





# X-57 Wing Structural Load Testing

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# Agenda

- Background
- Project Schedule
- Airworthiness Approach
- Objectives and Success Criteria
- Test Article
- Load Cases
- Setup and Hardware
- Instrumentation
- Test Procedures
- Test Results
- Strain Gage Calibration Results
- Summary

# Background

## Mod I



Ground validation of DEP



Flight-testing of baseline TECNAM P2006T

Goals:
- Establish baseline TECNAM performance
- Pilot familiarity

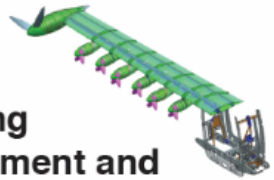
## Mod II



Ground and flight-test validation of electric motors, battery, and instrumentation

Goals:
- Establish electric power system flight safety
- Establish electric TECNAM retrofit baseline

## Mod III



DEP wing development and fabrication



Flight-test electric motors relocated to wing tips on DEP wing including nacelles (but no DEP motors, controllers, or folding props)

Achieves Mod III (high-speed) objectives

## Mod IV



Flight test with integrated DEP motors and folding props (cruise motors remain in wing tips)

Achieves Mod IV (low-speed) objectives

Mod I

Mod II

Mod III and IV

# Partners

## Armstrong Flight Research Center

- Oversight and project management
- Airworthiness/design reviews
- Mission management
- Piloted simulation
- Ground and flight testing
- Power system design specification



## Langley Research Center

- Wing design requirements
- Wing structural analysis
- Vehicle design /analysis
- Flight dynamics simulation
- Wind tunnel testing
- Propulsor sizing



## Glenn Research Center

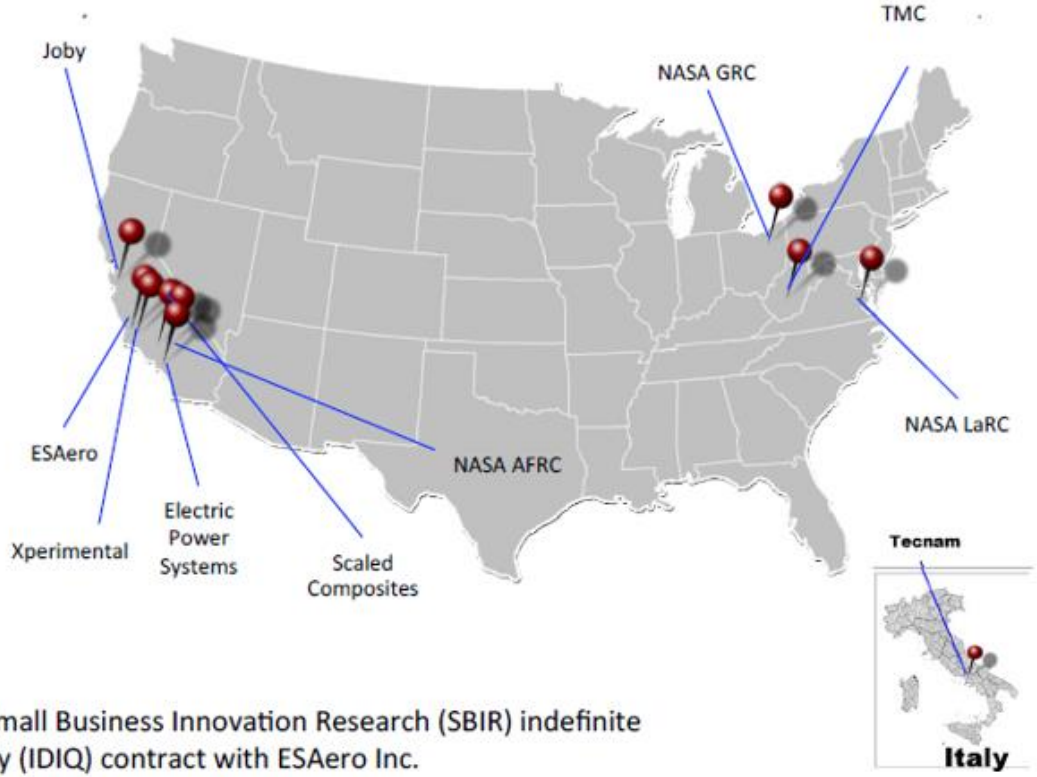
- Thermal Management analysis
- Battery Expertise



# Partners

**Prime Contractor**
ESAero Inc.

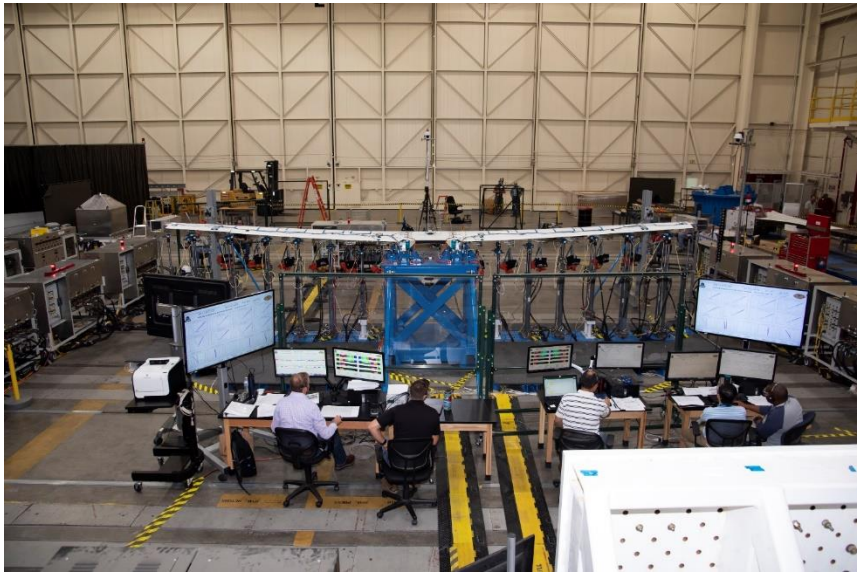
| | |
|---|---|
| **Motors/Controllers** Joby Aviation | **Mod III Wing Design & Fabrication** Xperimental |
| **Mod II Integration** Scaled Composites | **Battery Design & Fabrication** Electric Power Systems (EPS) |
| **Software V&V** TMC | **Airframe** Tecnam |

