algorithm out-of-plane bending moment diagram for concentrated wingtip load case.

Appendix C: Out-of-plane Shear Diagrams

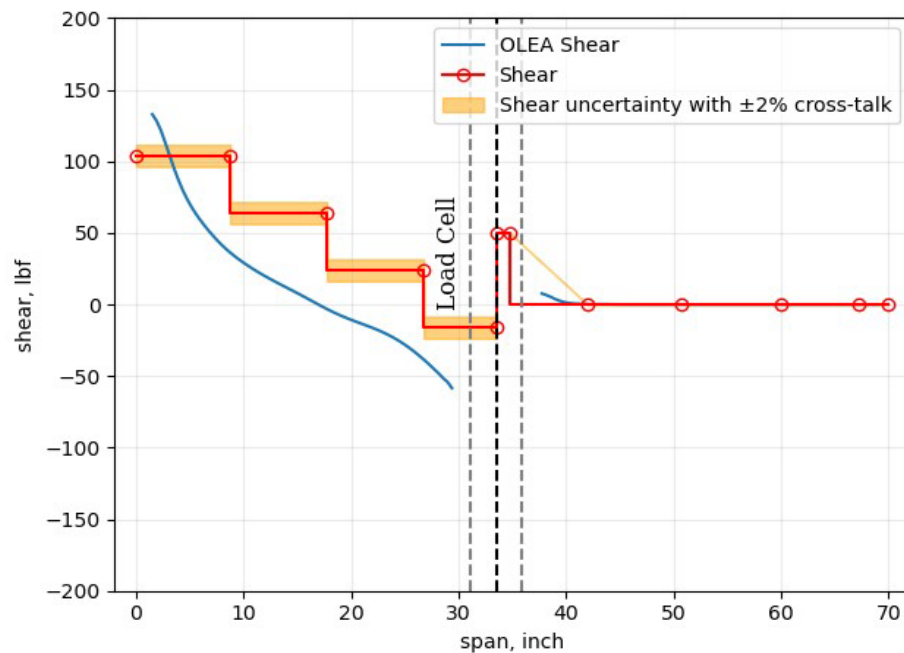


Figure C1. Out-of-plane shear diagram for root-biased load case.

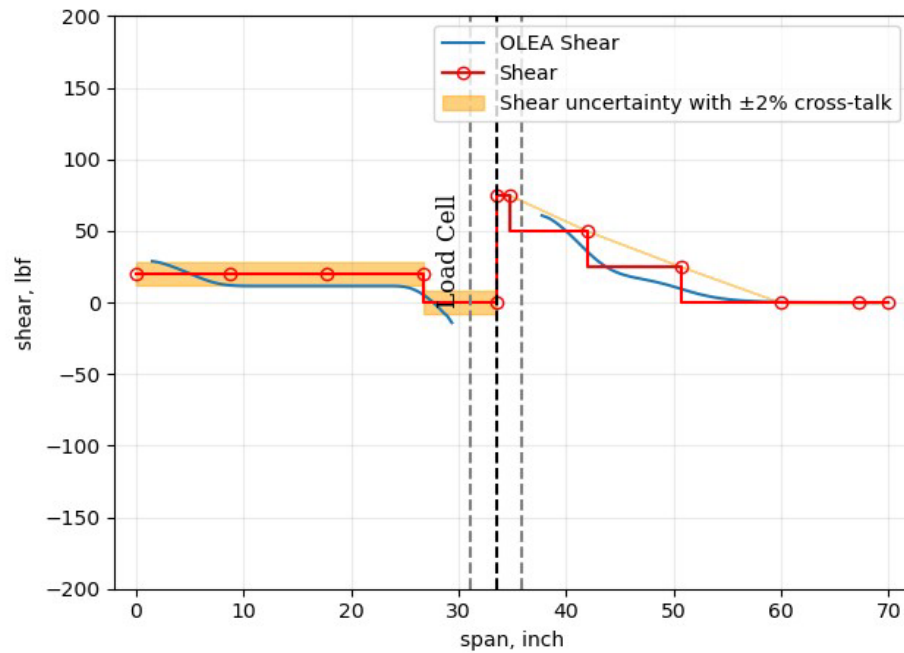


Figure C2. Out-of-plane shear diagram for mid-span-biased load case.

