X-57 Structural Analysis, Wing Design, & Testing (Statics)

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Outline

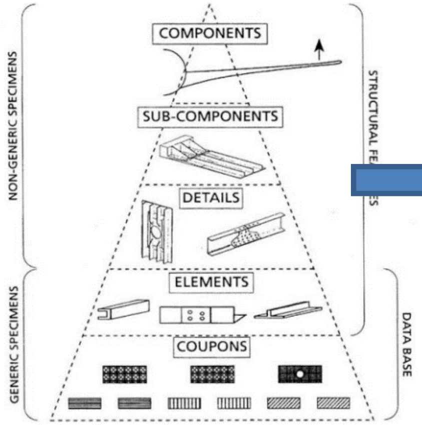
- NASA AFRC Aircraft Structural Safety of Flight Guidelines
- X-57 Structural Design Criteria and Loads Requirements
- Mod II Modification
- Mod III Wing Airworthiness Approach
- Mod III Wing Design
- Mod III Wing Proof Test
- Documents and Publications
- Recommendations and Lesson Learned

Aircraft Structural Safety of Flight Guidelines

- X-planes and NASA research aircraft are not normally FAA or DOD certified aircraft
  - NASA provides own airworthiness
    - Organization which can determine airworthiness are FAA, DoD, and NASA
- NASA AFRC Aerostructures Branch has developed an Aircraft Structural Safety of Flight Guidelines (AFG-7123.1-001) - publicly available
- Many approaches to design, test, and operate "one-of-a-kind" aircraft or to modify certified aircraft at AFRC
  - Consider combination of design, analysis, testing, monitoring techniques, and inspection plan
- This guidelines can be tailored based on the risk posture of an individual project

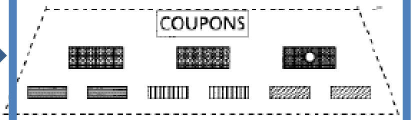
Composite Structures

- Mechanical performance VERY dependent upon materials and fabrication processes
- Building block approach is used
  - Requires time and money -> Impractical to test everything
  - But reduces risk → Balance between analysis and test
- X-57 Mod III Wing: performed coupon testing to support analysis, and proof testing for safety of flight



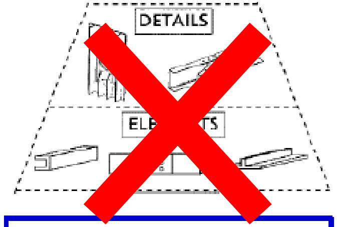
MIL-HDBK-17-1F (2002)

Destructive coupon testing



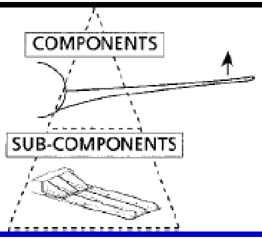
Gets the design started

Destructive testing of design features



Project risk reduction

On aircraft proof loading

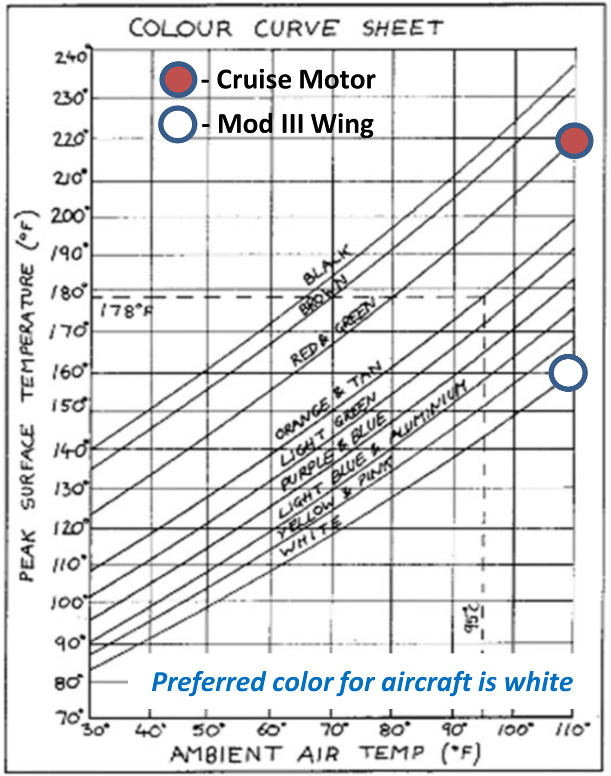


Safety of flight

Temperature Requirements

- Thermal loads should be considered in assemblies with dissimilar coefficients of thermal expansion (CTE)
- Material properties (i.e., composite resins, polymer Tg) are impacted by the surface color of the component
  - Darker colors exposed to direct sunlight may reach temperatures over 200 °F on the Edwards AFB flightline
- Mod III Wing (White)
  - Designed to +165 °F
- Mod III/IV Cruise motor (Red --> reach over 200 °F)
  - Operation is limited by the adhesive strength of the magnet and the motor's surface at startup temperature

Cruse Motor Surface Startup Temp, °F	Operation Limit
> 203	Operation is not allowed
> 181	Up to idle RPM
< 181	No limit



Colour - Temperature relationship.

Load Factor Requirements

- Standard Tecnam P2006T is certified for 2712 lbs and +3.8 / -1.7g Nz
- X-57 is a retrofit aircraft (Mod II ~3000 lbs and Mod III/IV ~3200 lbs)
- The increase in gross weight required to reduce the maneuver and landing load factor by scaling the Nz and gross weight
  - Nz reduced +3.1/-1.4g (Mod III/IV)
- Gust load (3.4g due to 50 fps gust) is higher than the maneuver Nz
  - Limited the operation condition no more than to mitigate high gust load
  - Mitigation: Not allowed to operate in conditions of above “light” turbulence
- Further reduction in operational load factors is needed
  - Due to ~800 lbs concentrated weight of the battery installed on the fuselage, affected the load path and stress on the airframe, resulting in an impact on the structural limits of the wing, fuselage, and landing gear

Static Structures Airworthiness Approach

- The overall static structure airworthiness approach for X-57 is summarized below.

Component	Material Type	Factor of Safety	Notes
Mod II exiting structure	Metallic	1.50	Verified by analysis only
Mod II new and modified structure Mod III cruise nacelle Mod IV high-lift motor assembly Mod IV high-lift pylon and nacelle	Metallic	2.25	Verified by analysis only
	Composite	3.00	Verified by analysis only Required well established composite processes and materials
	Additive	3.00	Verified by analysis and proof tested to >120% design limit loads 20% material allowable knock down for B-Basis statistical reliability 50% material allowable knock down if no material testing All hardware are qualification tested to 105% operational loads
Mod III Wing	Metallic	2.25	Verified by analysis only
	Composite	1.80	Required well established composite processes and materials Poof tested to 120% design limit loads Allowed to flight to 100% proof tested loads Instrumented and loads calibrated for in-flight loads monitoring

Loads for Floor and Equipment Support

- Documented in REQ-CEPT-007
- Inertial loads
  - Flight Maneuver Loads
  - Ground Loads
    - Taxi Bump
    - Landing
    - Crash Landing
    - Ground Handling

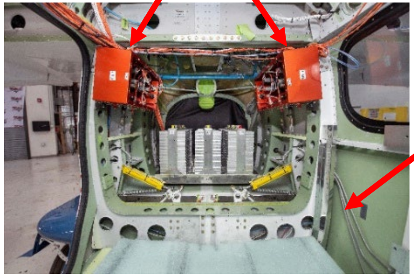
Loads Requirements for Floor and Equipment Support Structure		
Condition		Design Limit Load Factor (G's)
Maneuver loads	Upward, Nz	+3.4
Maneuver loads	Downward, Nz	-1.4
Crash loads	Forward, Nx	-18.0
Crash loads	Sideward, Ny	+/- 4.5
Crash loads	Downward, Nz	-6.0

- Items within cabin that could injure the pilot will be secured to fuselage structure to withstand the crash loads conditions

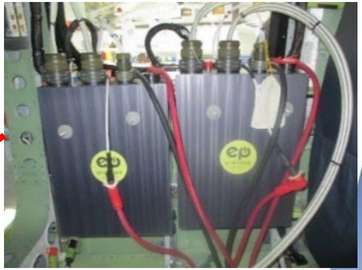
Fuselage - Battery Integration

- Several modifications were made to the aircraft to accommodate the integration of a battery system
  - Two battery trays added at cargo and rear passenger area for all battery modules
  - Lockout/Tagout (LOTO) box installed on the front battery tray
  - Mounted Battery Control Modules (BCM) and Contactor pallet mounted on the side of the fuselage
  - Co-pilot seat removed to make room for instrumentation and other necessary equipment

Contactor pallet (left and right)



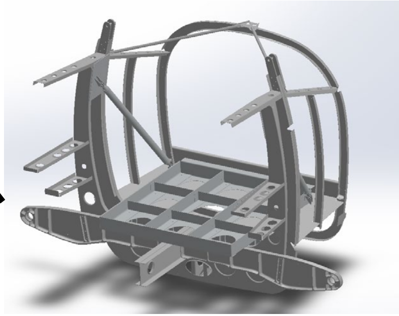
Battery Control Modules



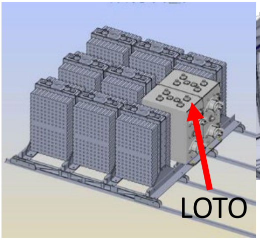
Battery Venting Assembly

Battery Venting (3” dia)

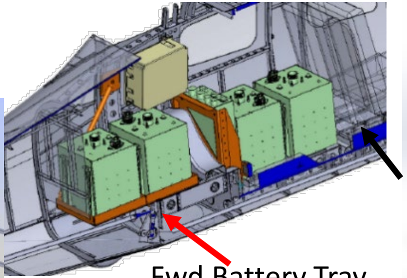
Aft Battery Tray



Equipment Pallet



LOTO



Fwd Battery Tray

Image Reference:
https://ntrs.nasa.gov/api/citations/20190026541/downloads/20190026541.pdf

High-Lift Blade Proof Test

- Injection molding
- 40% Chopped fiber (~0.2 lbs)
- Good balance of strength and mass
- Design meets FOS (3.0) requirements at 5460 RPM load condition
- Static pull test completed on early chopped fiber blade prototype
- Tested assembly
- Max Load
  - 6,047.7 N (1359.6 lb)
    - 171% load @ 5500 RPM
  - Failure occurred in fixture

