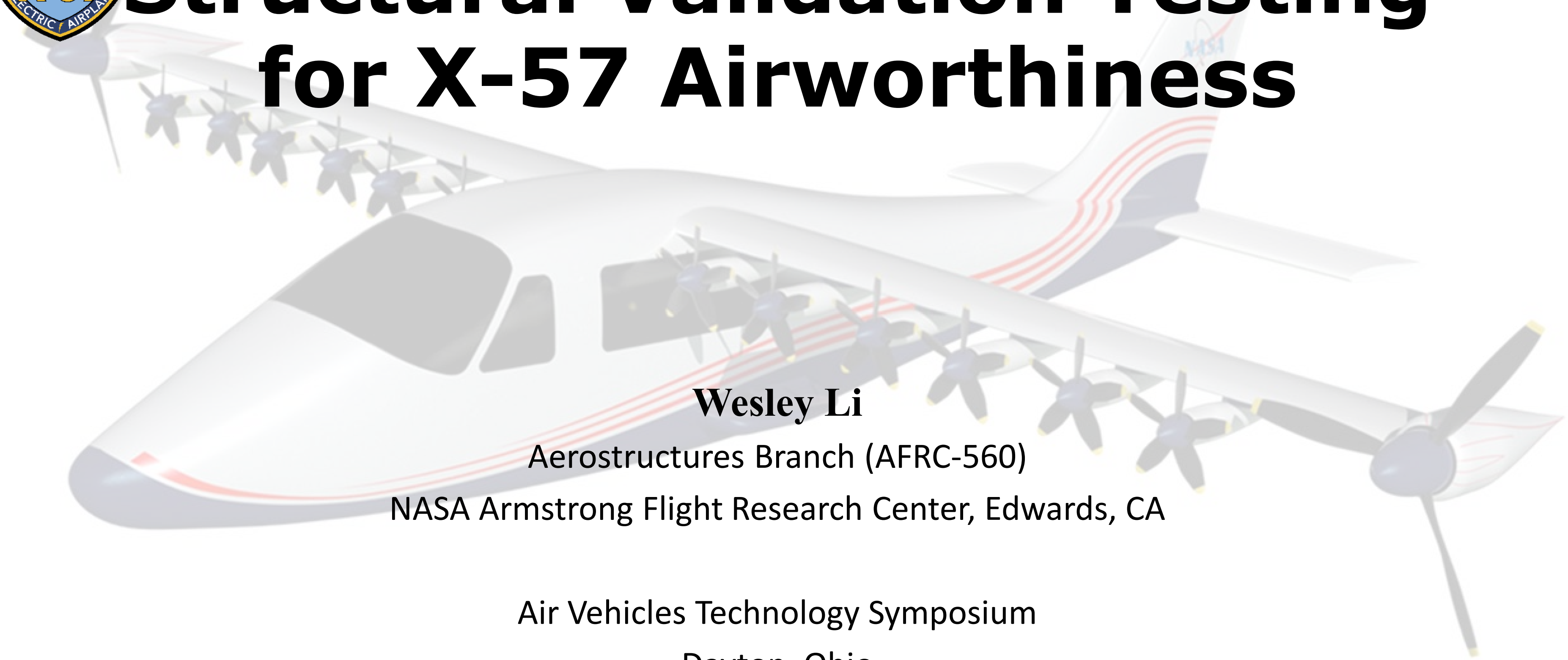
Structural Validation Testing for X-57 Airworthiness



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NASA Armstrong Flight Research Center, Edwards, CA

Air Vehicles Technology Symposium

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Outline

- Aircraft Structural Safety of Flight Guidelines
- X-57 Maxwell Overview
- X-57 Structural Design Criteria
- X-57 Wing Airworthiness Approach
- X-57 Wing Proof and Loads Calibration Test
- Summary and Lessons Learned

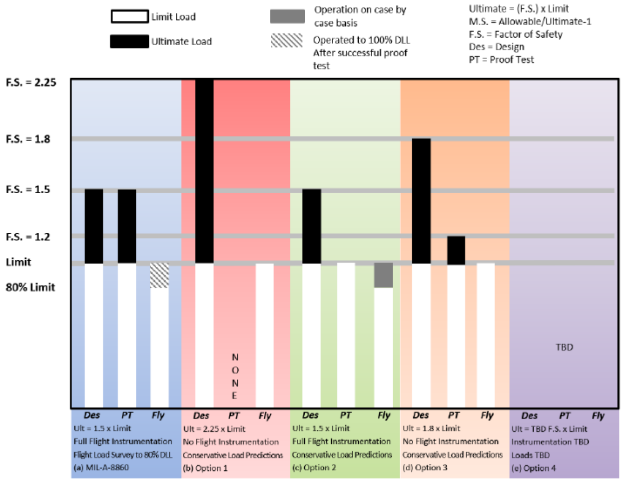
Aircraft Structural Safety of Flight Guidelines

- NASA Armstrong Flight Research Center (AFRC) Aircraft Structural Safety of Flight Guidelines, AFG-7123.1-001
- Purpose: to provide guidelines for the structural design of experimental aircraft, aircraft structural components, structural modifications to existing experimental aircraft, and a completely new one-of-a-kind experimental airplane operated at AFRC
- The initial design criteria and airworthiness approach consider design factor of safety, structural instrumentation options, proof test options, flight test operational envelope, and inspection options
- Can be tailored based on the risk posture of an individual project

Factor of safety for Design and Analysis

Factor of Safety	Material	Condition
2.25 ~ 3.0	Composite	Structure verified by analysis along with building block approach
2.25	Metal	Structures verified by analysis only
1.80	Metal or Composite	Structure verified by proof tests up to 120% Design Limit Load (DLL)
1.50	Metal or Composite	Structural proof test plus full flight instrumentation
additional 1.15	Joints and Fittings	Where failure of one fastener, pin, or lug could result in loss of a component

Integrated Design Criteria (AFG-7123.1, Fig 1)



X-57 Maxwell Background

Mod I

Ground validation of DEP

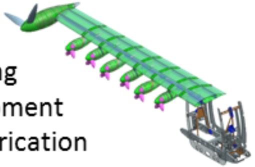
Flight testing of baseline Tecnam P2006T

Mod II

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

Mod III

DEP wing development and fabrication



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

Mod IV

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

Goal: To demonstrate a 500-percent increase in high-speed cruise efficiency.