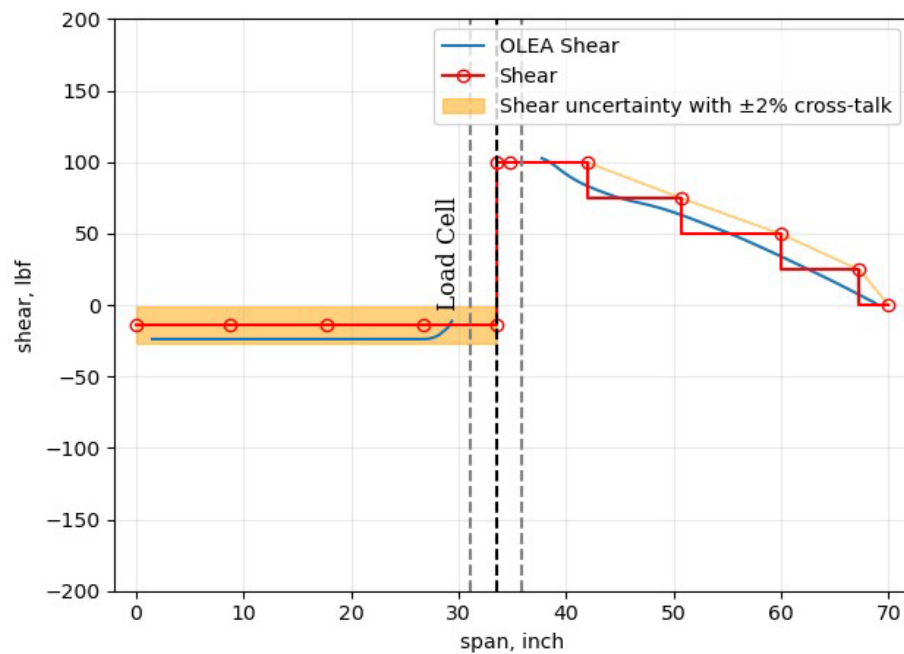


Figure C3. Out-of-plane shear diagram for wingtip-biased load case.

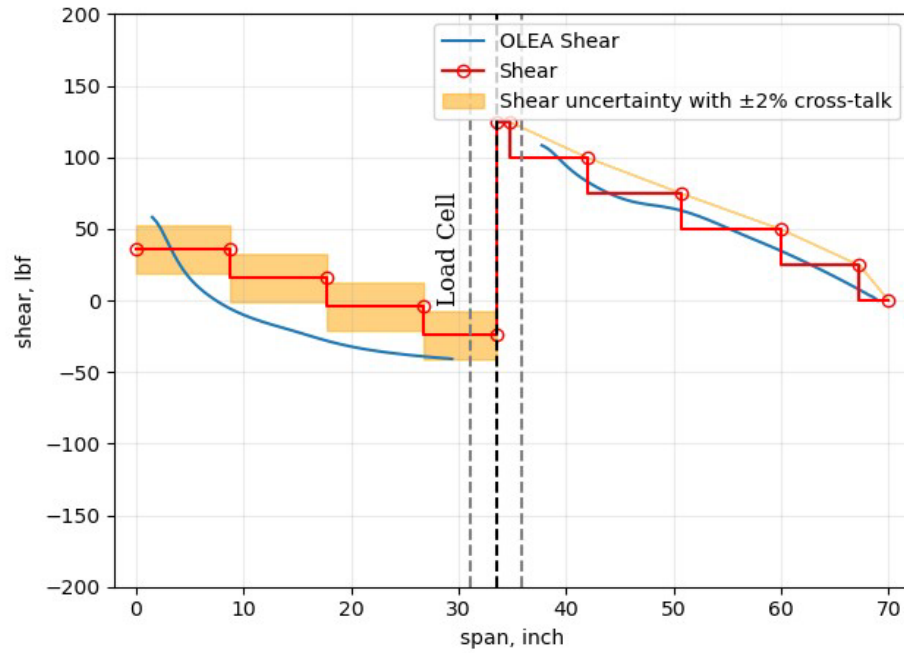


Figure C4. Out-of-plane shear diagram for uniform load case.

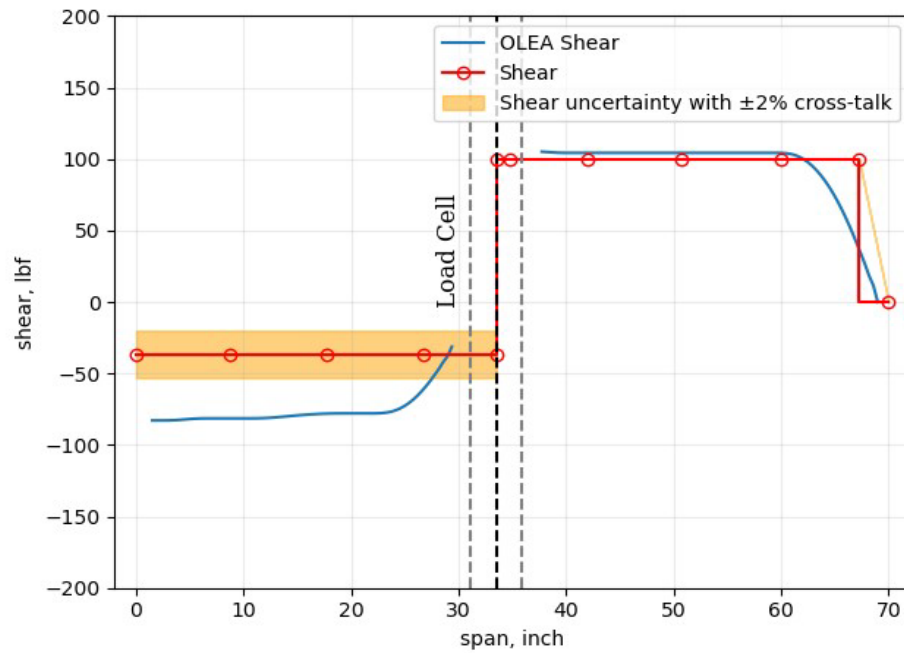


Figure C5. Out-of-plane shear diagram for concentrated wingtip load case.