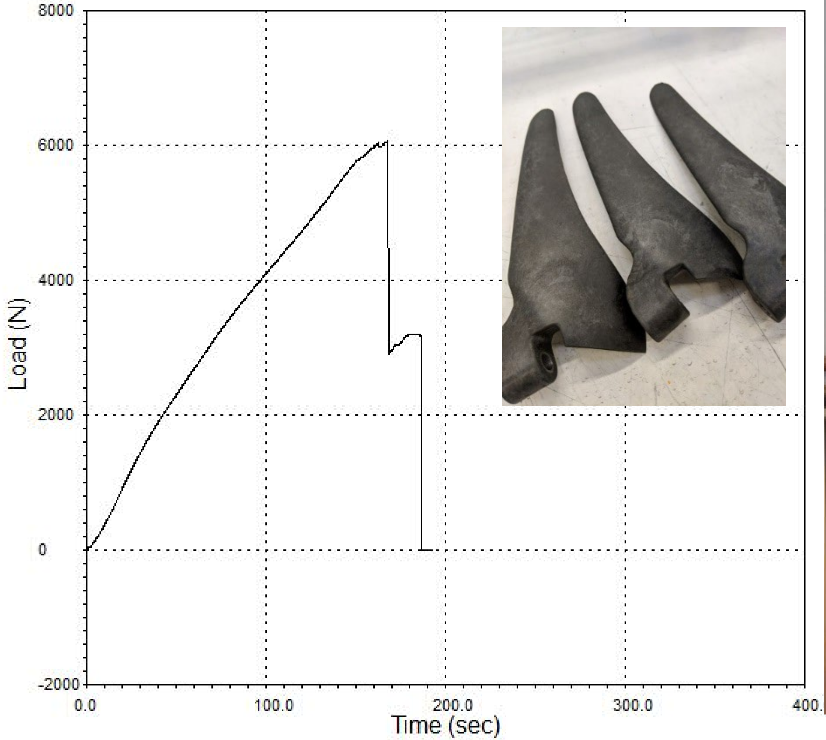
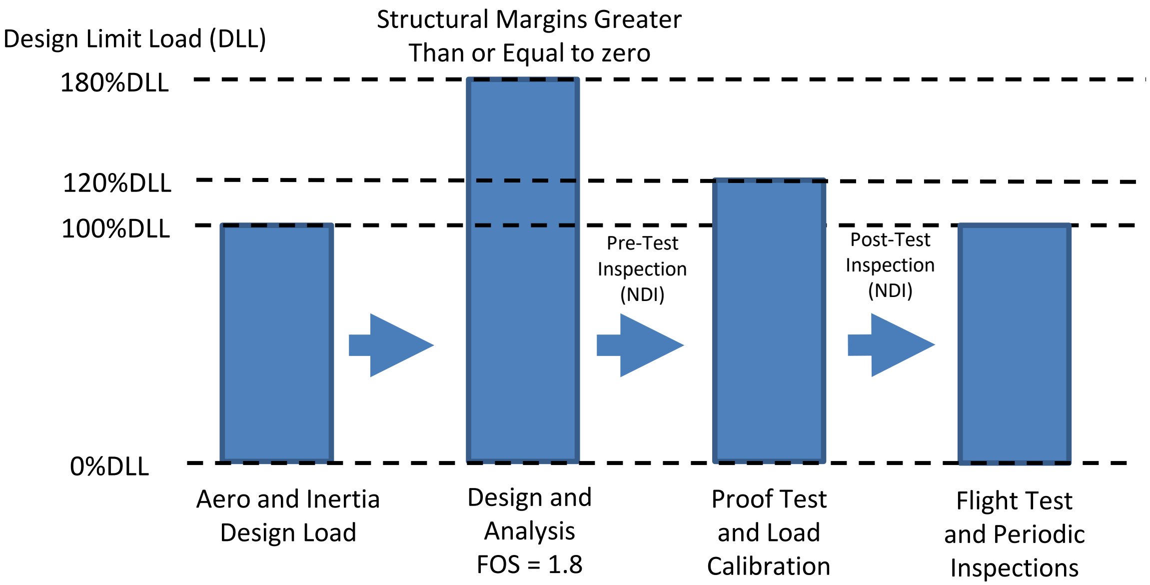


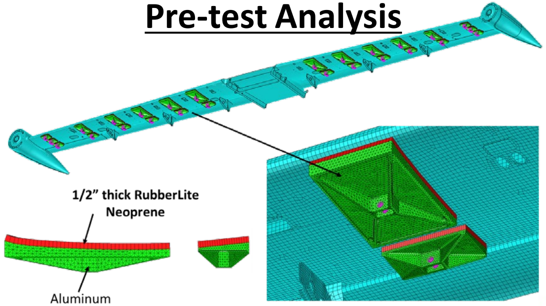
Image Source: 09_Mod IV CDR Slides-ESAero – FINAL.ptx

Mod III Wing Airworthiness Approach

- To demonstrate and validate the structural integrity of the wing for flight
- Designed to 1.8 FS, proofed to 120% flight limit, full flight instrumentation, allowed to fly to 100%