Partners

NASA Langley: Vehicle, Wing, Performance, Controls IPTs

NASA Armstrong: Power, Instrumentation IPTs, Flight Ops

NASA Glenn: Battery Testing, Thermal Analysis, HL Motor Controller Development (Mod IV)

Empirical Sys. Aero.: Prime contractor

Scaled Composites: Mod II Integration (batteries, motors, controllers, cockpit)

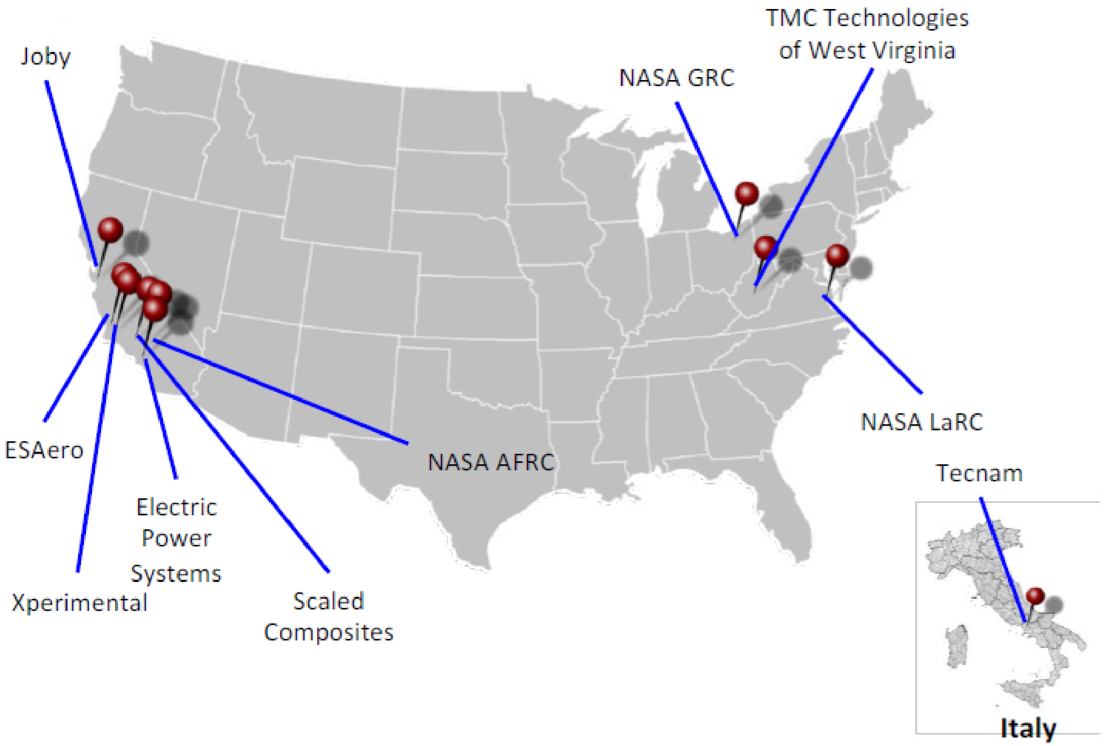
Joby Aviation: Mod II Cruise Motor & Controller development

Xperimental: Wing design and manufacturing

Electric Power Sys.: Battery development

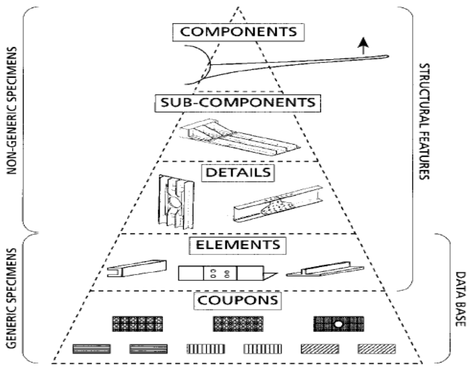
TMC Technologies: Software V&V

Tecnam: Baseline COTS airframe without engines

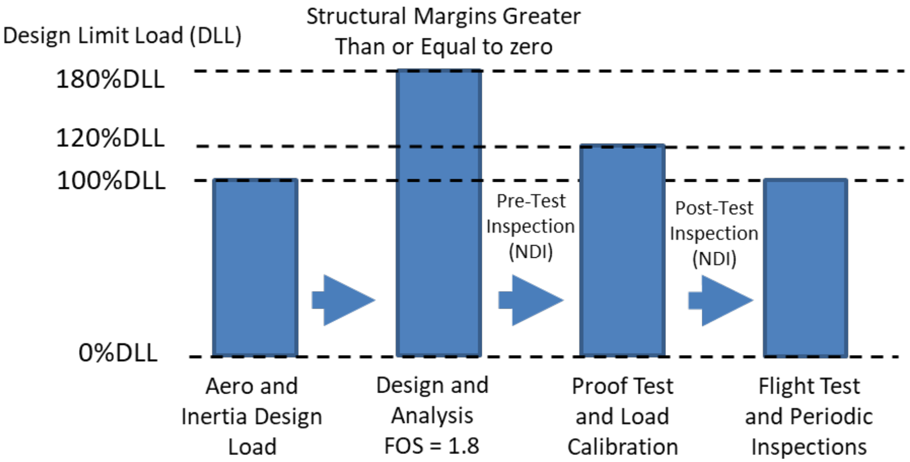


X-57 Composite Wing Airworthiness Approach

- Goal: To demonstrate and validate the structural integrity of the wing for flight
- Building-block approaches for testing and analysis
  - Contractors provide their composite cure process, process specification, and process control for AFRC review and approve
  - Coupon and component tests
- Design to 1.8 FS, proof to 120% flight limit, full flight instrumentation, fly to 100% proof load