Appendix D: In-plane Bending Diagrams

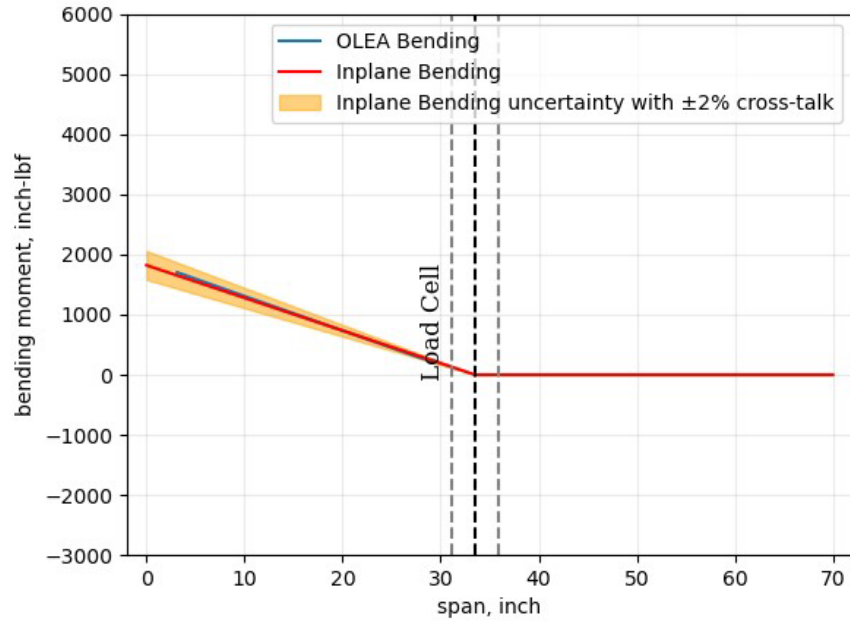


Figure D1. In-plane bending moment diagram for root-biased load case.

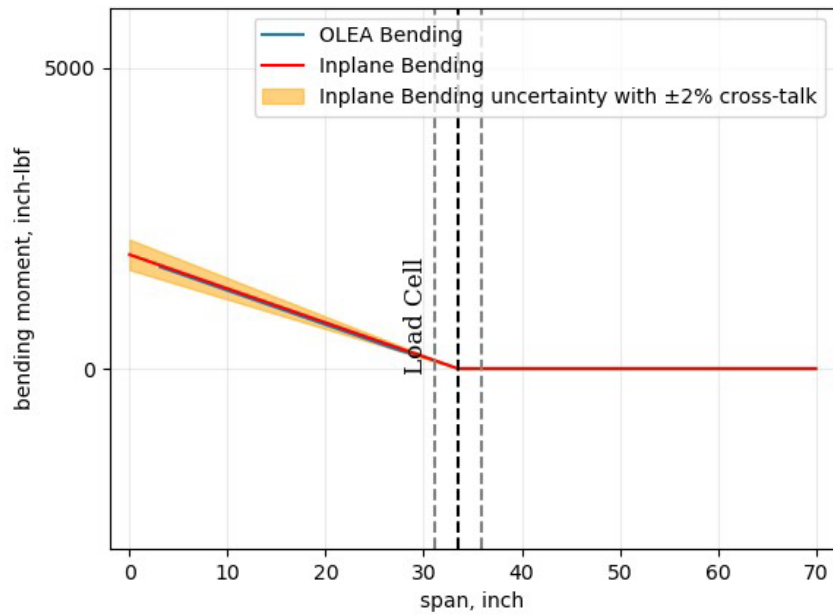


Figure D2. In-plane bending moment diagram for mid-span-biased load case.