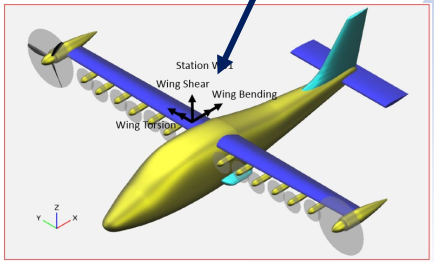


Pre-test Analysis

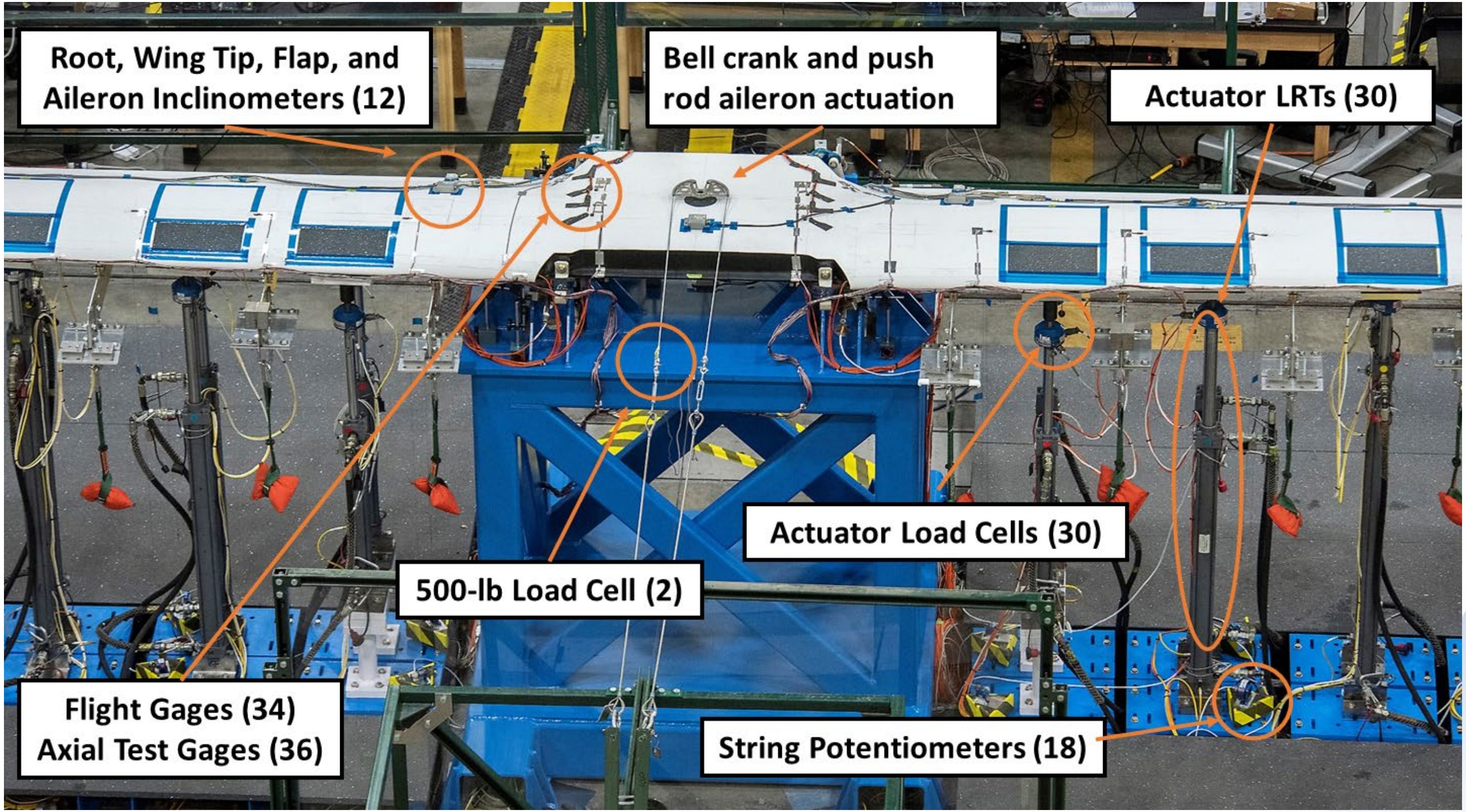


Flight Test Monitoring

Monitor loads at root inboard station

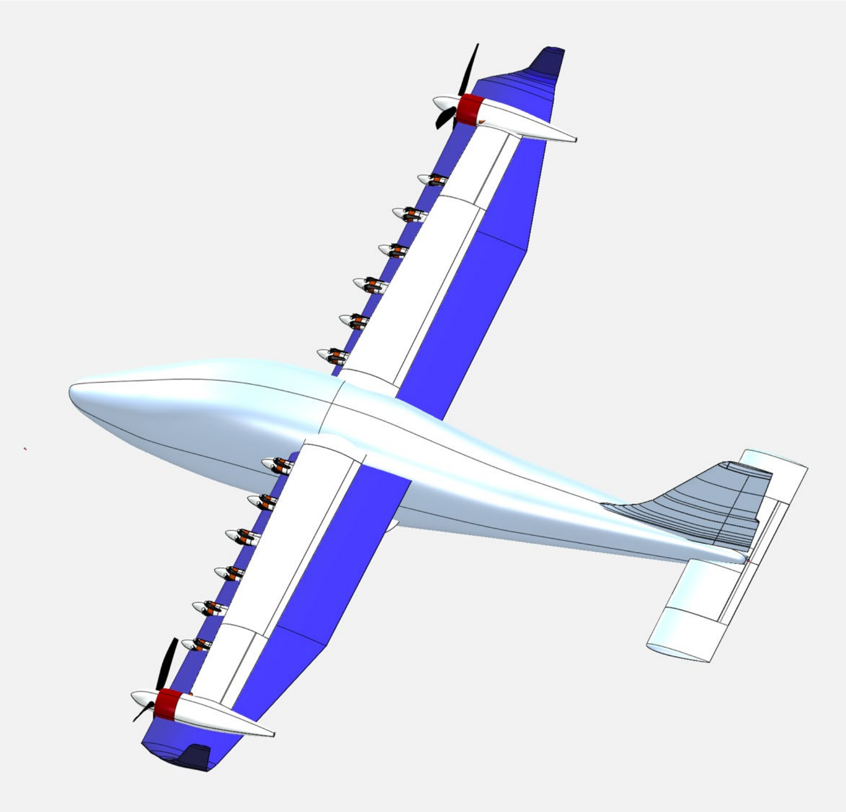


X-57 Wing Proof Test Instrumentation

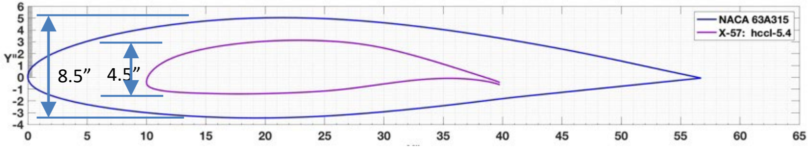


X-57 Mod III/IV Wing Design, Analysis, & Testing

Comparison X-57 Maxwell Wing to Tecnam P2006T



Wing Root Airfoil Comparison

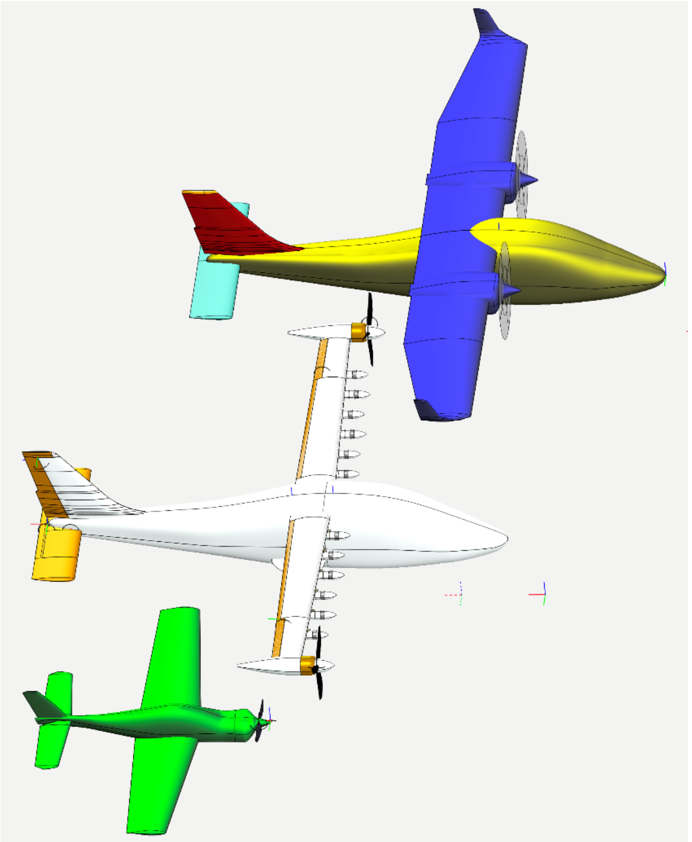


58% Reduction in Wing Area

Wetted Area Comparison
Tecnam P2006T: 730.0 ft^2
X-57 Maxwell: 597.3 ft^2

18% Reduction in Configuration Wetted Area

X-57 Wing Area Perspective

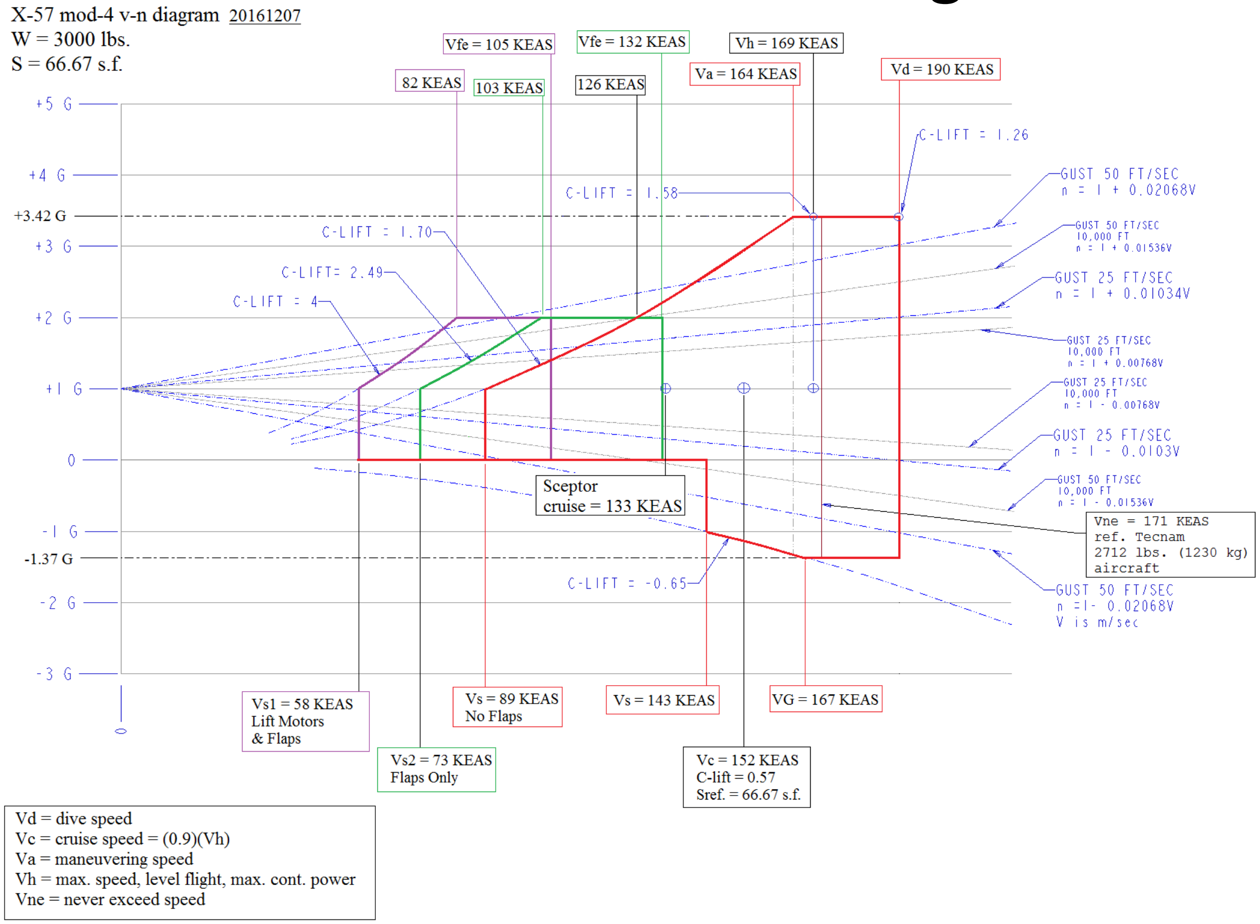


Tecnam P2006T
W_G = 2700 lbs
S = 158.9 ft^2
AR = 8.8
W/S = 17 lb/ft^2

X-57 Maxwell
W_G = 3000 lbs
S = 66.7 ft^2
AR = 15
W/S = 45 lb/ft^2

IF1 – Formula One (Nemesis Reno racer)
W_G = 770 lbs
S = 66.6 ft^2
AR = 6.8
W/S = 11.6 lb/ft^2

X-57 V-N Diagram



Configuration

Cruise (Mod III/IV)

Flap 30° No HL Power (Mod III/IV)

Flap 30° With HL Power (Mod IV)

Wing Design Load Criteria – 14CFR Part23 Airworthiness Standards: Normal Category Airplanes

Flight Loads – Part 23 Amendment 45

	SYMMETRICAL § 23.331	UNSYMMETRICAL § 23.347
GUST	**Clean Airplane** Discrete Vertical Gusts [§ 23.333(c), § 23.341] ± 50 fps @ V_C and ± 25 fps @ V_D; ± 66 fps @ V_B (commuter category only)	**Vertical Surfaces** Lateral gust: ± 50 fps @ V_C [§ 23.443(a)]
GUST	**High Lift Devices** [§ 23.345] ± 25 ft/sec vertical 25 ft/sec head-on; **Wing Flaps** [§ 23.457(a)]	Commuter category [§ 23.443(b)] Gusts normal to plane of symmetry @ V_B, V_C, V_D clean airplane @V_F high lift devices
GUST / MANEUVER	**Horizontal Stabilizing and Balancing Surfaces** [§ 23.425] Clean airplane and with high lift devices	**Horizontal Stabilizing and Balancing Surfaces** [§ 23.427] Loads from gusts combined with yawing and slipstream effects, clean airplane and with high lift devices
GUST / MANEUVER	[§ 23.373] **Speed Control Devices**	[§ 23.445] / [§ 23.445(d)] **Outboard Fins or Winglets**
MANEUVER	**Balancing Horizontal Tail Load** [§§ 23.331, 23.421]	**Vertical Surfaces** [§ 23.441] - @ V_A Yaw, sideslip, and rudder deflection
MANEUVER	**Limit Load Factor** [§ 23.337] Normal or Commuter Category n = 3.8*; Utility Category n = 4.4; Acrobatic Category n = 6.0; *May reduce for W > 4,118 lbs.	**Ailerons** [§ 23.445] Abrupt maximum control movement @V_A. Control deflection requirements @V_C and V_D
MANEUVER	**Pitching:** Checked and Unchecked. Applies to horizontal stabilizing and balancing surfaces [§ 23.423] Abrupt maximum control input @ V_A	**Rolling Conditions** [§ 23.349] – Wing and wing bracing. Category / Condition (See § 23.333) / Airload Distribution: Normal, Utility, Commuter / A / 100%/70% to 75%; Acrobatic / A and F / 100%/60%. Wing loads due to aileron deflections § 23.445
MANEUVER	**High Lift Devices** [§ 23.345] n = 2.0 g; **Wing Flaps** [§ 23.457(a)]	
ENGINE		**Engine Torque** [§ 23.361] – Combined with symmetrical limit loads @ V_A
ENGINE		**Side Load on Engine Mount** [§ 23.363]
ENGINE		**Gyroscopic and Aerodynamic Loads** [§ 23.371] – Pitching and yawing, applies only to turbine installations
ENGINE		**Unsymmetrical Loads Due to Engine Failure** [§ 23.367] – Turboprops only
OTHER	**Wing Flaps Slipstream Effects**, n = 1.0 [§ 23.457(b)]	**Pressurized Cabin Loads**, combined with flight loads [§ 23.365]
OTHER	**Rear Lift Truss**, reverse air flow [§ 23.369]	**Canard or Tandem Wing Configurations** [§ 23.302]

Flight Load Cases for Wing FEA

- Load Case Table – applicable to all fuselage configurations
  - Forces in Newtons (N), Moments/Torque in Newton-Meters (Nm), Load Factors (g's)
- One additional load case, asymmetric thrust at take-off
  - Applicable to Mod III/IV only

Case #	Airspeed	Load Factor	Weight	CG position	Altitude	Description
1	89kEAS (Vs)	+1.0	13351N	4044.81mm	0ft	Vs – 1g ASL
2	152kEAS(Vc)	+2.91	13351N	4044.81mm	0ft	Vc max nz due stall ASL
3	164kEAS(Va)	+3.42	13351N	4044.81mm	0ft	Va – positive maneuver ASL
4	190kEAS(Vd)	+3.42	13351N	4044.81mm	0ft	Vd – positive maneuver ASL
5	190kEAS(Vd)	-1.71	13351N	4044.81mm	0ft	Vd – negative gust ASL
6	89kEAS (Vs)	+1.0	13351N	4044.81mm	15000ft	Vs – 1g high altitude
7	152kEAS(Vc)	+2.91	13351N	4044.81mm	15000ft	Vc max nz due stall high alt.
8	164kEAS(Va)	+3.42	13351N	4044.81mm	15000ft	Va – positive maneuver high alt.
9	190kEAS(Vd)	+3.42	13351N	4044.81mm	15000ft	Vd – positive maneuver high alt.
10	190kEAS(Vd)	-1.71	13351N	4044.81mm	15000ft	Vd – negative gust high alt.
11	164kEAS(Va)	+2.99	13351N	4044.81mm	0ft	Asym – 100/75
12	164kEAS(Va)	+2.28	13351N	4044.81mm	0ft	Rolling at Va
13	164kEAS(Va)	+2.28	13351N	4044.81mm	0ft	Rolling at Va – max roll rate
14	190kEAS(Vd)	+2.28	13351N	4044.81mm	0ft	Rolling at Vd
15	190kEAS(Vd)	+2.28	13351N	4044.81mm	0ft	Rolling at Vd – max roll rate
16	130kEAS(Vf)	+2.00	13351N	4044.81mm	0ft	Flap