MIL-HDBK-17-1F (2002)

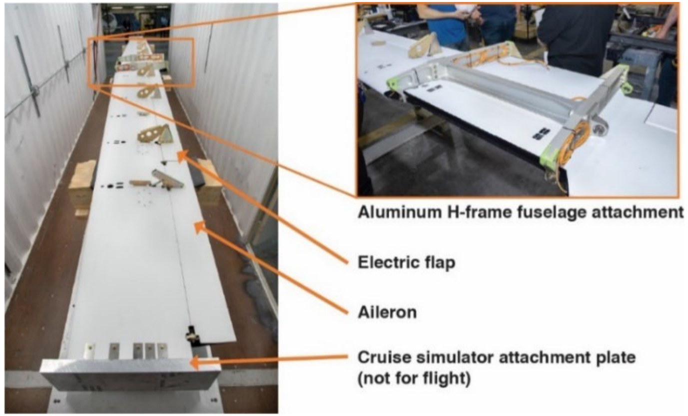


Proof and Loads Calibration Test Success Criteria

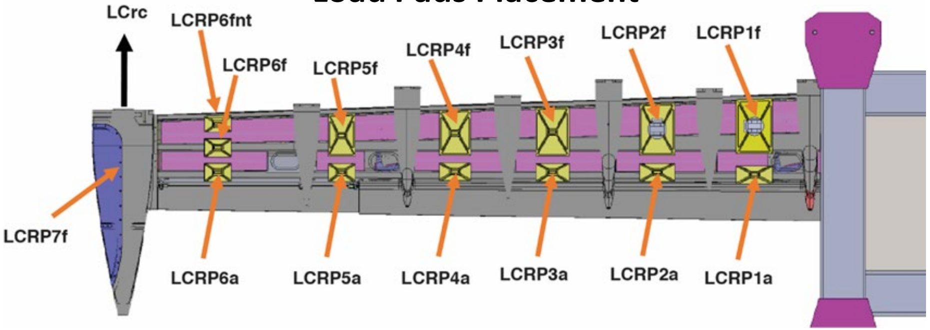
- Proof test (Qualification test) the wing structure to 120% Design Limit Load (DLL) (normal shear, bending, and torsion)
- Proof test cruise motor mount hard points to 120% DLL (axial in-plane)
- Loads Calibration test to produce a database suitable for deriving wing load equations by applying a set 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
- Pre- and post-NDI test to verify the structural integrity of the wing

Mod III Wing Test Article

- Designed, analyzed and fabricated by Xperimental in San Luis Obispo, CA
- Three spar, carbon composite wing with a span of 32ft and a chord of approximately 2ft
- Aerodynamic loads were calculated based on a 3000 lbs aircraft
- The load cases included positive and negative maneuver (+3.4/-1.7g), gust, rolling, asymmetric flight and flap retracted/extended conditions within the design flight envelope at sea level and 15k feet altitude
- Wing Configuration for Proof Test (257 lbs)
  - Weight Includes: Wing and H-Frame installed
  - High lift or cruise simulators not included
  - Total 26 load pads