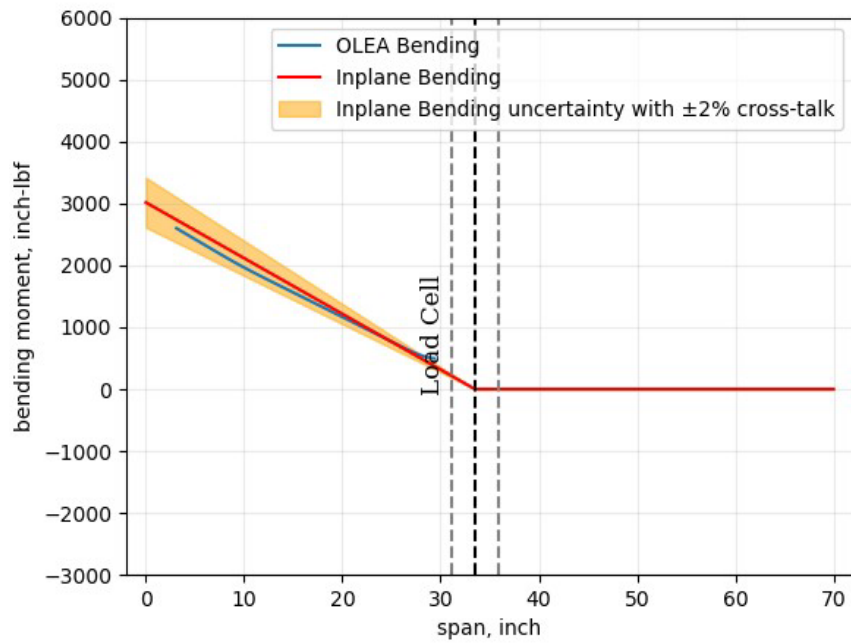


Figure D3. In-plane bending moment diagram for wingtip-biased load case.

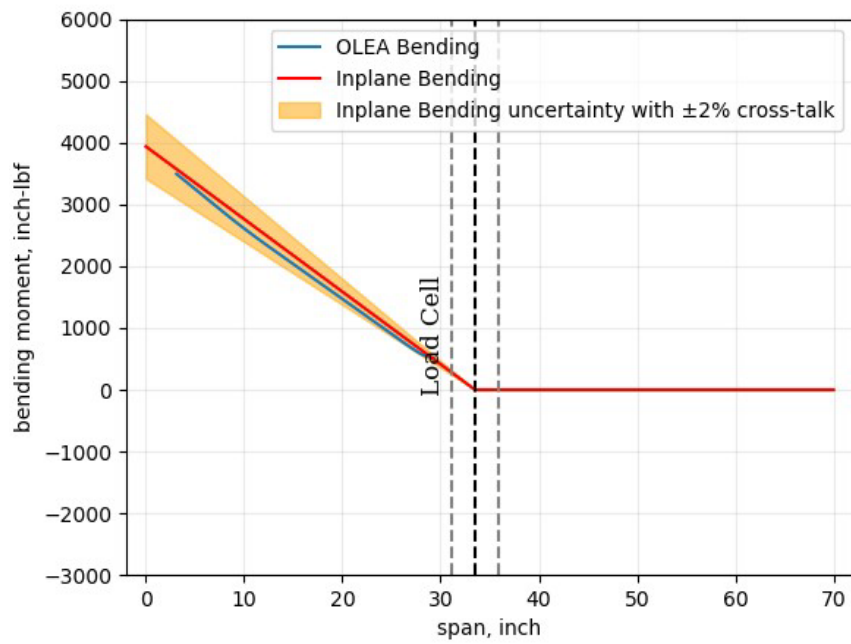


Figure D4. In-plane bending moment diagram for uniform load case.

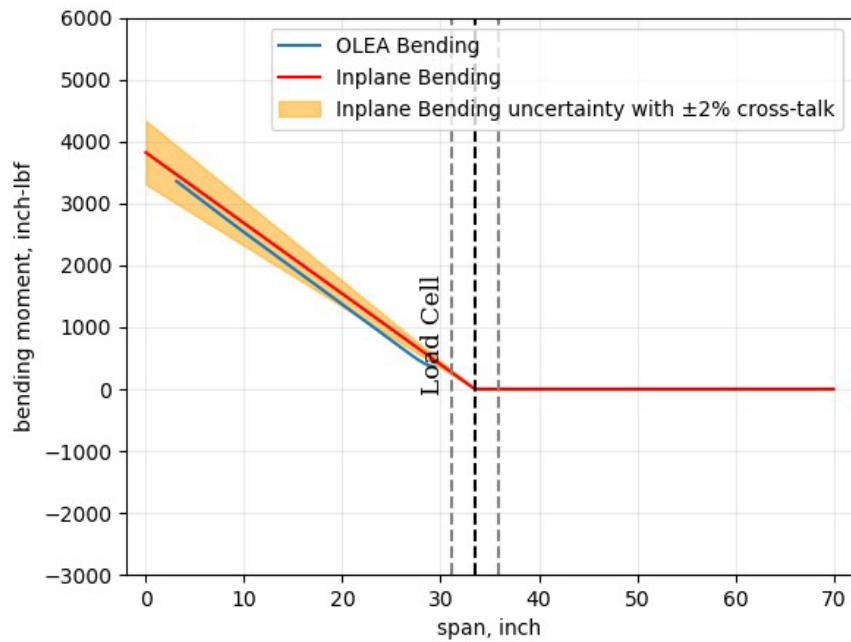


Figure D5. In-plane bending moment diagram for concentrated wingtip load case.