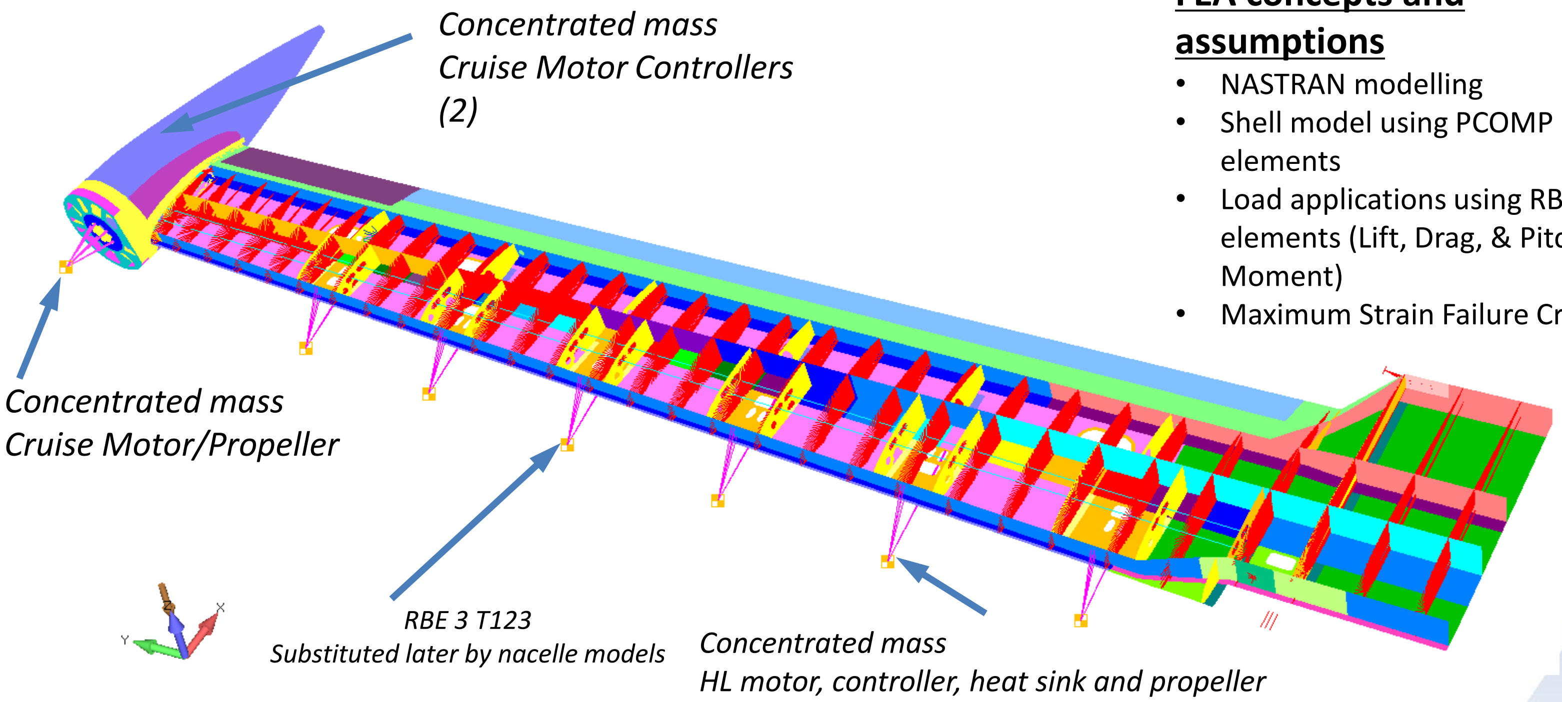
Propeller Thrust (LL)	
Cruise Motor	2450 N (550 lb)
High-Lift Motor	490 N (110 lb)

Engine Torque Loads (LL)	
SCEPTOR	
Cruise Motor (max take-off)	470 Nm
Cruise Motor (max continuous)	400 Nm
High-Lift Motor	100 Nm or TBD6

Case #	Airspeed	Load	Weight	CG position	Alt	Fx	Mx	My	Mz
17	164	+2.565	13351N	4044.81mm	0ft	1927	376.25	0	0
18	164	+3.42	13351N	4044.81mm	0ft	1400	318.75	0	0
19	164	+2.5	13351N	4044.81mm	0ft	1542	0	261.5	104.6

Maximum Take-off Torque
Maximum Continuous Torque
Gyroscopic Moment

FEM of Mod III/IV Wing



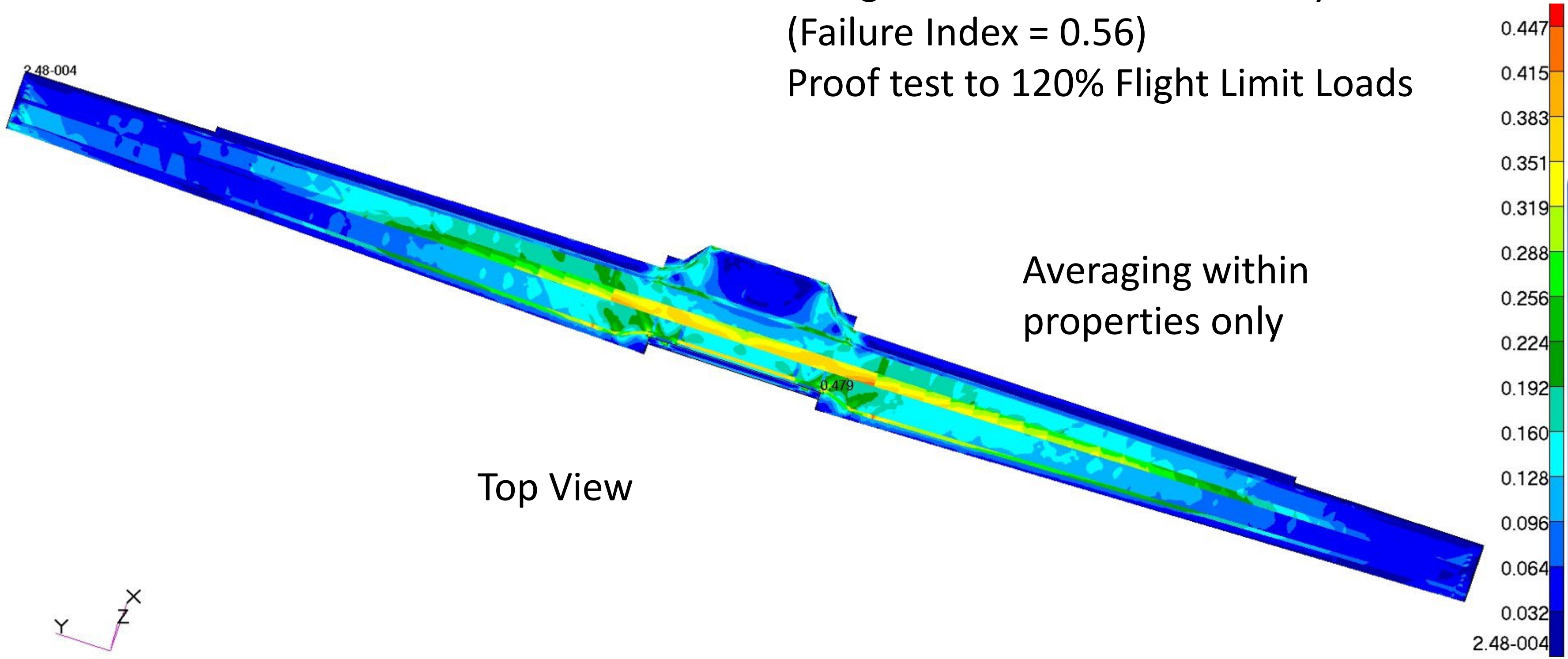
FEA concepts and assumptions

- NASTRAN modelling
- Shell model using PCOMP elements
- Load applications using RBE3 elements (Lift, Drag, & Pitching Moment)
- Maximum Strain Failure Criteria

Reference: Slide 108, page 88.
https://www.nasa.gov/wp-content/uploads/2021/09/sceptor_cdr_day_2_package.pdf?emrc=23ae02

Load Case 11 –Max Failure Index
Full Vehicle with Inertia Relief

Designed with a factor of safety = 1.8
(Failure Index = 0.56)
Proof test to 120% Flight Limit Loads

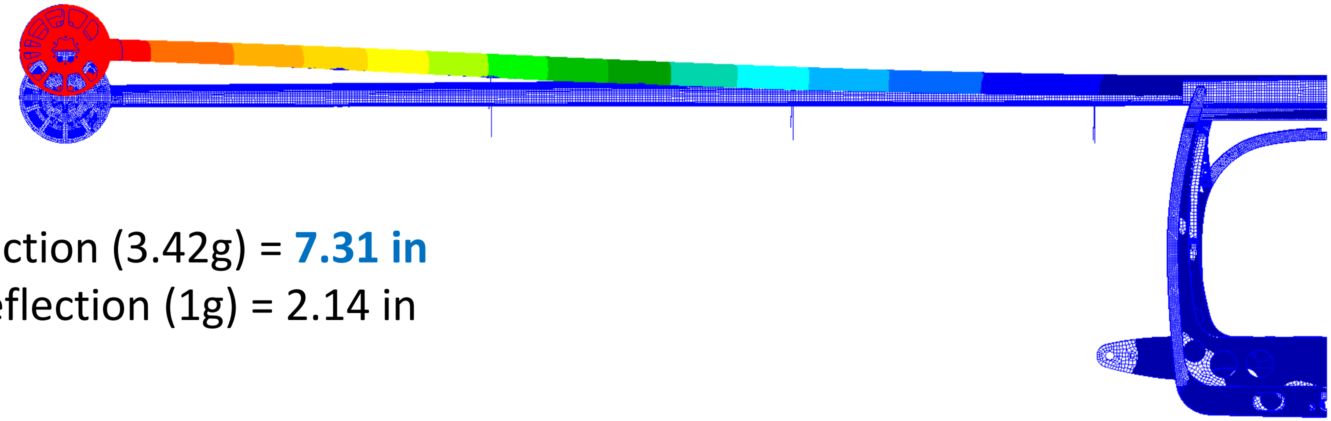


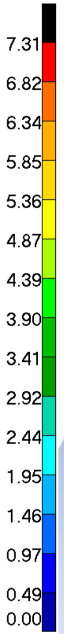
Averaging within properties only

Top View

X-57 FEA wing Displacement

- Max displacement identified at limit pull-up maneuver (3.42 g)