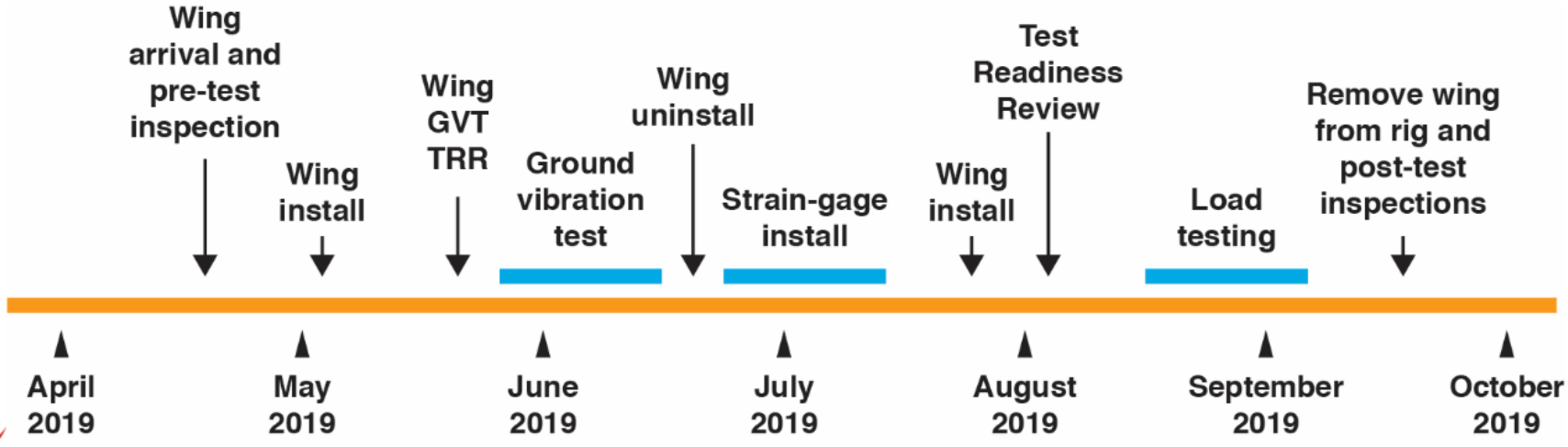



- NASA AFRC has Phase III Small Business Innovation Research (SBIR) indefinite delivery/indefinite quantity (IDIQ) contract with ESAero Inc.
  - NASA AFRC manages Phase III SBIR IDIQ contract with ESAero
  - ESAero manages all subcontracts with suppliers

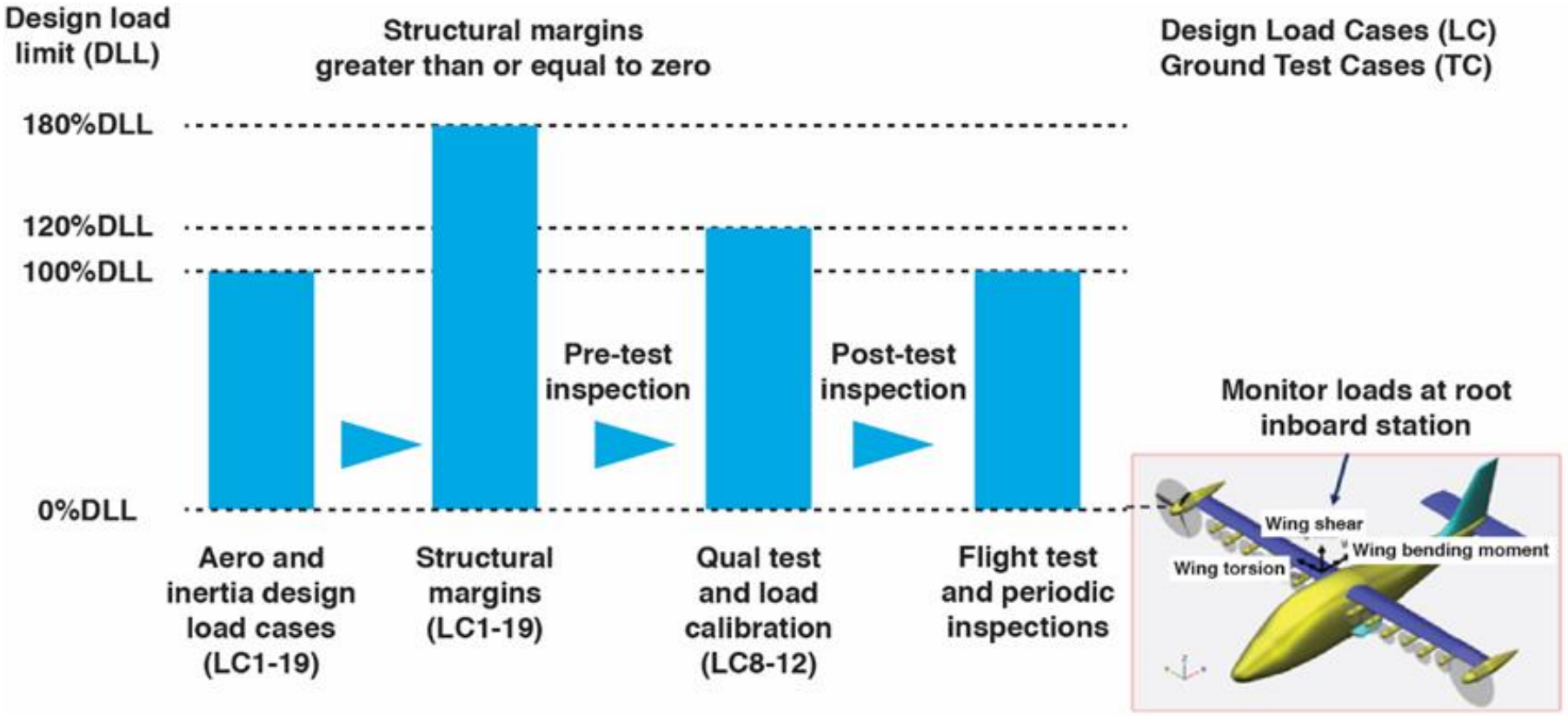
# Project Schedule

- The effort to test the wing began in earnest beginning of April 2019 with the arrival of the wing to the Flight Loads Lab
- The project completed the wing ground vibration and load testing in September 2019