Appendix E: In-plane Shear Diagrams

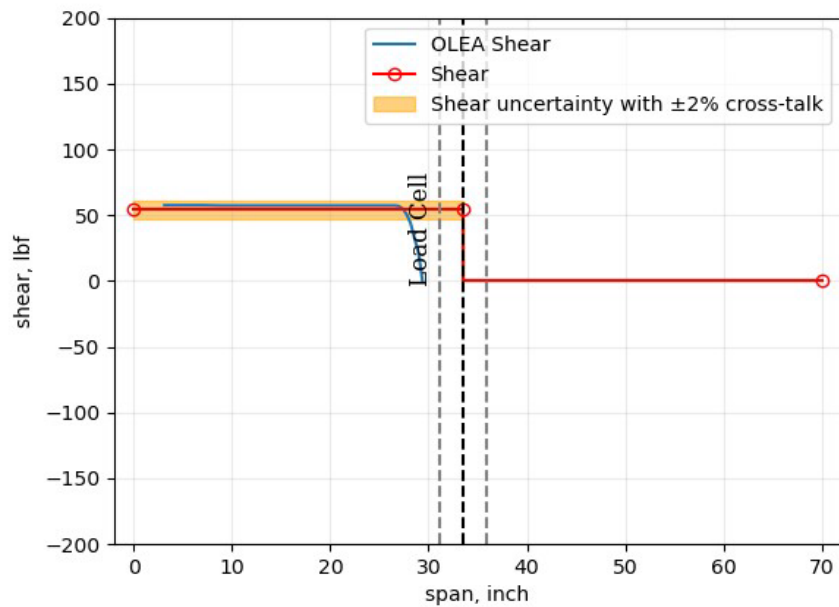


Figure E1. In-plane shear diagram for root-biased load case.

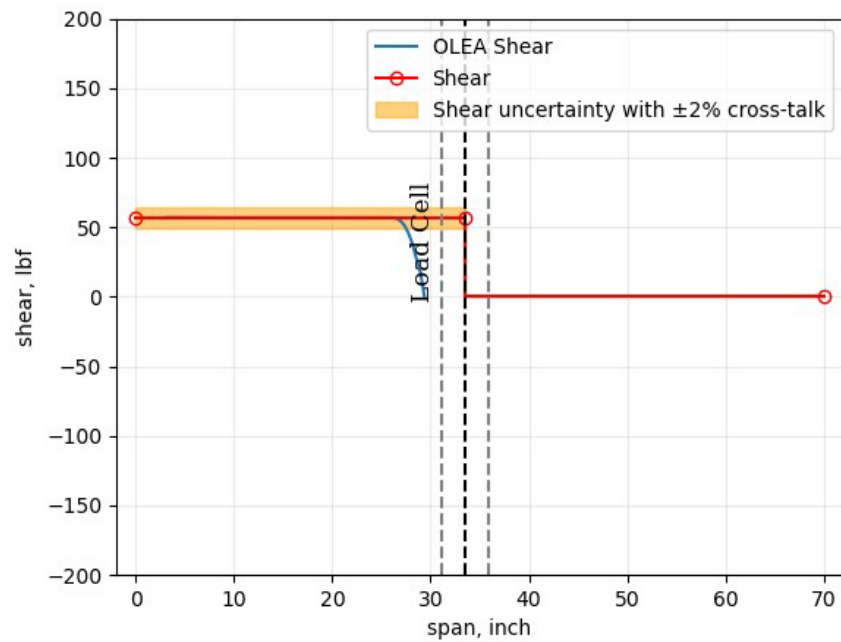


Figure E2. In-plane shear diagram for mid-span-biased load case.