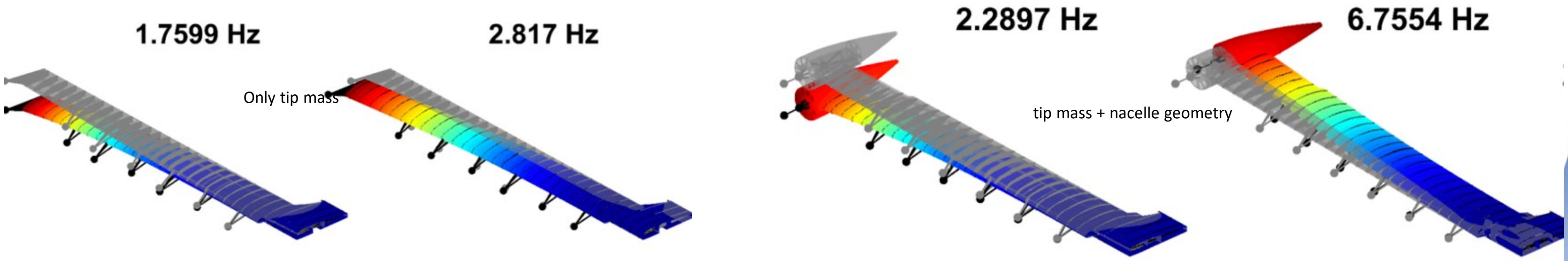


Max deflection (3.42g) = **7.31 in**
Cruise Deflection (1g) = 2.14 in

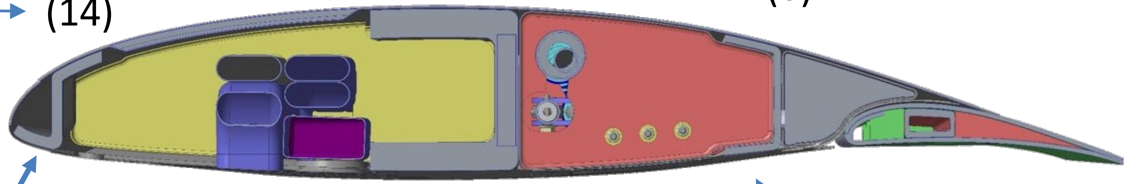
Tuning Wing Modes Because of Tip Mass

Version 1 FEM → Version 2 FEM

1st: Out-of-Plane Wing Bending | 2nd: In-Plane Wing Bending | 1st: Out-of-Plane Wing Bending | 2nd: In-Plane Wing Bending



Added layers of Uni-directional → (14) → (6)



Front (Z) Spar

Main Spar (C) Spar

Aft (C) Spar

Wing Construction Materials

Prepreg Resin system (spars)

Patz F4

- Cure at 250° F (Tg 320° F)
- Inside and outside autoclave
- Interlaminar Shear Strength > 50MPa (up to 70MPa)

Wet Lay-up Resin System (skins)

MGS L285

- Approved by the German Federal Aviation Authority for sailplanes
- Multi hardener system – 10min to 7h of pot life
- Post cure at 175° F (Tg 212° F)
- Interlaminar Shear Strength 47 to 55MPa

Fibers

IM2C/UDP – Uni directional tape for spar caps

IM2A/2T – Bias fabric for shear web

CMH12K – HM63 – Non crimped biaxial fabric for skin

Hexcel 282 – fairings and small components

Core

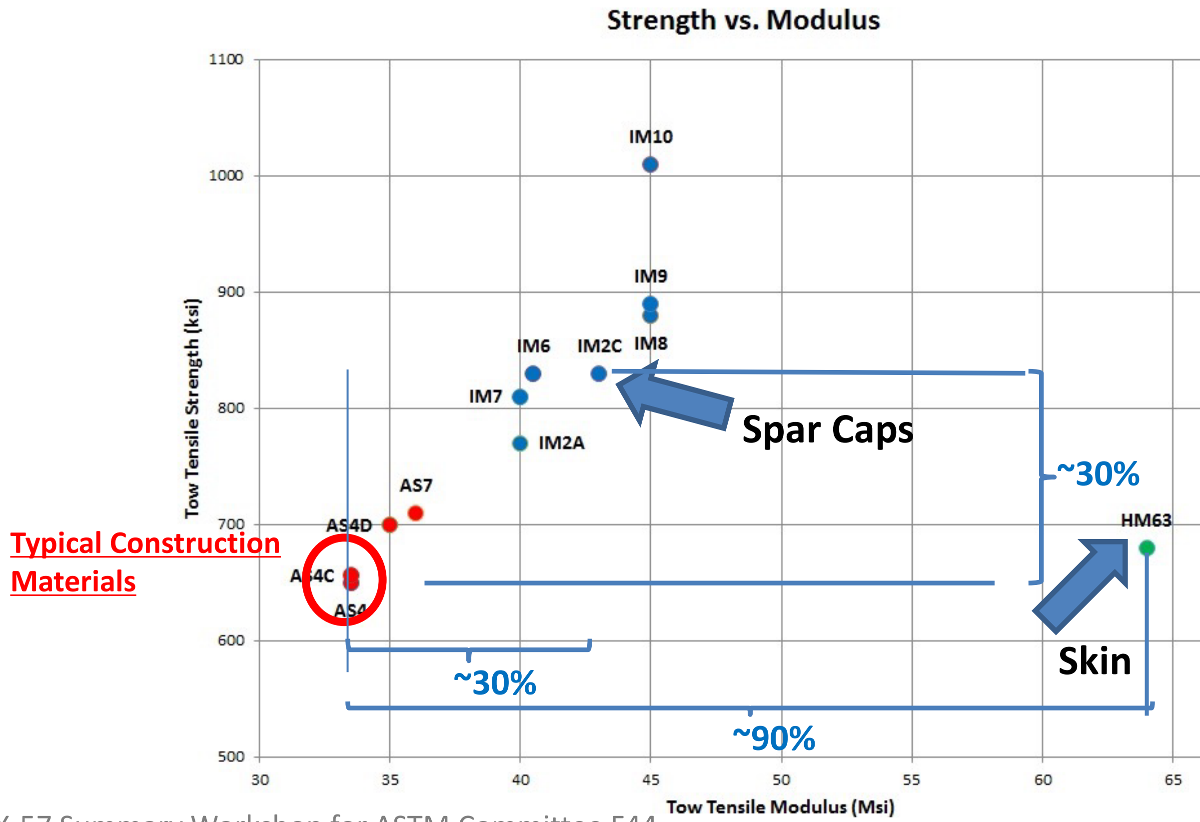
- Divinycell PVC foam H60 (1/4")

Glue

Hysol 9359.3

- Shear strength of 4500psi at 77F
- Shear strength of 2000psi at 180F
- Peel strength 60lb/in
- 5mil glass beads for thickness control

Comparison of Composite Fiber Strength and Modulus



X-57 Wing Carbon Fiber Fabric

IM2C/UDP – Uni directional tape for spar caps

IM2A/2T – Bias fabric for shear web

CMH12K – HM63 – Non crimped biaxial fabric for skin

Properties of Wing Composite Materials Compared to Typical Construction Materials

Uni-directional Spar:

- 30% > strength
- 30% > modulus

Skin:

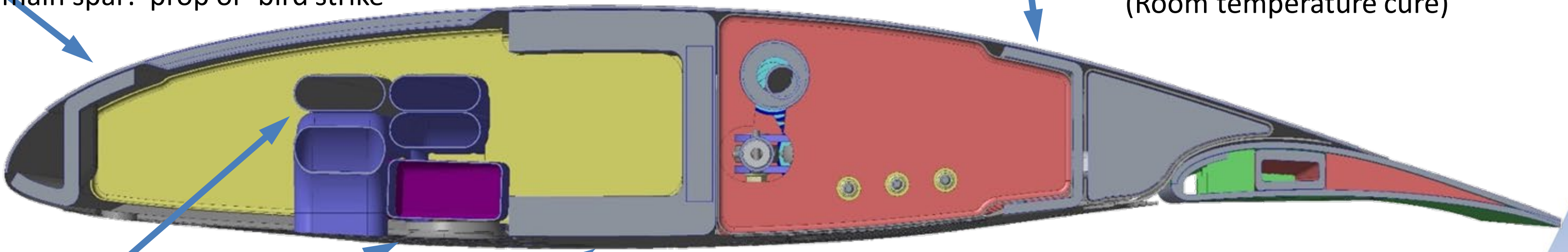
- 90% > modulus

X-57 Wing Construction Features

Front Spar
- Z shape
- Stiffen Torsion box
- Hard point for HL nacelles
- Protects main spar: prop or bird strike

Rear Spar
- C shape
- Closes the back torsion box
- Hard point for bell cranks and aileron hinges

Carbon fiber skin with ¼ in PVC foam
(Room temperature cure)