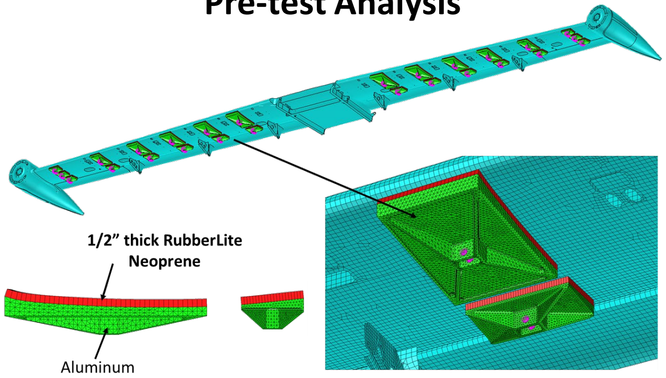
Load Pads Placement



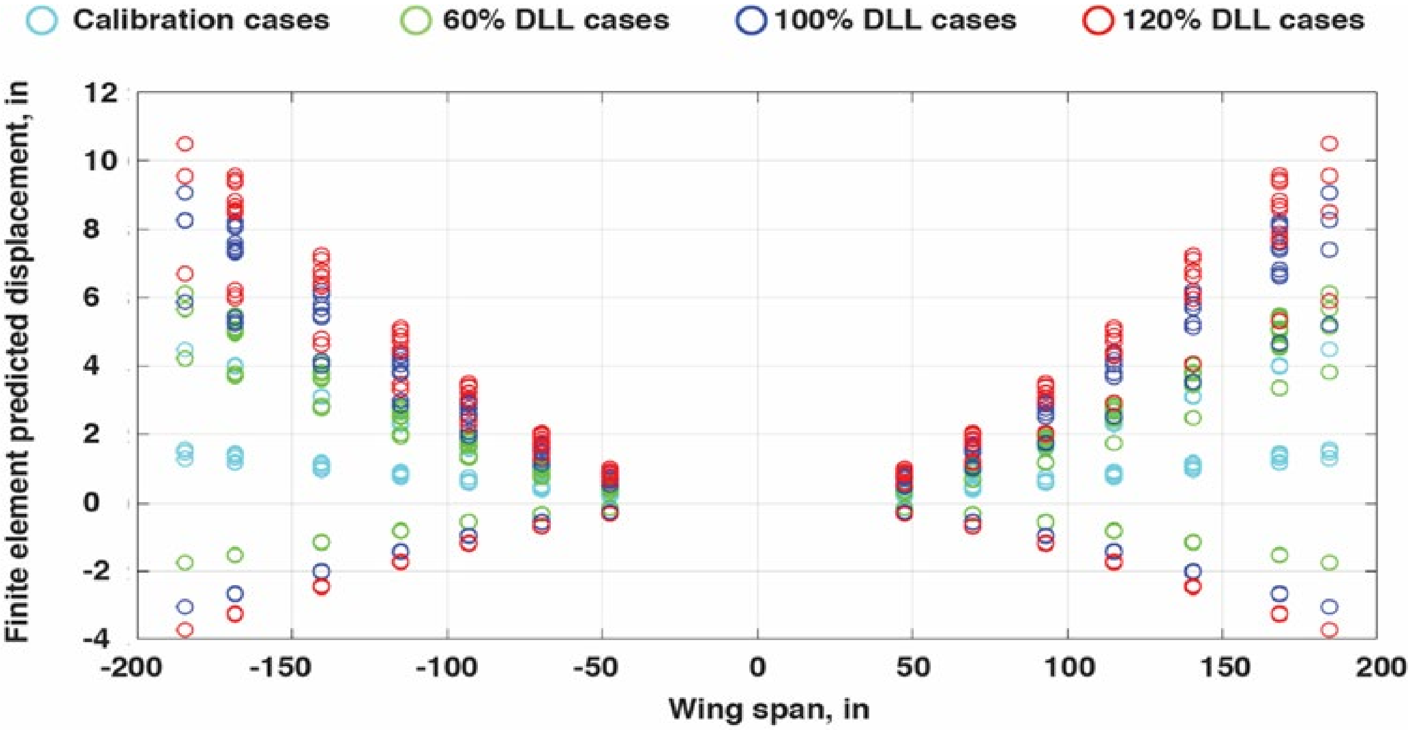
Test Load Case Overview

- Five maximum design load cases (shear, bending, torsion) were selected
- 100% Design Net loads = Aero Loads + Inertia Flight Wing + Inertia Flight Motors
- Target proof test loads = 1.2 * 100% Design Net Load
  - Shear loads < 120% DLL (especially inboard stations)
  - Pad pressure < 15 psi
- 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
- Pre-test analysis was performed
  - Loads applied to FEM to verify failure index