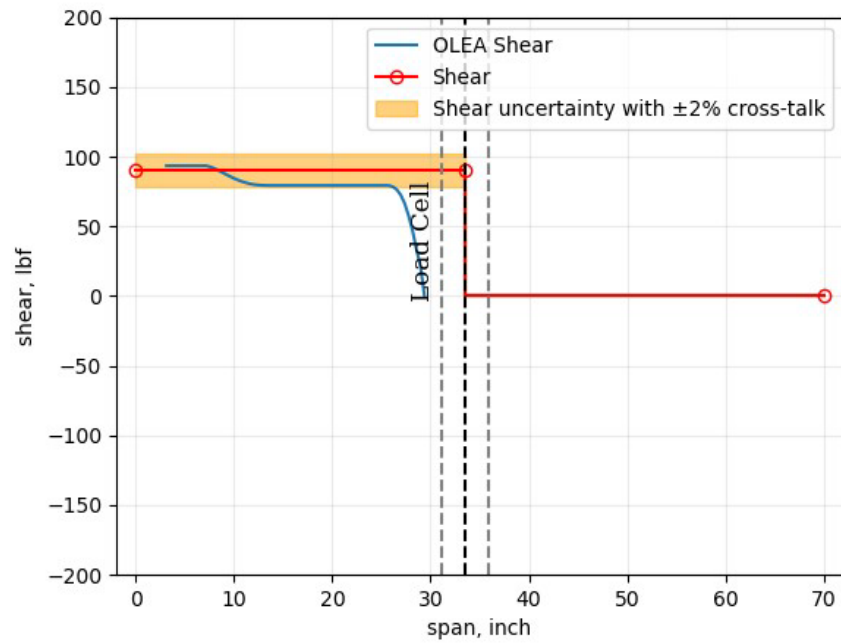


Figure E3. In-plane shear diagram for wingtip-biased load case.

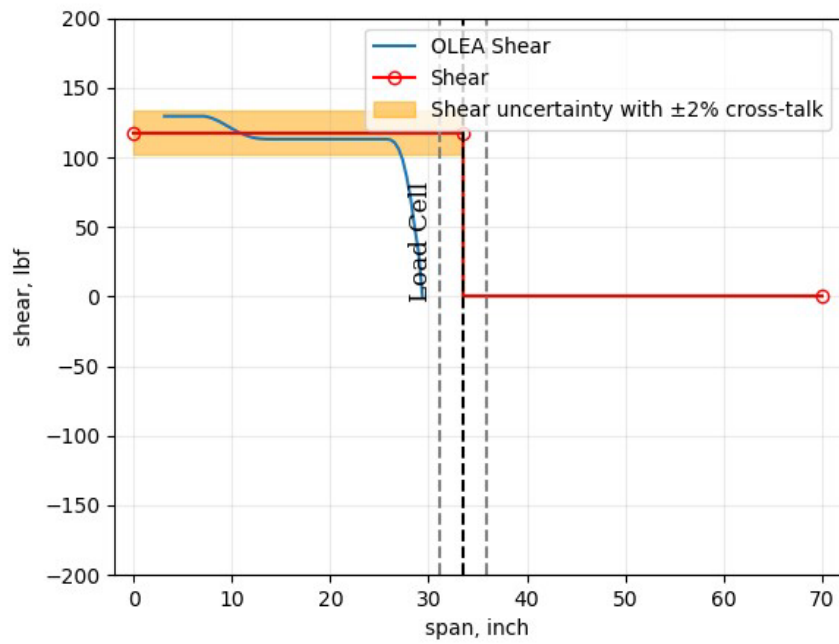


Figure E4. In-plane shear diagram for uniform load case.

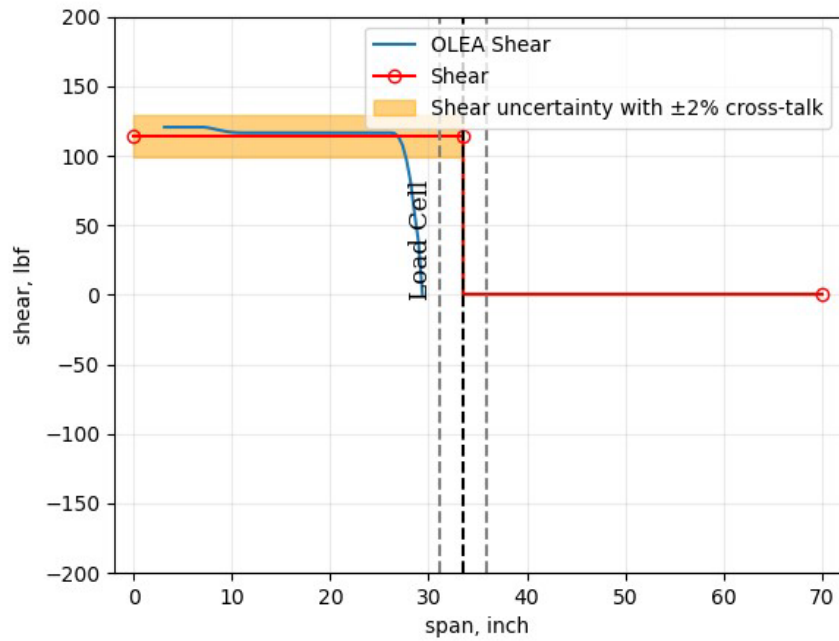


Figure E5. In-plane shear diagram for concentrated wingtip load case.