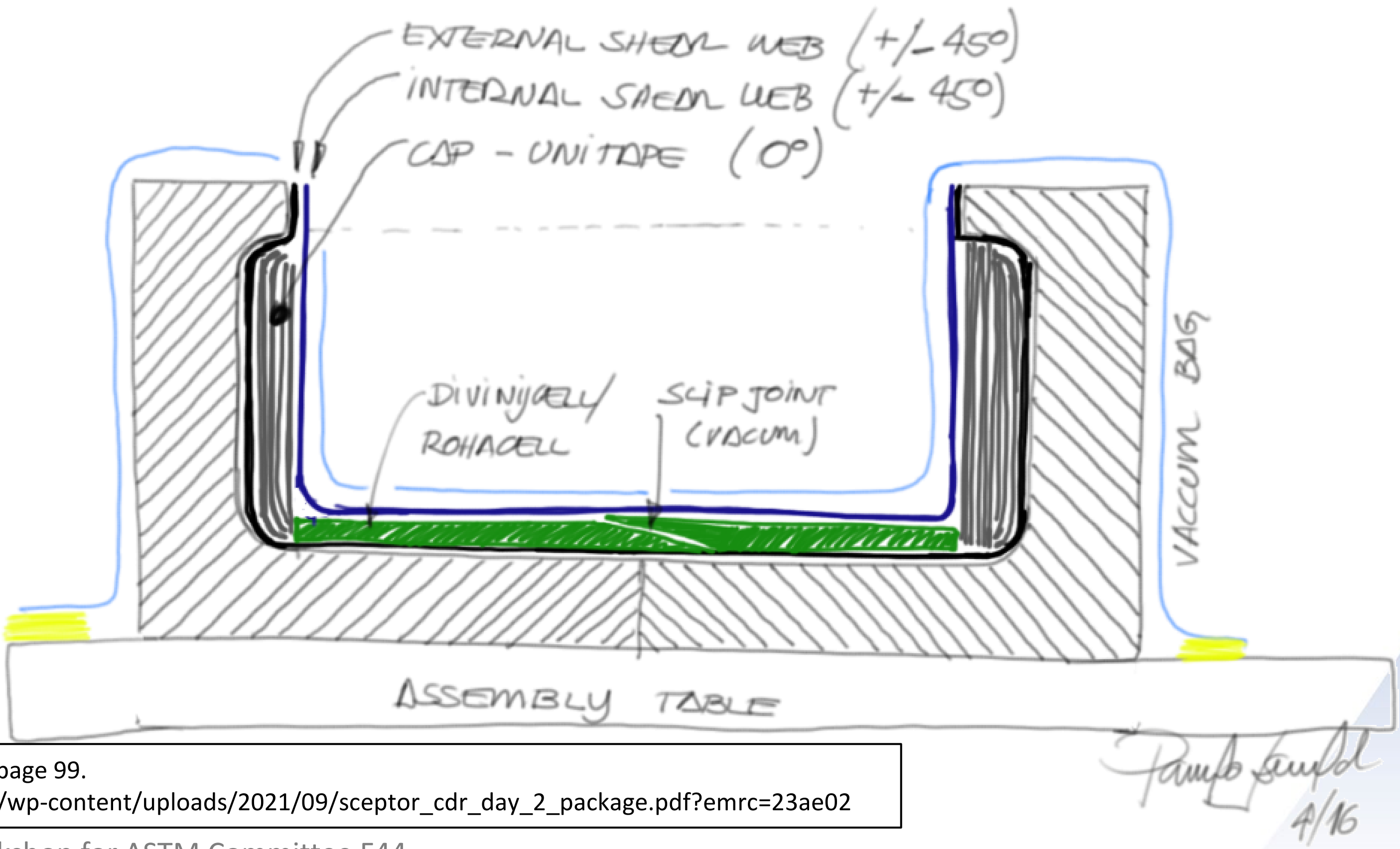


Main Bus ducts

Instrumentation duct

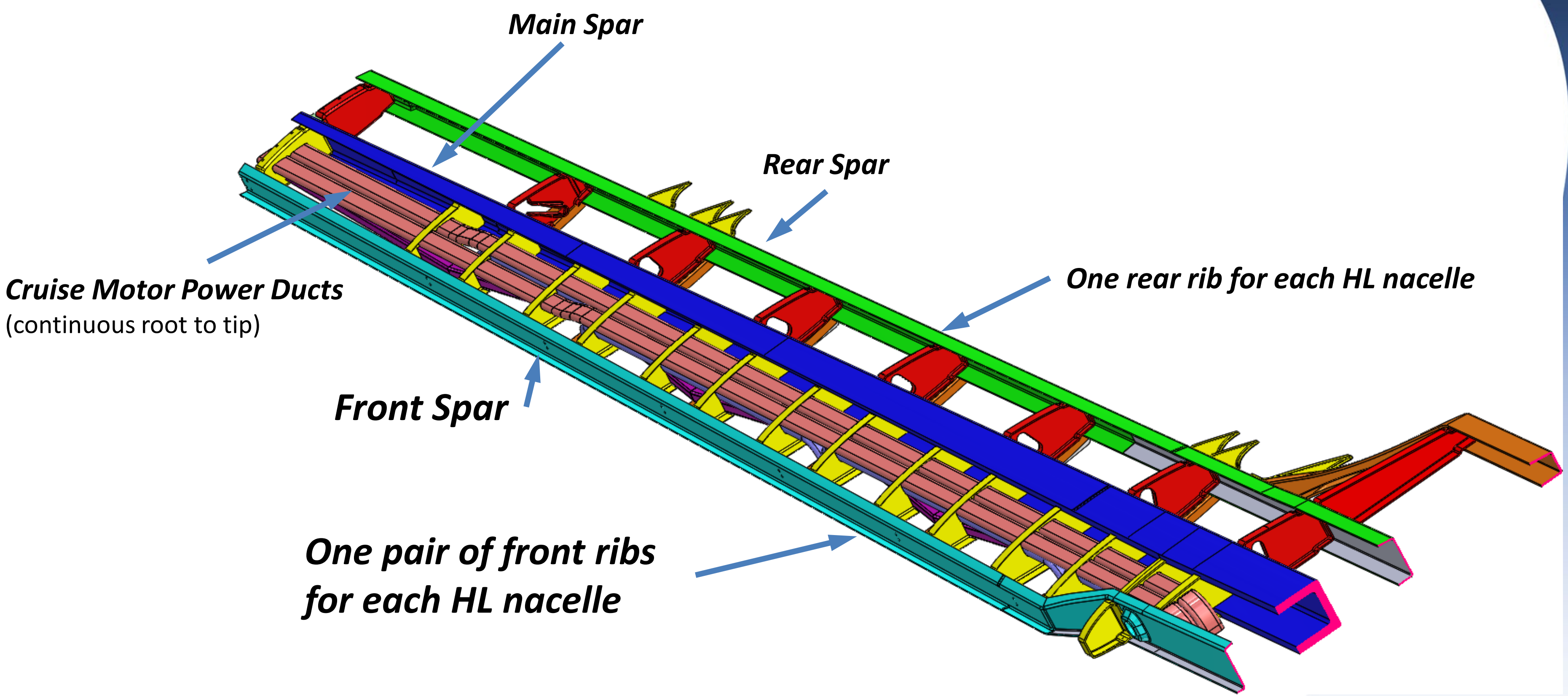
Main Spar
- C shape
- Uniform material no cutouts
- Pre-Preg fabrication, high temp cure
- Front ribs will act as stiffener for warp deformation
- **Depth 4.5” at root**

Wing Main Spar Layup

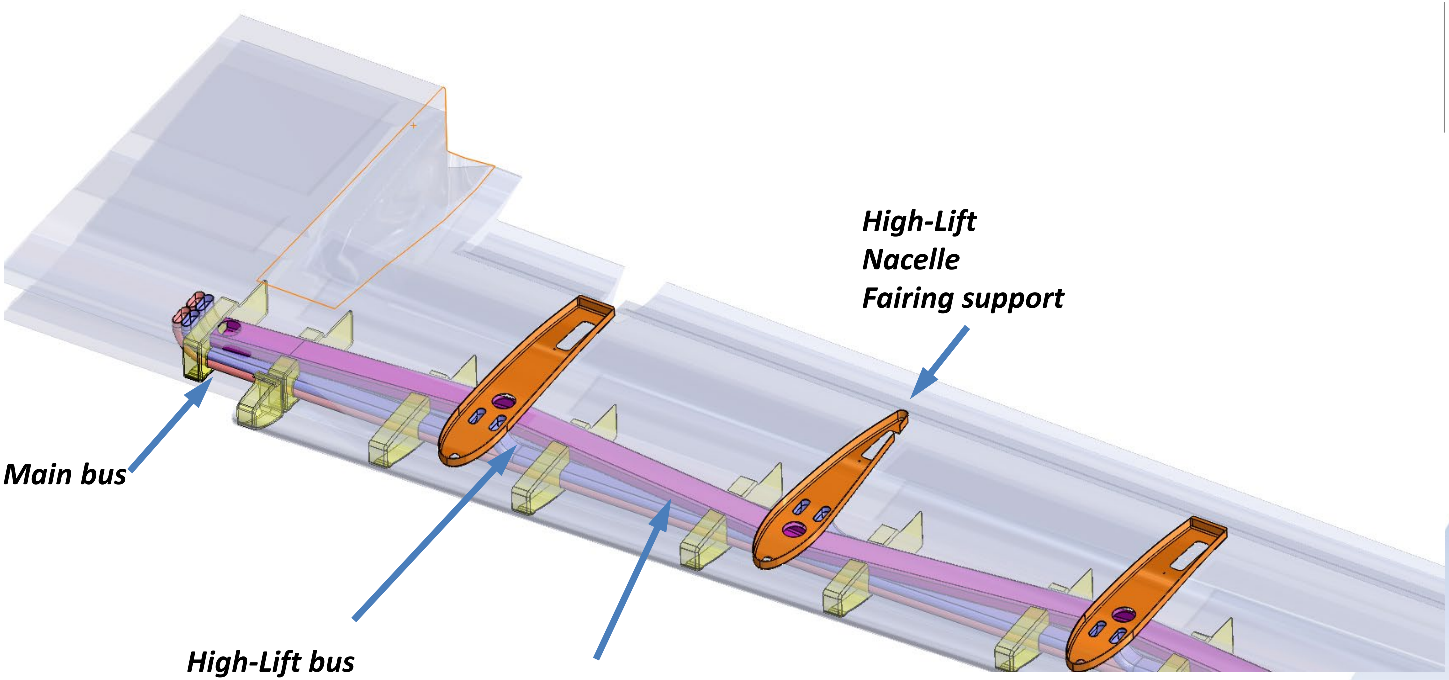


Reference: Slide 130, page 99.
https://www.nasa.gov/wp-content/uploads/2021/09/sceptor_cdr_day_2_package.pdf?emrc=23ae02