# Structures Airworthiness Approach



# Objectives and Success Criteria

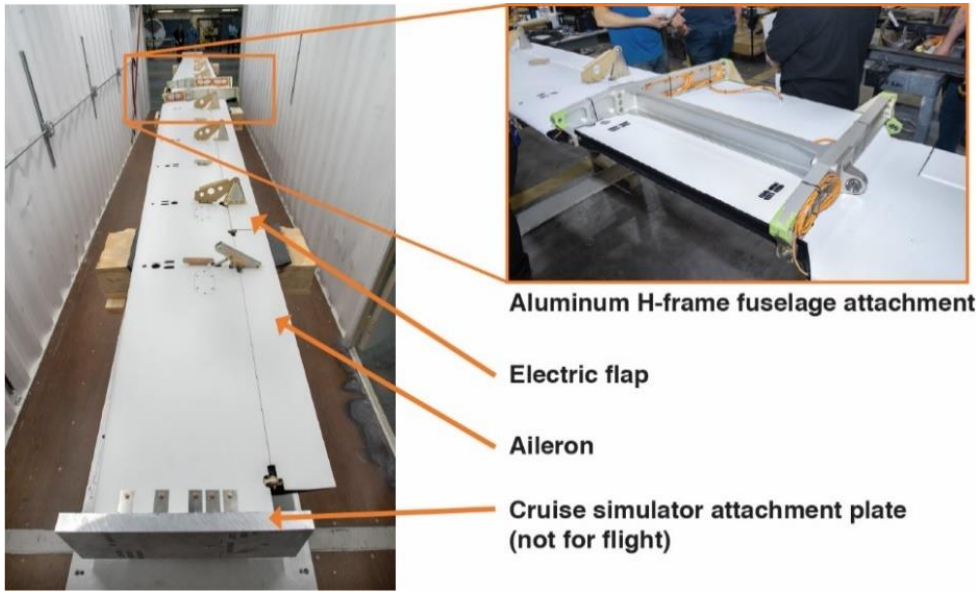
- Goal:
  - To demonstrate and validate the structural integrity of the wing for flight
- Objective:
  - Qualification test the wing structure to 120% Design Limit Load (DLL) (normal shear, bending, and torsion)
  - Qualification test cruise motor mount hard points to 120% DLL (axial in-plane)
  - Produce a database suitable for deriving wing load equations by applying a set of known loads
    - Wing loads will be kept below 100% DLL during flight
  - Verify the control surfaces (flaps and ailerons) are free of binding while the wings are loaded to 100% DLL
  - Collect wing deflection measurement data for FEM model comparison and model tuning

# Objectives and Success Criteria

- Success Criteria
  - Qualification and calibration test loads are applied to the wing as specified in the test plan
  - Data is collected as prescribed in the DAS setup worksheet and test Go/NoGos
  - Flaps and ailerons are deflected throughout their full range at 100% Design Limit Load and any discrepancies in jamming; excessive friction; or excessive deflection are documented

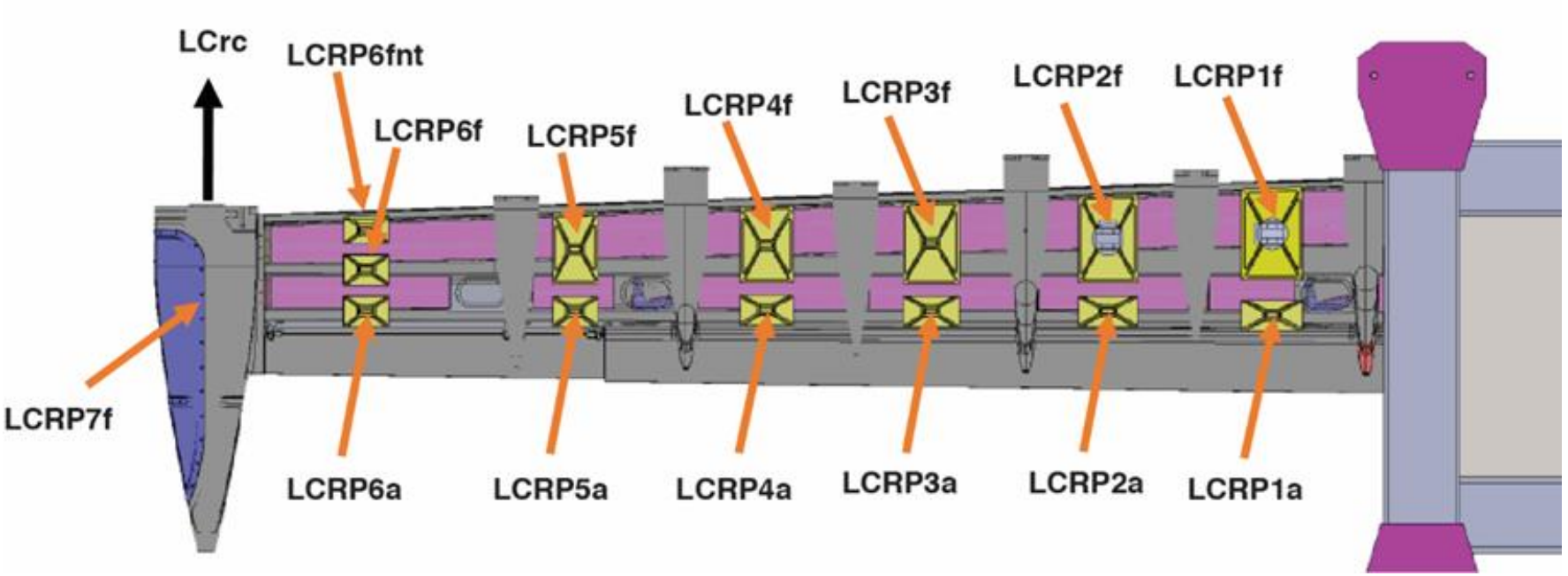
# Test Article

- Three spar, carbon composite wing with a span of 32ft and a chord of approximately 2ft
- Wing Configuration for Proof Test (257lbs)
  - Weight Includes: Wing and H-Frame installed, high lift or cruise simulators not included
- Electric flap actuation system
- Bell crank and push rod aileron actuation