Pre-test Analysis

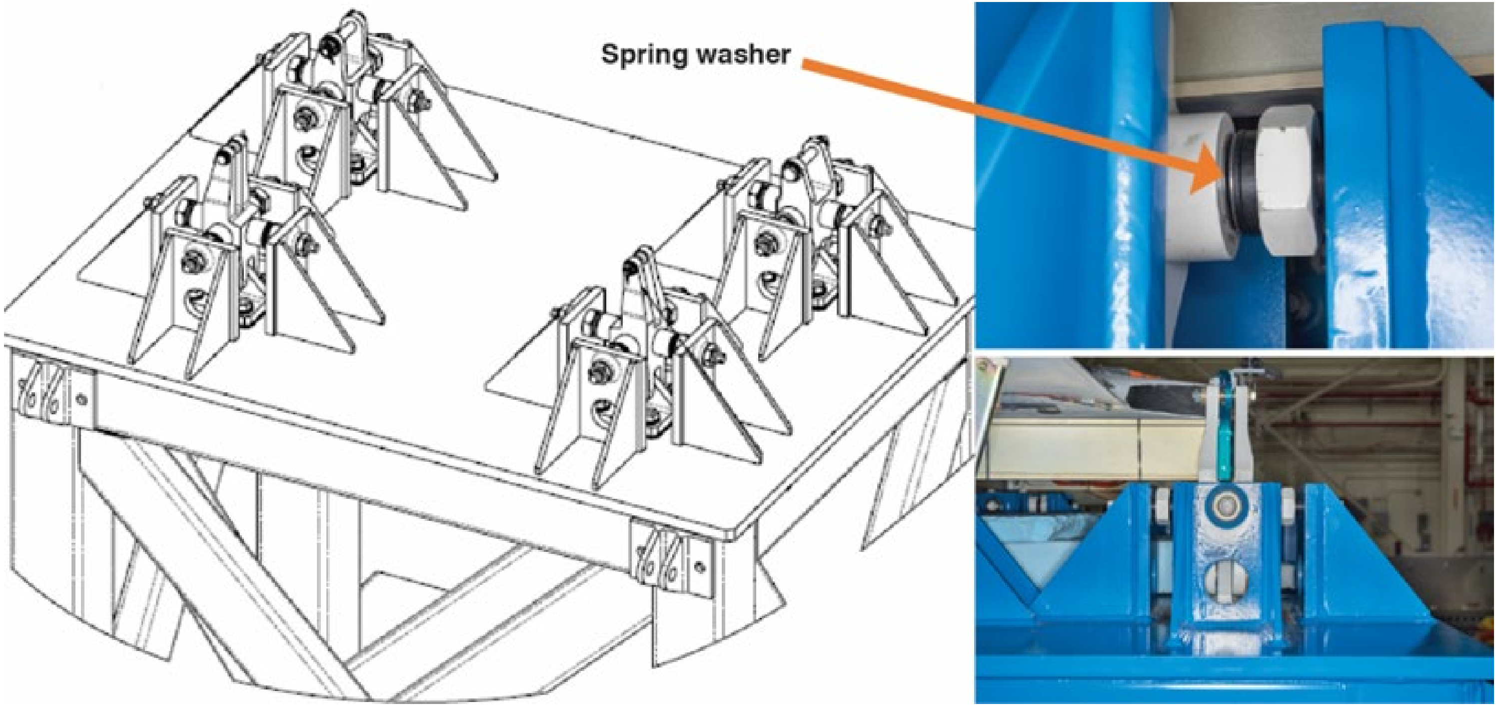


Predicted Displacements from FEM



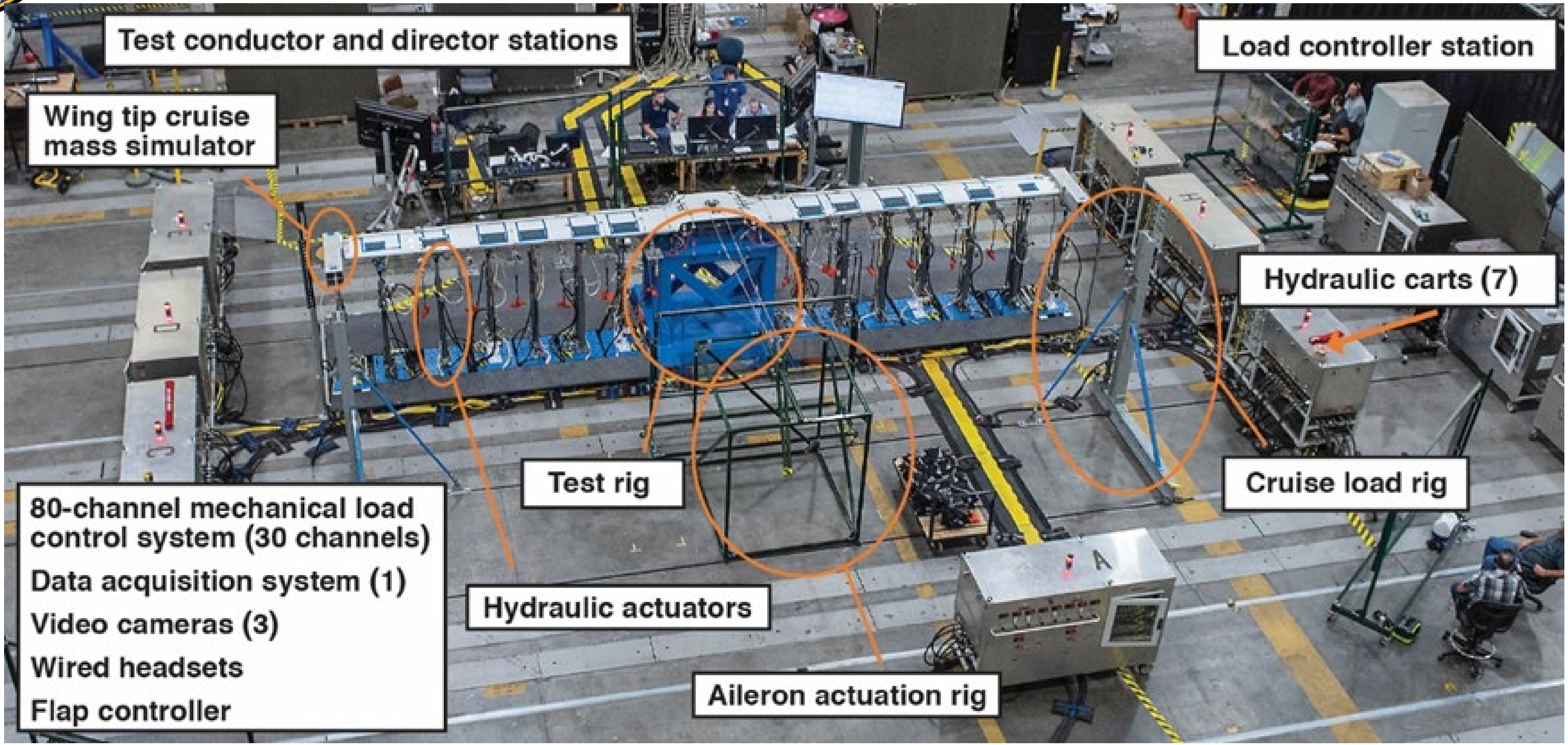
Predicted displacements provided actuator stroke ranges