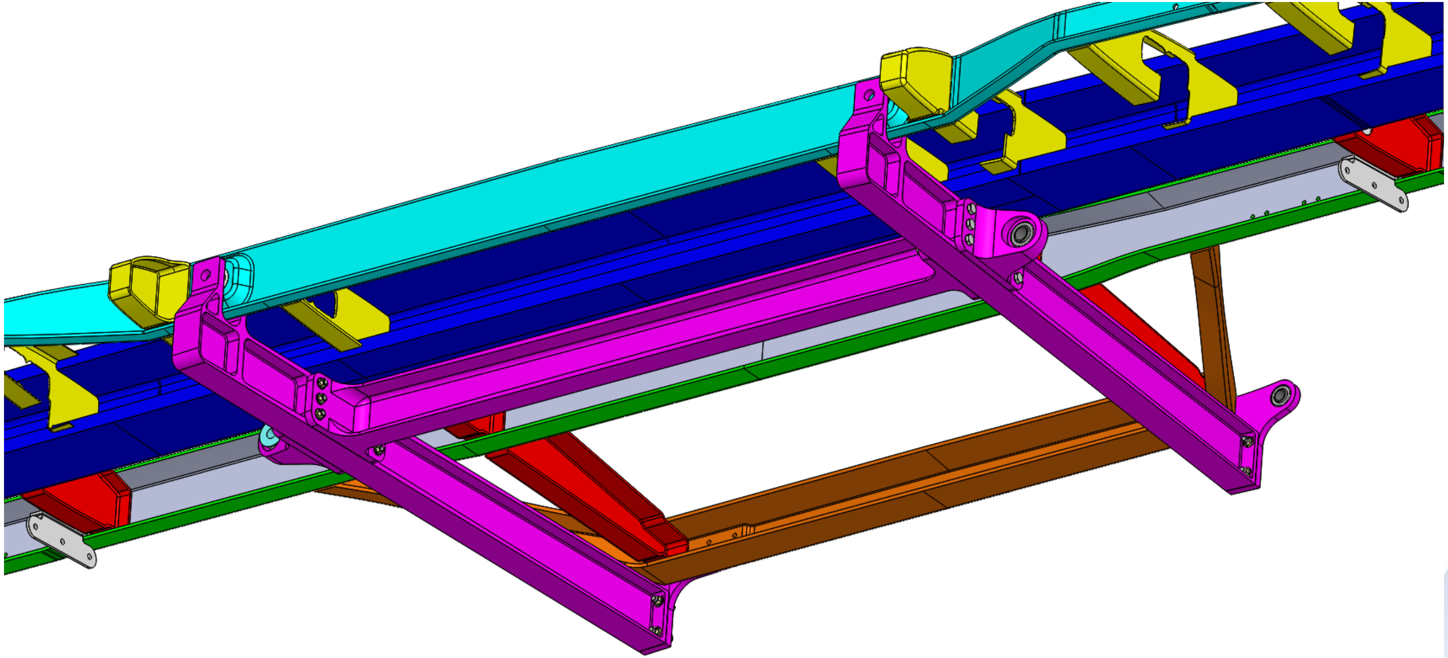
Wing Internal Structural Features



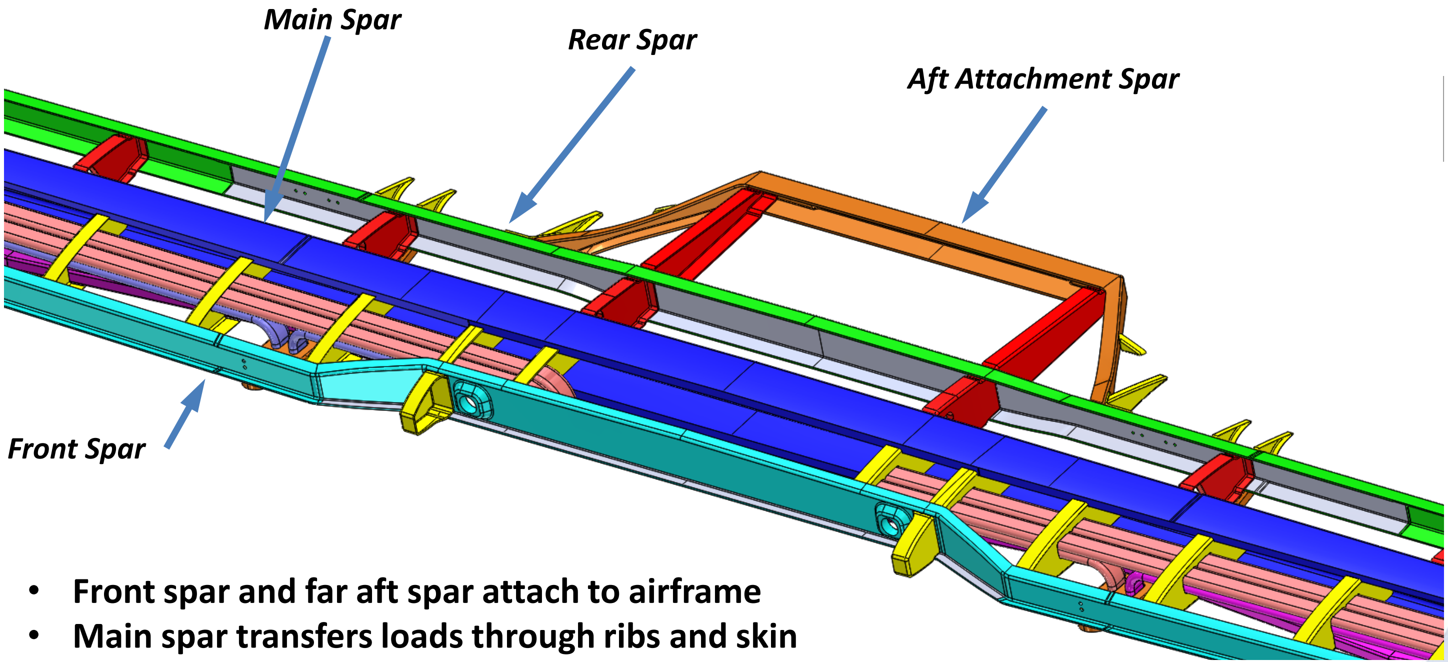
Internal Ducts for Power and Instrumentation Wiring (Lower Surface View)



Wing Attachment Frame (purple)



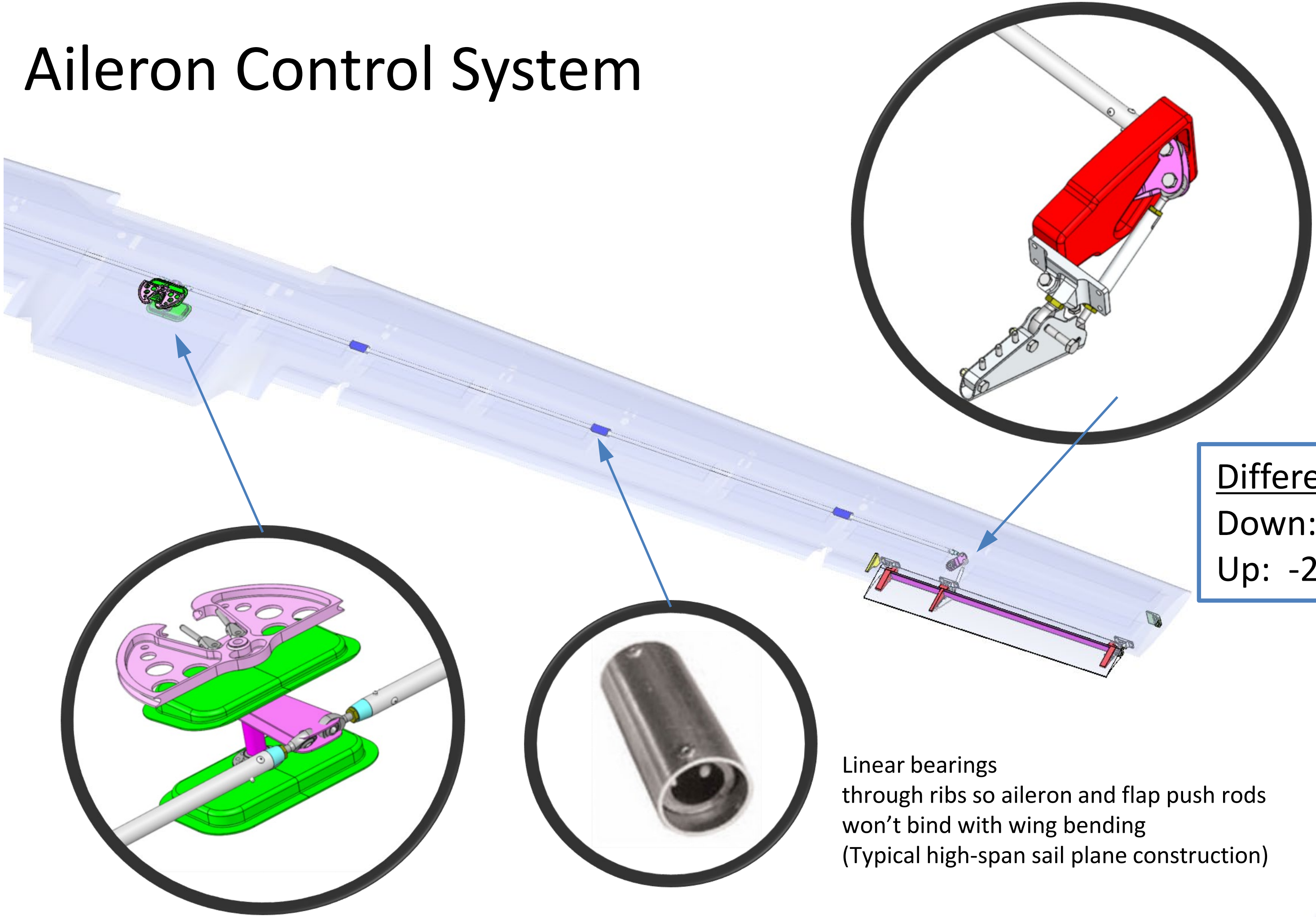
Wing Center Section



- Front spar and far aft spar attach to airframe
- Main spar transfers loads through ribs and skin

- Load path from main spar to fuselage – through composite skin and rib interfaces

Aileron Control System



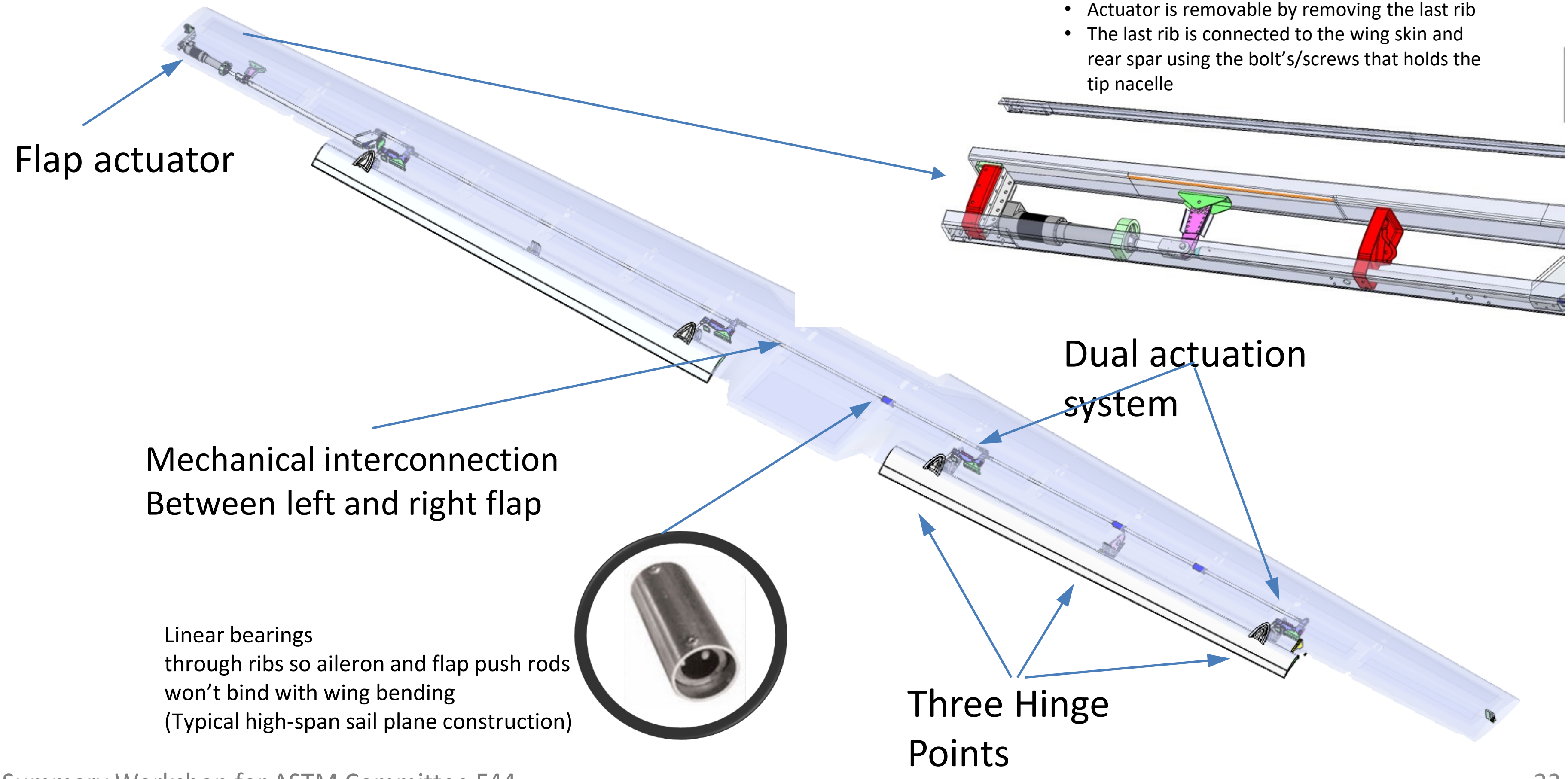
Linear bearings
through ribs so aileron and flap push rods
won't bind with wing bending
(Typical high-span sail plane construction)

Differential Aileron Travel
Down: 17.5˚
Up: -25.0˚

Flap Control System

Flap Actuator

- Actuator is removable by removing the last rib
- The last rib is connected to the wing skin and rear spar using the bolt's/screws that holds the tip nacelle