Appendix F: Out-of-plane displacement

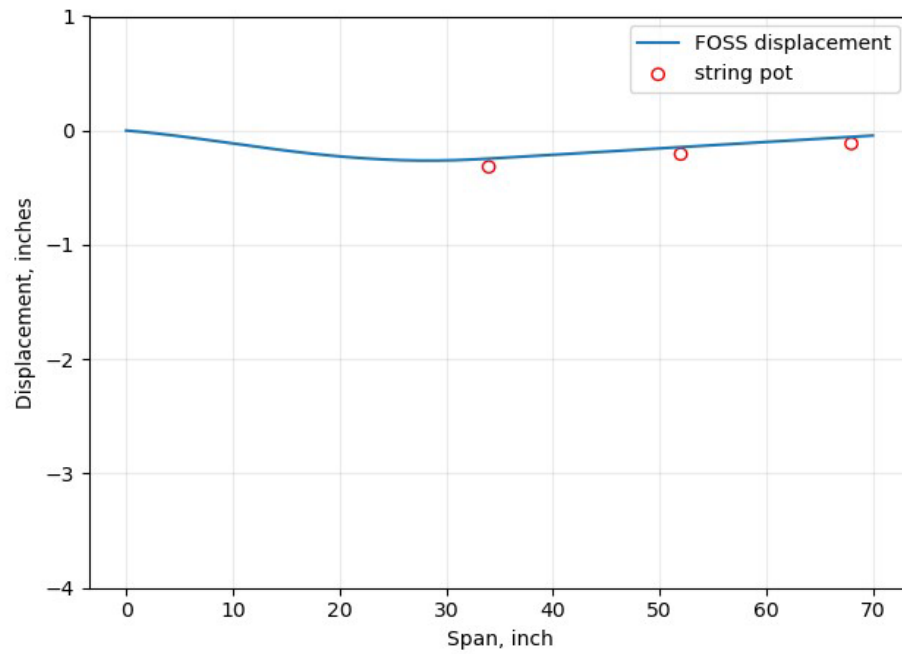


Figure F1 Out-of-plane displacement for root-biased load case.

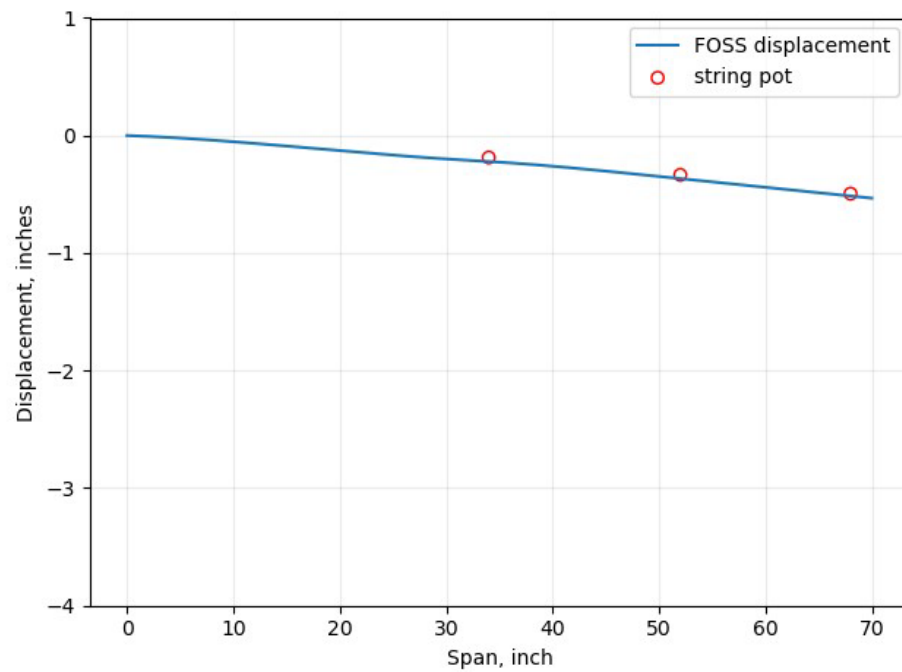


Figure F2. Out-of-plane displacement for mid-biased load case.