# Load Pad Placement



# Load Case Overview

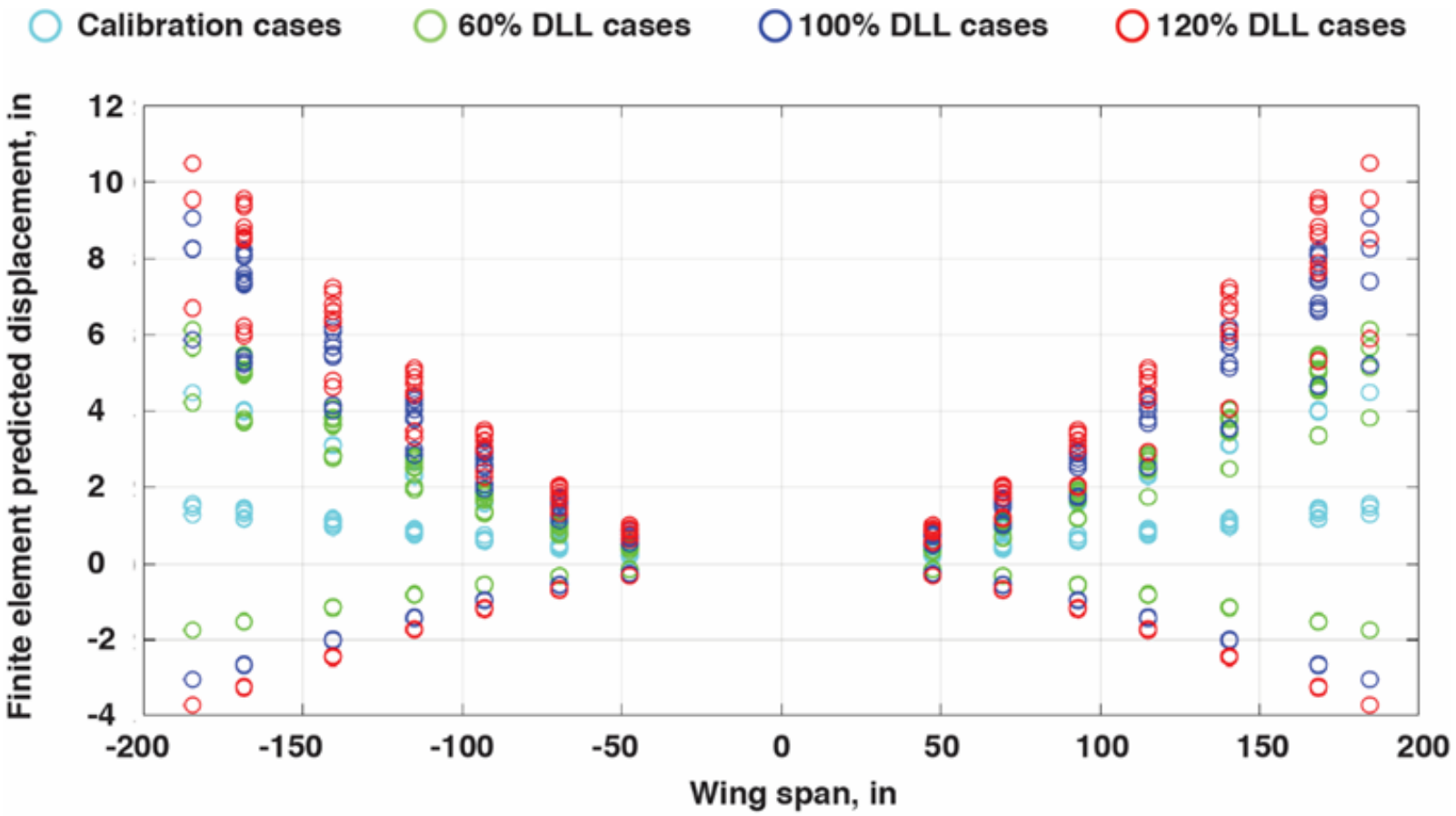
- Aerodynamic loads were calculated based on a 3000 lb aircraft
- The load cases included positive and negative maneuver, gust, rolling, asymmetric flight and flap retracted/extended conditions within the design flight envelope at sea level and 15,000 feet altitude
- Five maximum design load cases (shear, bending, torsion) were selected
- 100% Design Net loads = Aerodynamic Loads + Inertia Flight Wing + Inertia Flight HL + Inertia Flight Cruise
- Target proof test loads = 1.2 * 100% Design Net Load
  - Shear loads < 120% DLL (especially inboard stations)
  - Pad pressure < 15 psi
- Loads applied to FEM to verify failure index

# Load Case Overview

- Symmetric and asymmetric load cases
- 60%: Initial check on displacements and strains
  - Approximately 2g load -> flap actuation binding check
- 100%: Max expected loads in-flight
  - Aileron actuation binding check
- 120%: Qualification loading to verify wing strength