Test Setup



To simulate fuselage and wing attachment stiffness

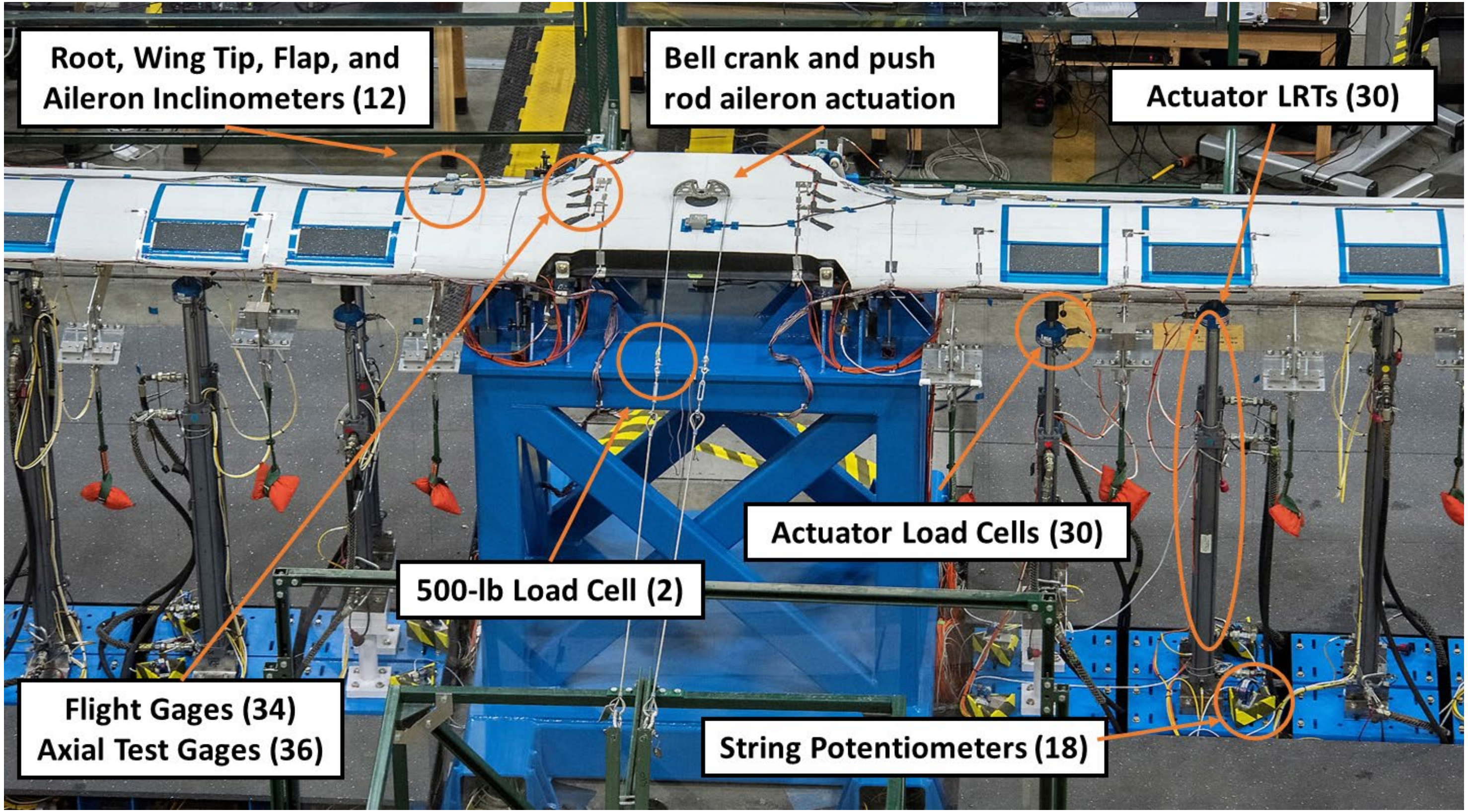
Test Setup



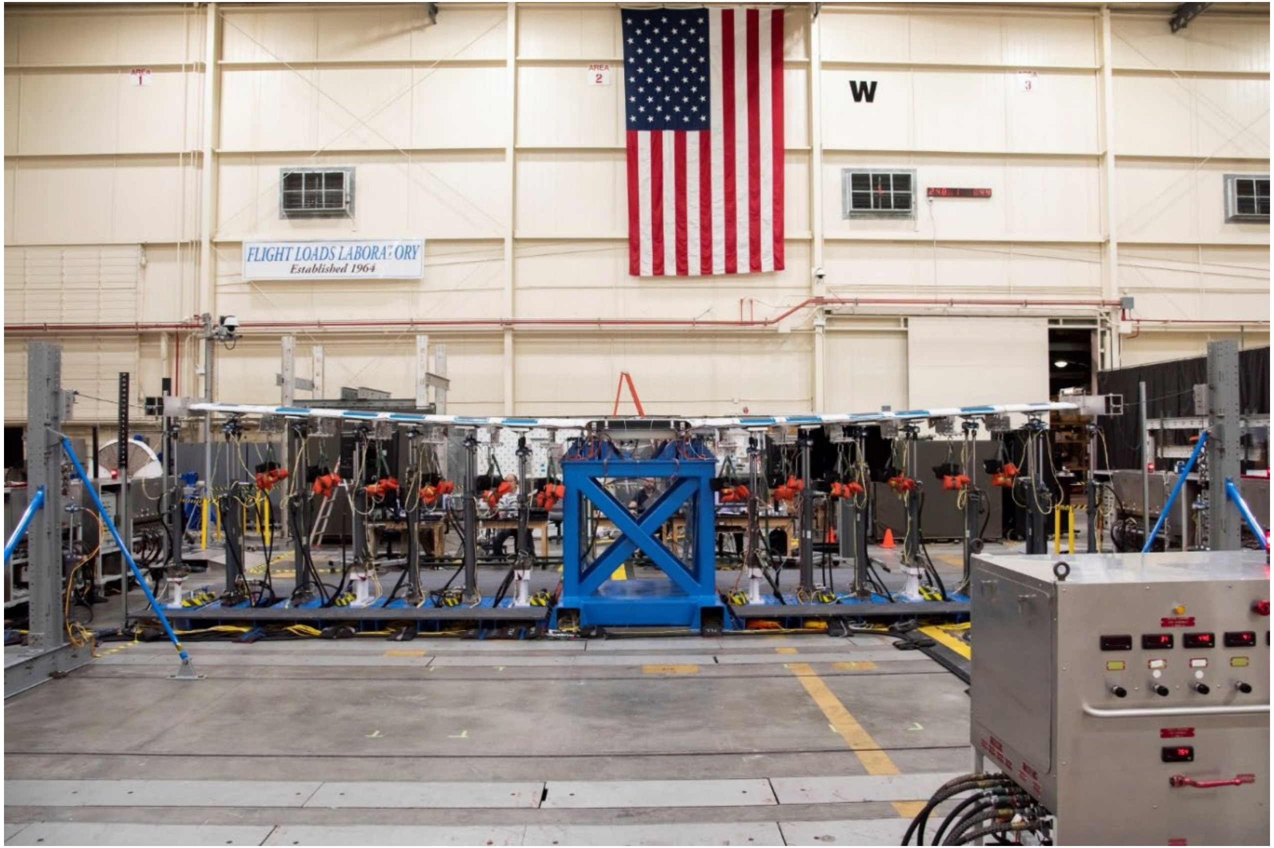
Test conductor and director stations
Load controller station
Wing tip cruise mass simulator
Hydraulic carts (7)
Test rig
Cruise load rig
80-channel mechanical load control system (30 channels)
Data acquisition system (1)
Video cameras (3)
Wired headsets
Flap controller
Hydraulic actuators
Aileron actuation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