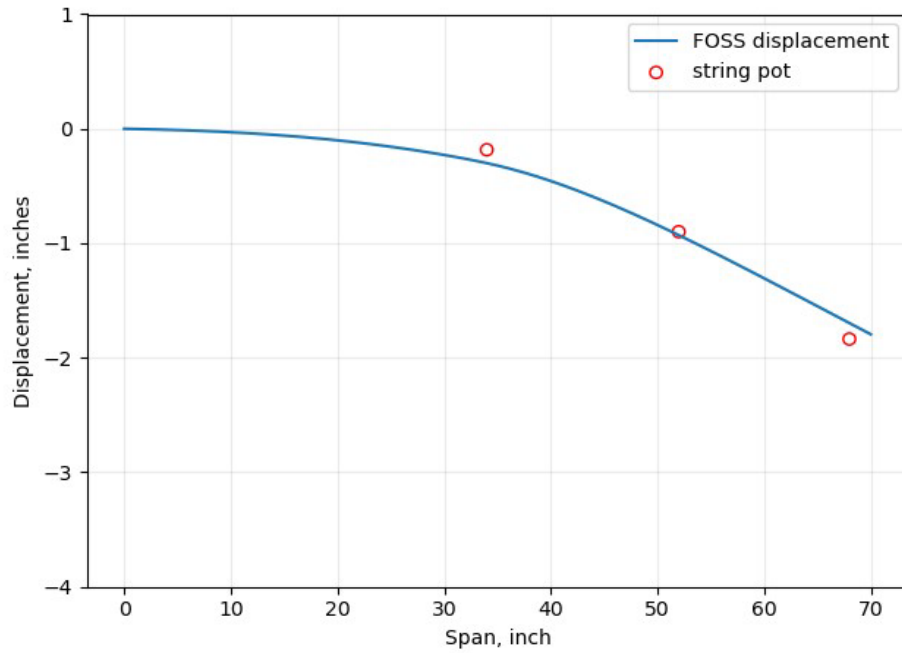


Figure F3. Out-of-plane displacement for tip-biased load case.

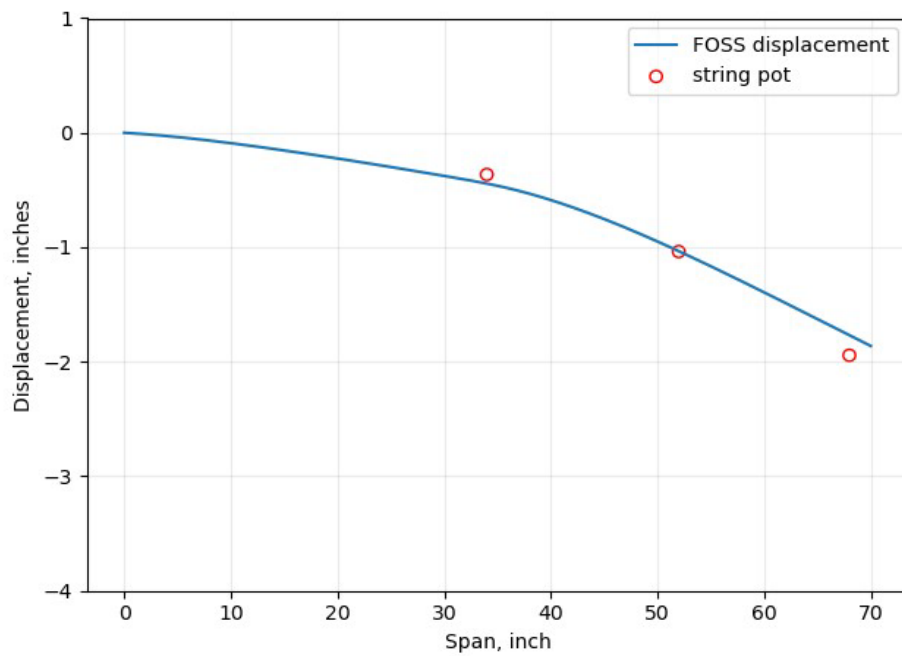


Figure F4. Out-of-plane displacement for uniform load case.

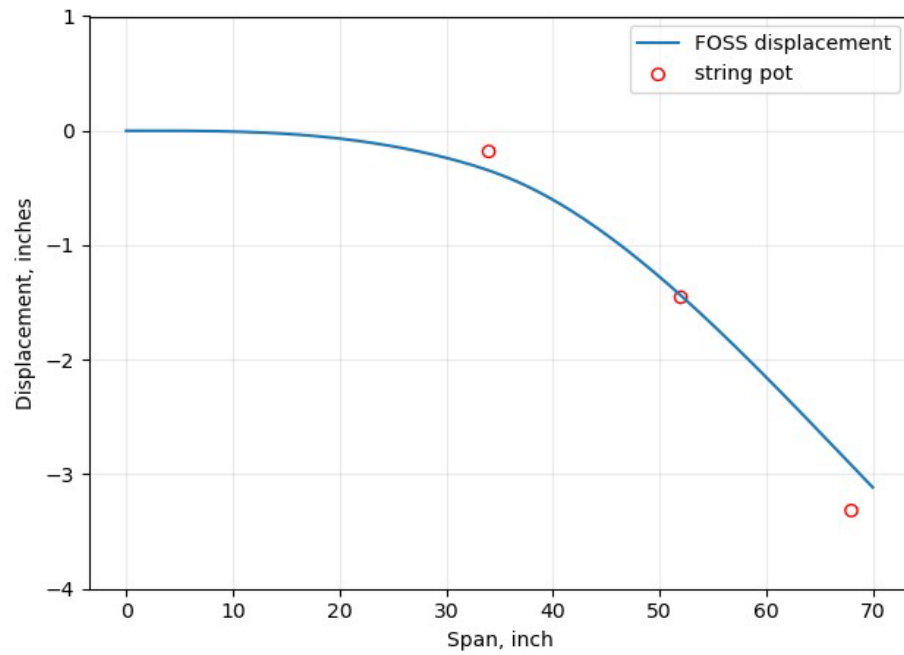


Figure F5. Out-of-plane displacement for concentrated wingtip load case.