- Each condition had a corresponding high lift inertial loading

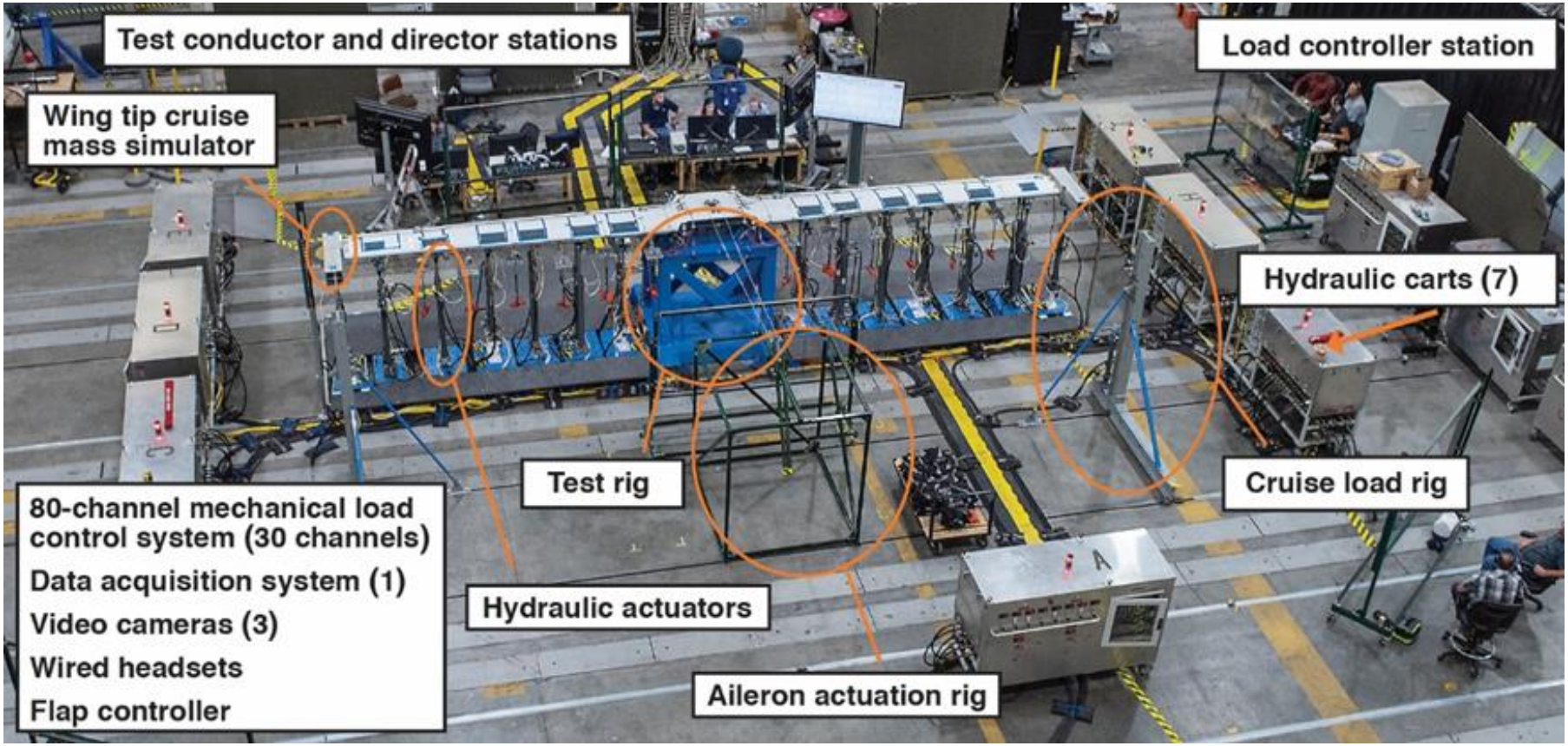
| Case Description Load (lbs) | Design Case | Load Factor | LCLP6fnt | LCLP6a | LCLP6f | LCLP5a | LCLP5f | LCLP4a | LCLP4f | LCLP3a | LCLP3f | LCLP2a | LCLP2f | LCLP1a | LCLP1f | LCRP1f | LCRP1a | LCRP2f | LCRP2a | LCRP3f | LCRP3a | LCRP4f | LCRP4a | LCRP5f | LCRP5a | LCRP6f | LCRP6a | LCRP6fnt |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Positive Bending (60%DLL) | 8 | 0.6 | 100 | 175 | 100 | 175 | 200 | 139 | 259 | 139 | 286 | 125 | 325 | 120 | 230 | 230 | 120 | 325 | 125 | 286 | 139 | 259 | 139 | 200 | 175 | 100 | 175 | 100 |
| Positive Bending (100%DLL) | 8 | 1.0 | 167 | 292 | 167 | 292 | 333 | 231 | 431 | 232 | 476 | 208 | 542 | 201 | 383 | 383 | 201 | 542 | 208 | 476 | 232 | 431 | 231 | 333 | 292 | 167 | 292 | 167 |
| Positive Bending (120%DLL) | 8 | 1.2 | 200 | 350 | 200 | 350 | 400 | 278 | 517 | 279 | 571 | 250 | 650 | 241 | 459 | 459 | 241 | 650 | 250 | 571 | 279 | 517 | 278 | 400 | 350 | 200 | 350 | 200 |