Test Setup

Instrumentation

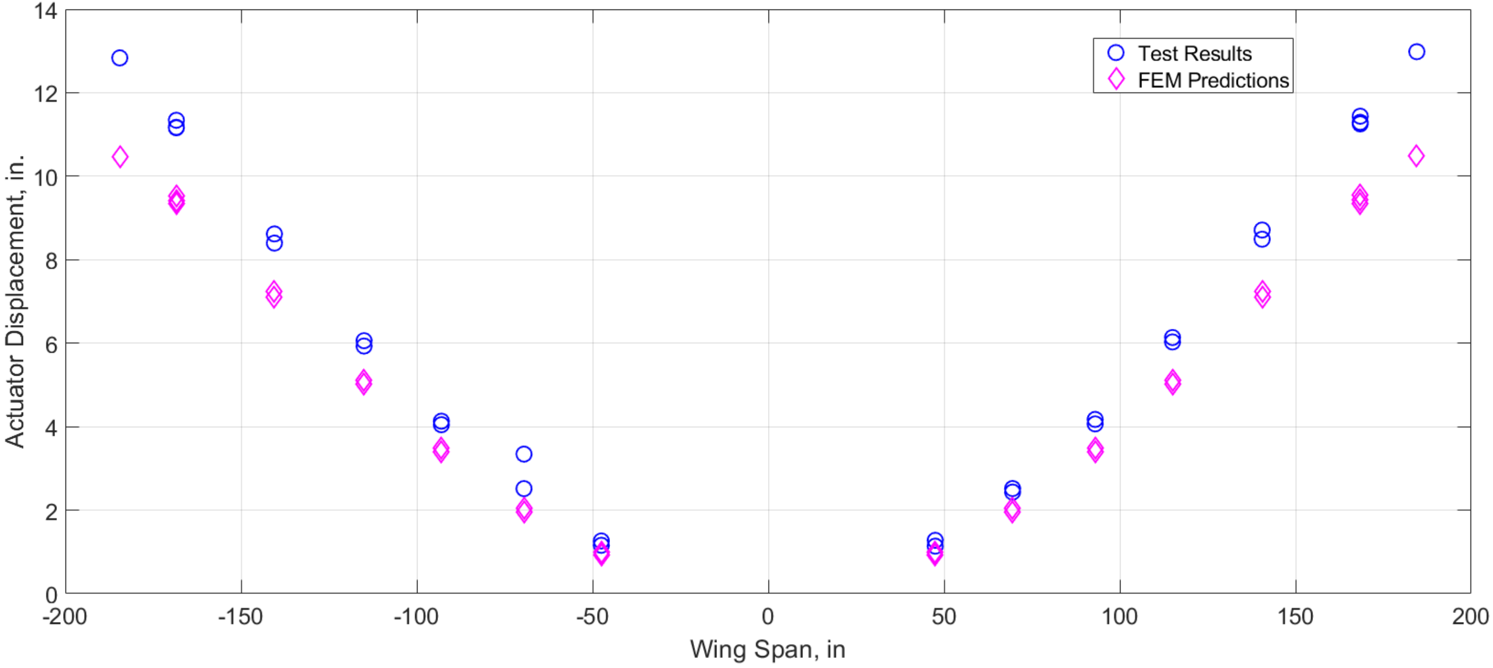


Hydraulic Upload Testing



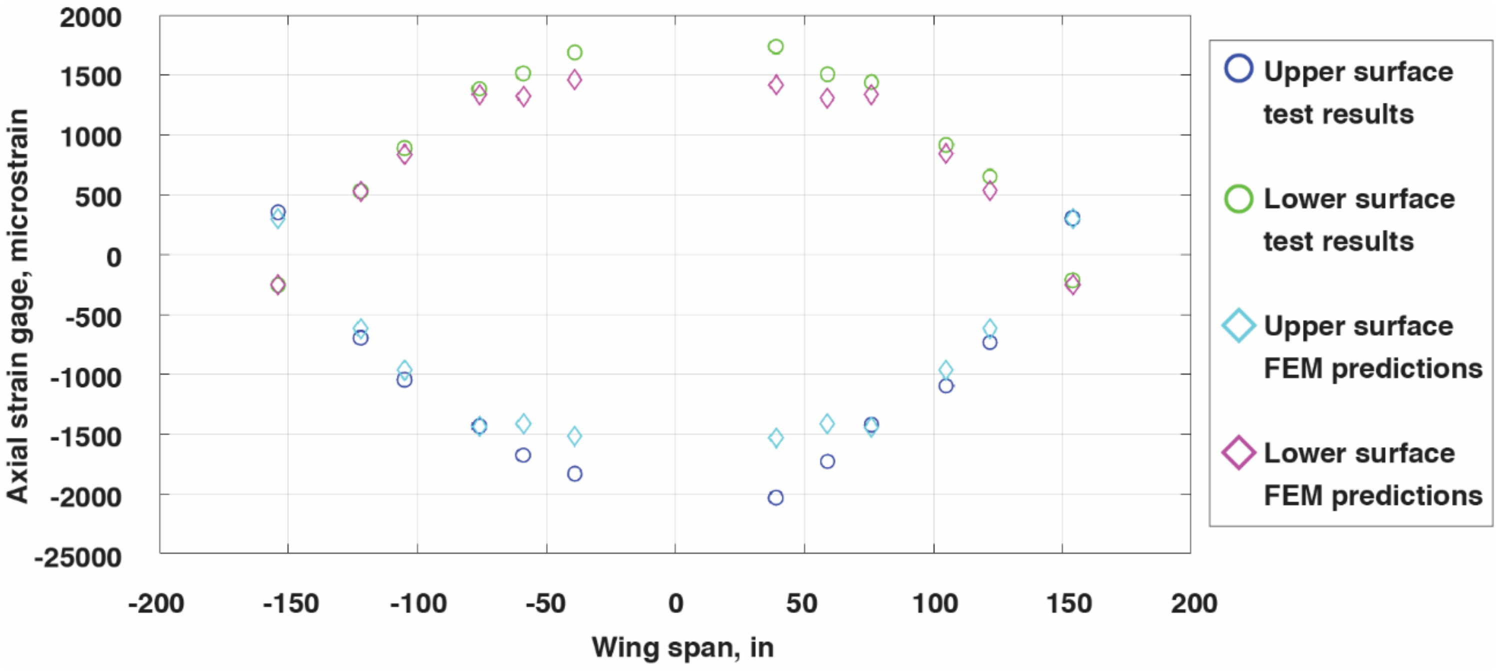
Shotbag Download Testing

120% DLL Test Results (Max Bending Case)



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

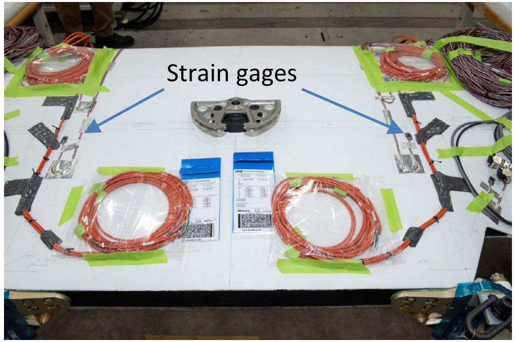
120% DLL Test Results (Max Bending Case)



- 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 and 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%

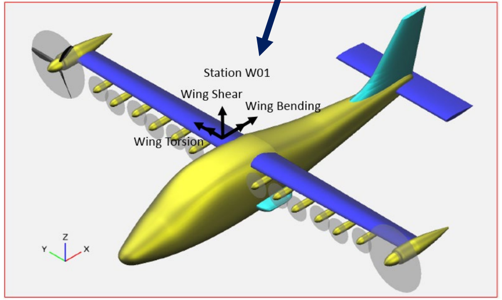


	GAGE ID				EQDE RMS ERROR %	Check RMS ERROR %
Leftwing Shear	LWS023fs	LWS017ms	LWS017rs	LWRB014msl	2.21	4.29
Leftwing Bending	LWS023fs	LWS017ms	LWB017rsl	LWT017fsl	2.24	5.56
Leftwing Torsion	LWT017fsl	LWT017rsu	LWT017rsl	LWRB014rsu	3.70	7.92
Right Wing Shear	RWS023fs	RWS017ms	RWB017rsu	RWRB014msu	2.60	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,
0xx – Wing Station in inches,
fs – front spar,
ms – main spar,
rs - rear spar,
l – lower,
u - upper

Flight Test Monitoring

Monitor loads at root inboard station



Summary and Lessons Learned

- The X-57 Wing design criteria and airworthiness approach were developed based on AFRC Aircraft Structural Safety of Flight Guidelines, AFG-7123.1-001 and the risk posture of the X-57 project
  - Considered design factor of safety, structural instrumentation options, proof test options , flight test operational envelope, and inspection options
  - Design to 1.8 FS, full flight instrumentation, proof to 120% flight limit, fly to 100% proof load
- 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
  - You can not scale 60%, 100%, 120% loads due to inertial loading
- Complex wing root load path affected strain gage output and wing FEM comparisons
- Wing deflections were about 20% higher than predicted
- Wing showed no observable or audible problems during load testing
- Pre- and post-NDI test verified the structural integrity of the wing -> the wing is airworthy
- The Wing FEM was then correlated with displacement test data to ensure that error falls within a 10% range for any subsequent analysis

AFRC Analysis Capabilities

- Loads and Stress analysis (Hand Calc and FEA)
- Finite Element Analysis
  - Static, Dynamics and Aeroelasticity
  - MSC Patran and Nastran, FEMAP, and ZONA/ZAERO
- Object-oriented multi-disciplinary analysis and optimization (MDAO) tool
  - In-house MDAO tools since 2008
  - Design, Analysis and Optimization
  - Static and Dynamics model correlation and turning
  - Test prediction, such as sensor placement
- In-house Loads Equation Derivation (EQDE)

Questions?