# Predicted Displacements from FEM

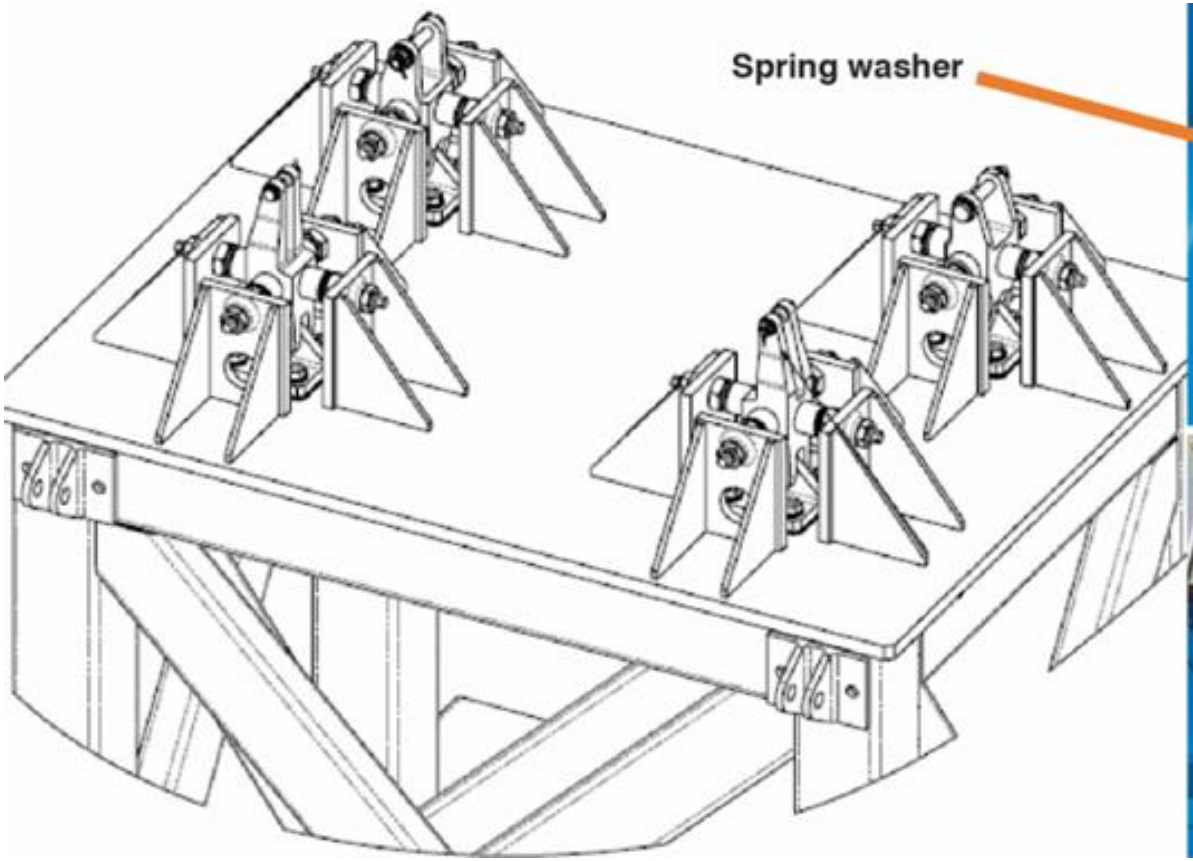


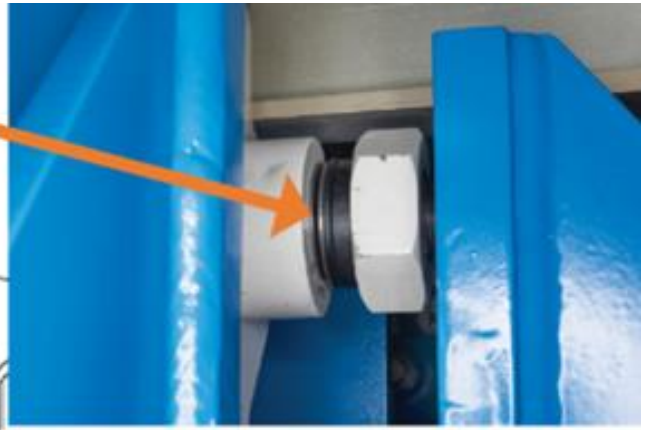

- Predicted displacements provided actuator stroke ranges

# Test Setup


Test conductor and director stations
Load controller station
Wing tip cruise mass simulator
Hydraulic carts (7)
Test rig
Cruise load rig
80-channel mechanical load control system (30 channels)
Data acquisition system (1)
Video cameras (3)
Wired headsets
Flap controller
Hydraulic actuators
Aileron actuation rig

# Test Setup



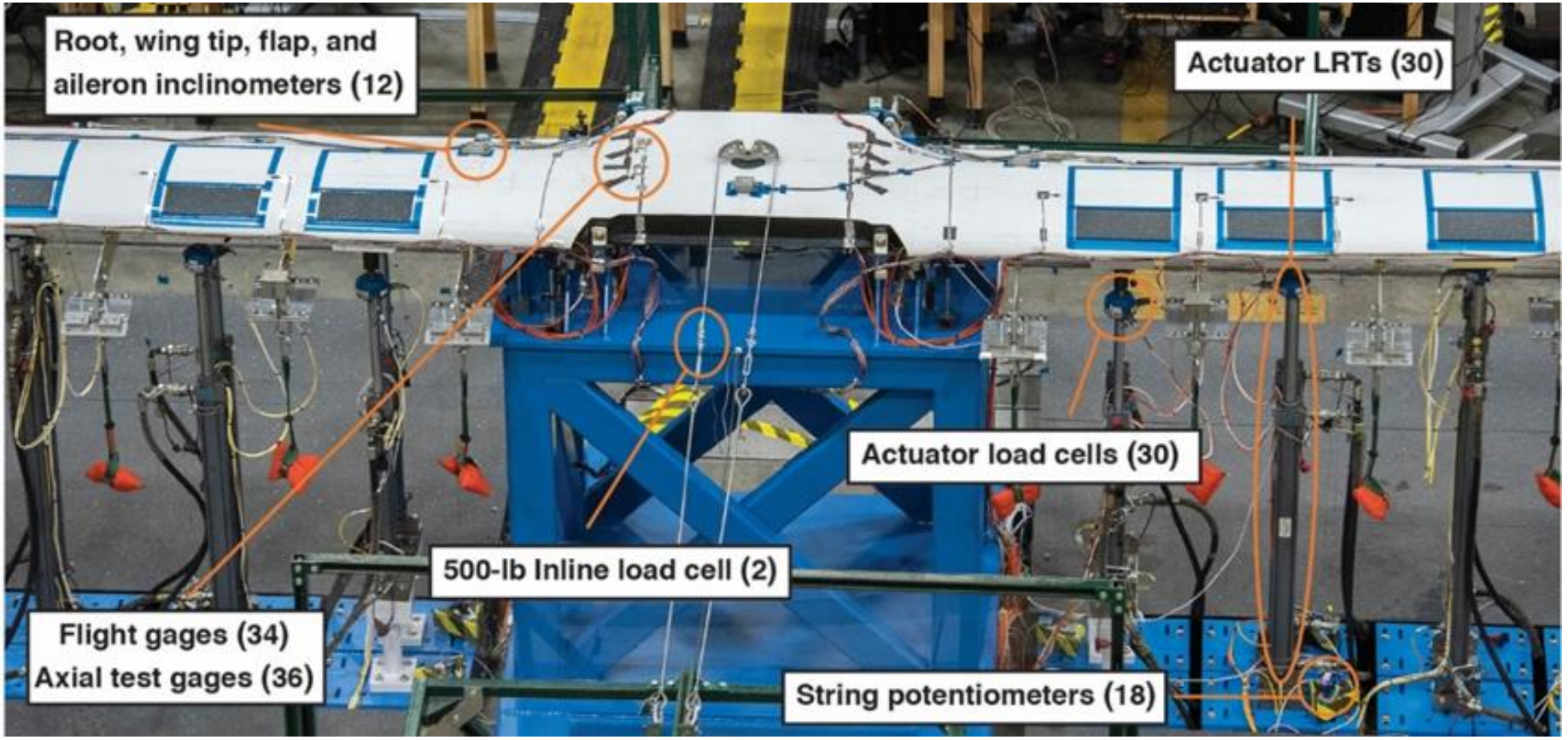





# Test Setup



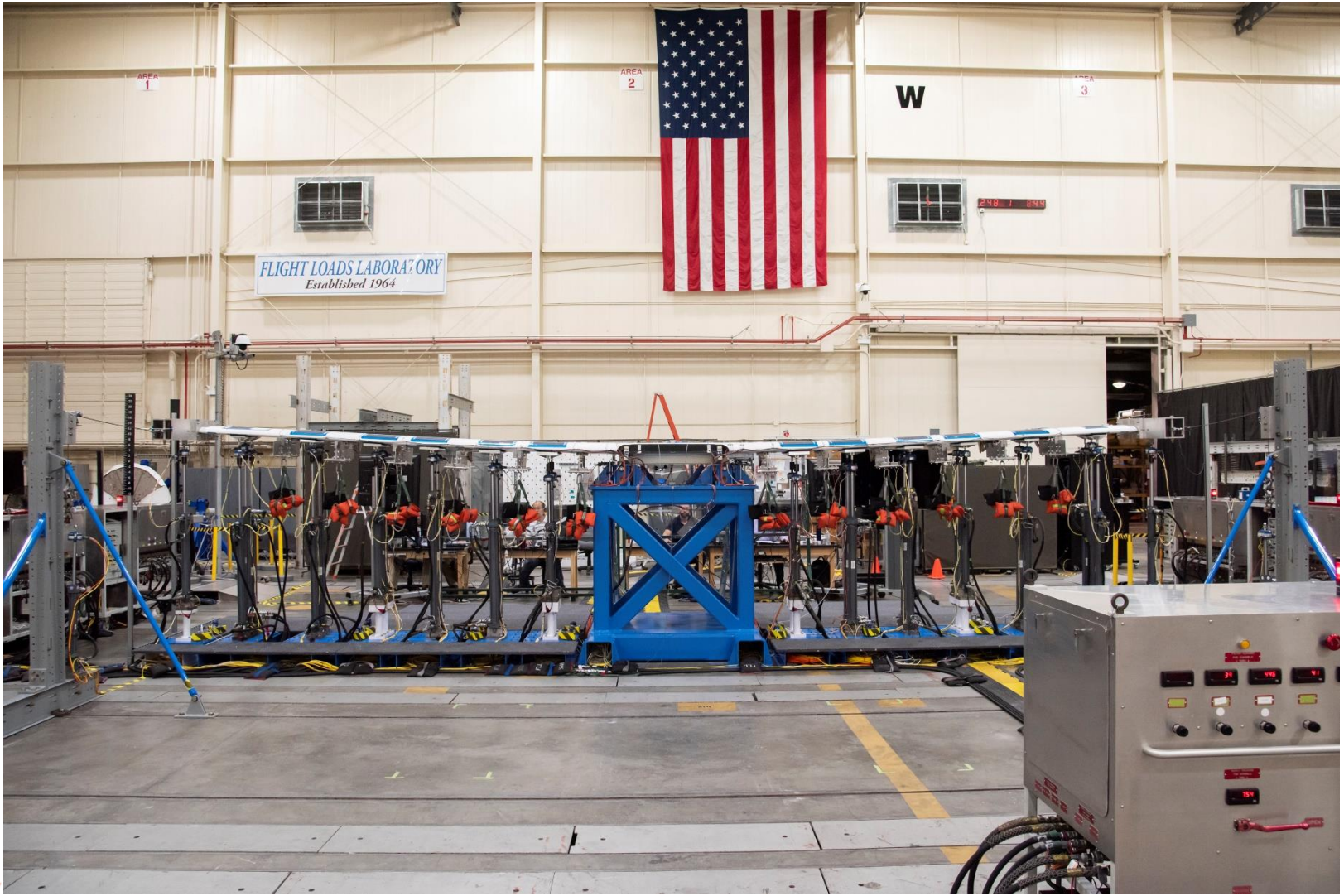
# Instrumentation



# Test Sequence

| Load Sequence | Hydraulic or Shot bag | Flap Check | Aileron Check |
|---|---|---|---|
| 2g inertia landing, 120% Shot Bag | Shot Bag | | |
| Cruise Case, 120% | Hydraulic | | |
| 2g inertia landing, 120% w/Cruise | Shot Bag + Hydraulic | | |
| Cal, 9a | Hydraulic | | |
| Cal, 9c | Hydraulic | | |
| Cal, 9g | Hydraulic | | |
| Cal, 9i | Hydraulic | | |
| #8, 60% | Hydraulic | Yes | |
| #9, 60% | Hydraulic | Yes | |
| #11, 60% | Hydraulic | Yes | |
| #11, 60% | Hydraulic | Yes | |
| #8, 60% | Hydraulic | Yes | |
| #8, 60% - w/Cruise | Hydraulic | Yes | |
| #12, 60% | Hydraulic | Yes | |
| #12, 60% | Hydraulic | Yes | |
| #8, 60% | Hydraulic | Yes | |
| #8, 100% | Hydraulic | | Yes |
| #9, 100% | Hydraulic | | Yes |
| #11, 100% | Hydraulic | | Yes |
| #11, 100% | Hydraulic | | Yes |
| #12, 100% | Hydraulic | | Yes |
| #12, 100% | Hydraulic | | Yes |
| #8, 120% | Hydraulic | | |
| #8, 120% - w/Cruise | Hydraulic | | |
| #9, 120% | Hydraulic | | |
| #11, 120% | Hydraulic | | |
| #11, 120% | Hydraulic | | |
| #12, 120% | Hydraulic | | |
| #12, 120% | Hydraulic | | |
| Cruise Case, 120% | Hydraulic | | |
| #10, 60% Shot Bag | Shot Bag | | |
| #10, 100% Shot Bag | Shot Bag | | Yes |
| #10, 120% Shot Bag | Shot Bag | | |
| #8, 60% | Hydraulic | | |
| #9, 60% | Hydraulic | | |
| #9, 60% - w/Cruise | Hydraulic | | |

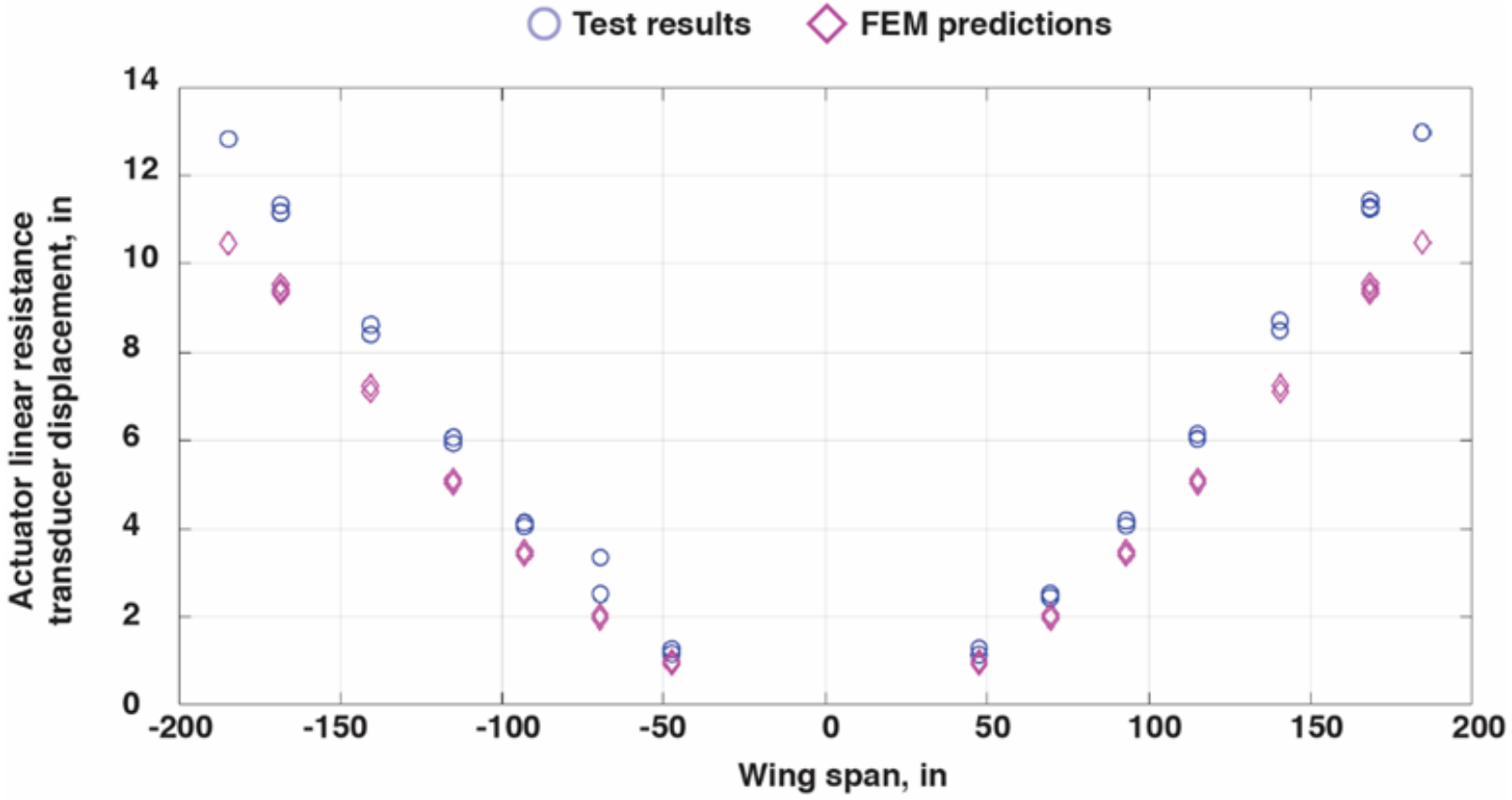
# Hydraulic Upload Testing



# Shotbag Download Testing

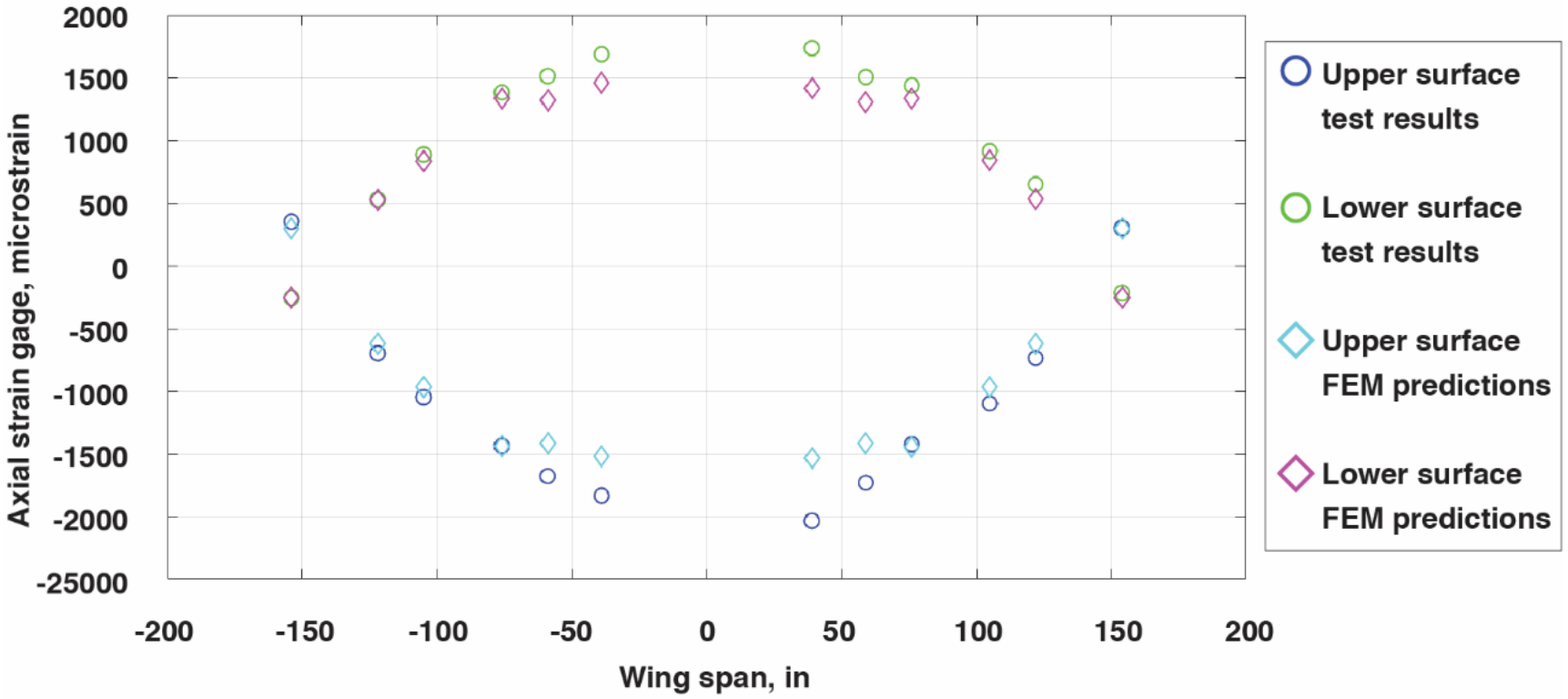


# Case 8 120% DLL Test Results




- Finite Element Model under predicted the wing displacement by about 20% at wing tips

# Case 8 120% DLL Test Results




- Finite Element Model (FEM) outboard axial strains matched reasonably well to the test data.
- Axial strains near the wing root were under predicted by the FEM

# Strain Gage Calibration Results

- Full bridge metallic strain gages were installed on the left and right wing root
- Gages were located and oriented to measure
  - Shear,
  - Bending Moment
  - Torque
- Load equations were calculated using a linear regression of the applied loads and strain gage output
- Check case errors range from 4% to 8%



| | GAGE ID | | | | EQDE RMS ERROR % | Check RMS ERROR % |
|---|---|---|---|---|---|---|
| Leftwing Shear | LWS023fs | LWS017ms | LWS017rs | LWRB014msl | 2.21 | 4.29 |
| Leftwing Bending | LWS023fs | LWS017ms | LWB017rsl | LWT017fsl | 2.24 | 5.56 |
| Leftwing Torsion | LWT017fsl | LWT017rsu | LWT017rsl | LWRB014rsu | 3.70 | 7.92 |
| Right Wing Shear | RWS023fs | RWS017ms | RWB017rsu | RWRB014msu | 2.60 | 8.51 |
| Right wing Bending | RWS023fs | RWB017rsl | RWT017fsl | RWT017rsu | 2.40 | 6.33 |
| Right wing Torsion | RWS017ms | RWB017msl | RWT017fsl | RWRB014msl | 3.43 | 7.16 |

LW – Left Wing, RW – Right Wing
S – Shear, B – Bending, T – Torque
014, 017, 023 – Wing Station in inches
fs – front spar, ms – main spar, rs - rear spar
l – lower, u - upper

# Summary and Lessons Learned

- Conservative time tested techniques -> successful test
- High lift and cruise inertial loads made for a challenging test design
  - Tip actuators pulled in opposite direction to the lift loads
  - Test wing vs real wing was a constant discussion
  - You can't scale 60%, 100%, 120% loads due to inertial loading
- Large number of actuators made for drawn-out day of test activities
- Complex wing root load path effected strain gage output and wing FEM comparisons
- Wing deflections were about 20% higher than predicted
- Wing performed flawlessly under the required loads