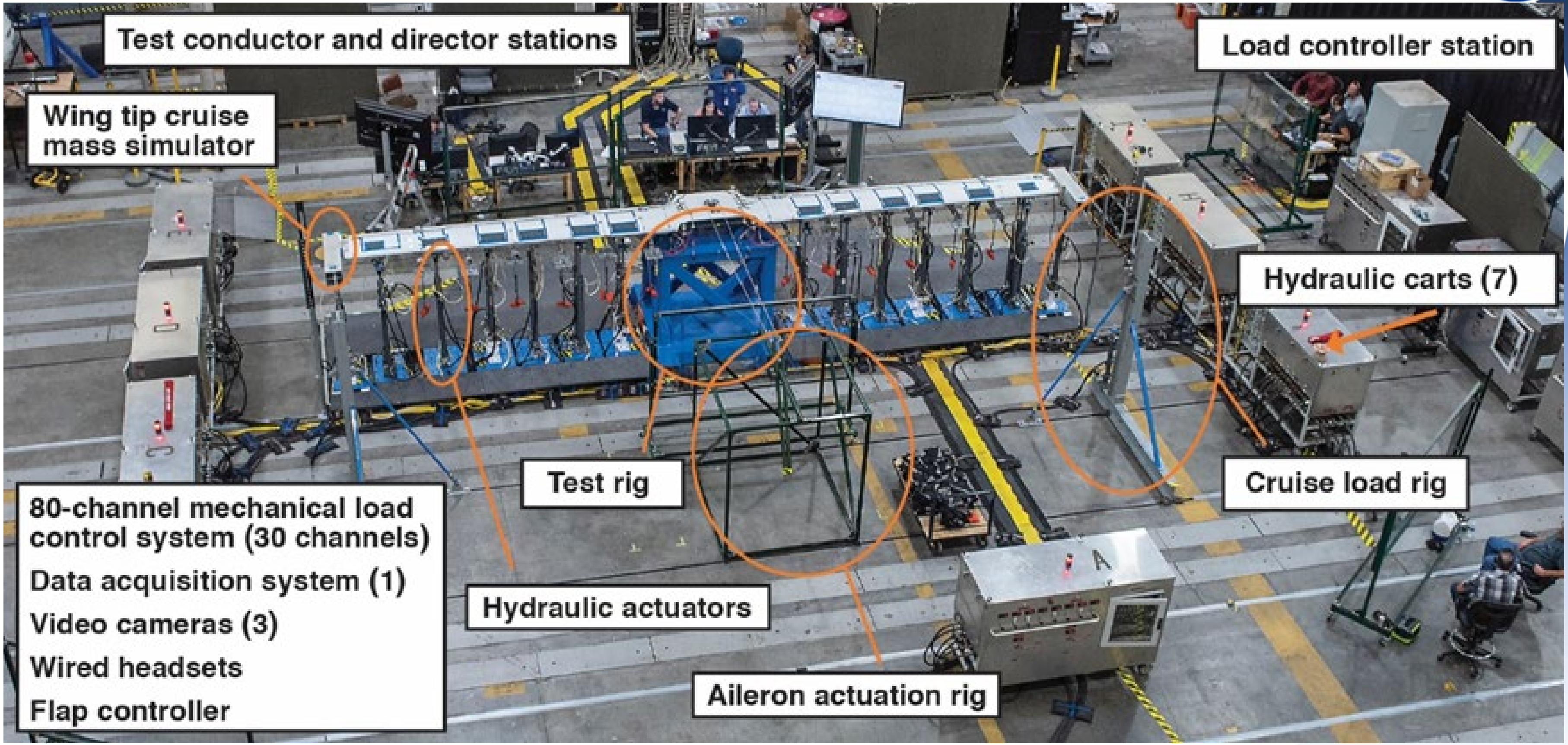
Linear bearings
through ribs so aileron and flap push rods
won't bind with wing bending
(Typical high-span sail plane construction)

X-57 Mod III Wing Before Closing

X-57 Wing Proof Test Setup

HL Simulator load + cruise motor thrust load

X-57 Proof Load Test
Armstrong Flight Loads Lab



Miller, et al. X-57 Wing Structural Load Testing, AIAA 2020-3090, 2020

Lessons Learned

- High aspect ratio wings with tip masses can have a different modal distribution than typical wings. There can be flutter concerns.
- The following construction techniques allowed for an efficient structure to make the Mod III/IV wing possible:
  - All uni-directional plies in spar cap were layed-up adjacent to each other, not interspersed with bi-directional plies
  - The main spar was fabricated without any physical hard points. The spar was bonded to the wing center section assembly. This minimized the weight and maximized the structural efficiency.

Recommendations

- Challenges with modifying a retrofit aircraft - especially when it comes to changes in the load path. Any modification that affects the load path must be analyzed and validated to ensure the structural integrity and safety of the aircraft.
- Increasing component weight - consider starting off with conservative load requirements such as higher maneuvering load factor and adjust as needed.
- Challenges with using composite materials and additive manufacturing - Mechanical performance very dependent upon materials and fabrication processes. Verify the material properties through testing rather than relying on the spec especially when used outside of spec.
- Consider the color of the aircraft components - Both the color of the components and the environmental temperature can impact material properties such as composite resins, and the glass transition temperature (Tg) of a polymer.
- Use multiple discipline analyses in preliminary design for new concept configurations (CFD, static structures, and aeroelasticity)

Backup-Topics

Backup-Performance

X-57 Induced Drag vs Span Sensitivities

(Without wing-tip power benefit)

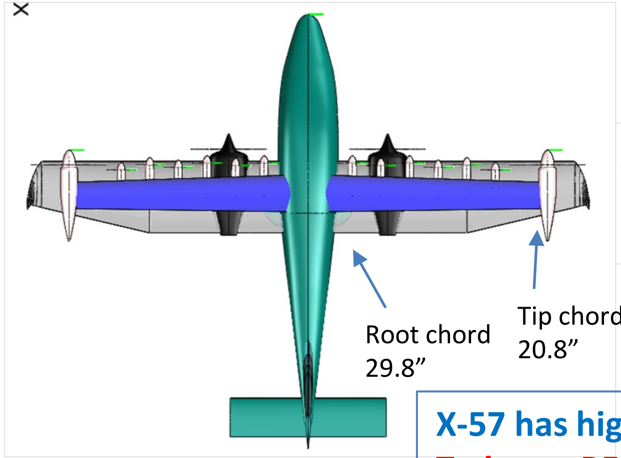
X-57: Design Target Cruise (150 KTAS @ 8,000 ft)

Tecnam

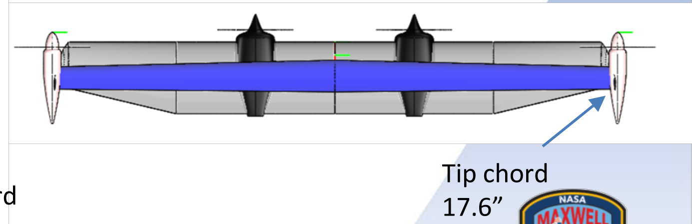
W_g = 2,700 lbs
Wing Area(S) = 158.9 ft^2
Span(b) = 37.4 ft
Aspect Ratio(AR) = 8.8
Di = 34.7 lbs

Tecnam
With Increased Gross Weight
W_g = 3,000 lbs
Span(b) = 37.4 ft
D_i = 42.8 lbs (+23.6%)

X-57
W_g = 3,000 lbs
Wing Area(S) = 66.67 ft^2
Span(b) = 31.62 ft
Aspect Ratio(AR) = 15
D_i = 59.9 lbs (+72.6%)
ΔD_i = 25.2 lbs (11.6% target cruise drag)

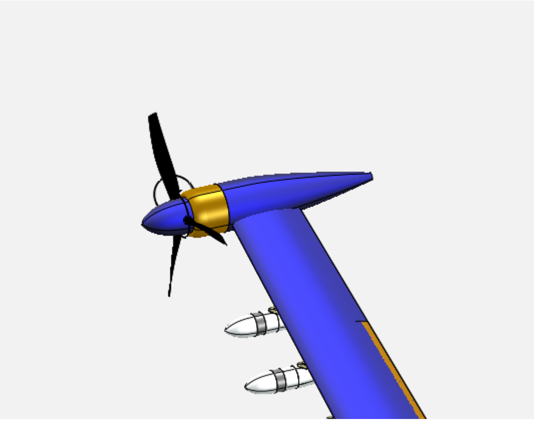


If X-57 Span = Tecnam Span
Induced Drag = Tecnam P2006T
@ 3,000 lbs
S = 66.67 ft^2, b = 37.4 ft
AR = 21.0
D_i = 42.8 lbs

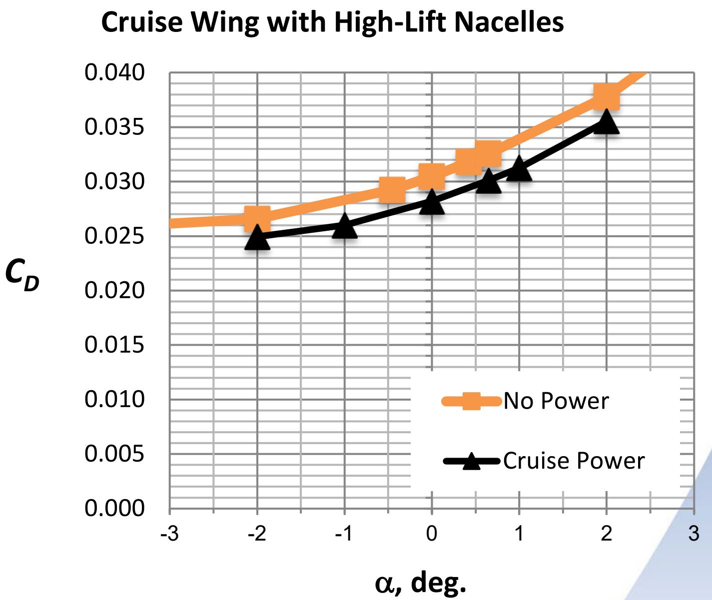


X-57 has higher induced drag than Tecnam:
Trying to REDUCE the penalty

Effect of *Cruise* Power on Drag



- FUN3D CFD – isolated wing + stabilator
- Cruise conditions 150 KTAS at 8,000 feet and C_L = 0.75
  - Unpowered tip propeller: C_D = 0.03290
  - Cruise powered tip propeller: C_D = 0.03006
    - 117.38 hp at 2250 RPM (both motors)
    - 28 count induced drag reduction
  - **This is a 18.6% reduction in calculated induced drag**
  - **4.9% of total target configuration drag**
  - **ΔD_i reduction of 11.2 lbs. (44% of penalty of X-57 reduced span & increased gross weight)**



Drag Estimation from CFD Analysis

X-57 Cruise Configuration

- Cruise speed goal: aircraft drag is ***D = 216.5lbs (plus a margin of 29.9 lbs)***
- CFD cruise drag: ***D = 201.1 lbs*** at $C_{L,total}$ = 0.75 (α = 0.91°)
- Some drag reduction expected from sources not modeled in the fully turbulent/unpowered CFD solution (ref. 2)
  - Induced drag reduction with cruise power: -11.2 lbs
  - Laminar flow on wing at cruise: -13.2 lbs (USM3D LM transition model)
  - High-lift propeller stored drag: + 6.0 lbs

- Revised CFD cruise drag + corrections: ***182.8 lbs (Margin = 33.4 lbs – 15%)***
- Real aircraft deformities, like rivets and surface intersections on fuselage/tail not modeled in smooth computational geometry

- This results in about a 24% reduction in configuration drag compared to the baseline aircraft

[2]*Deere et al.: AIAA 2017-3923*

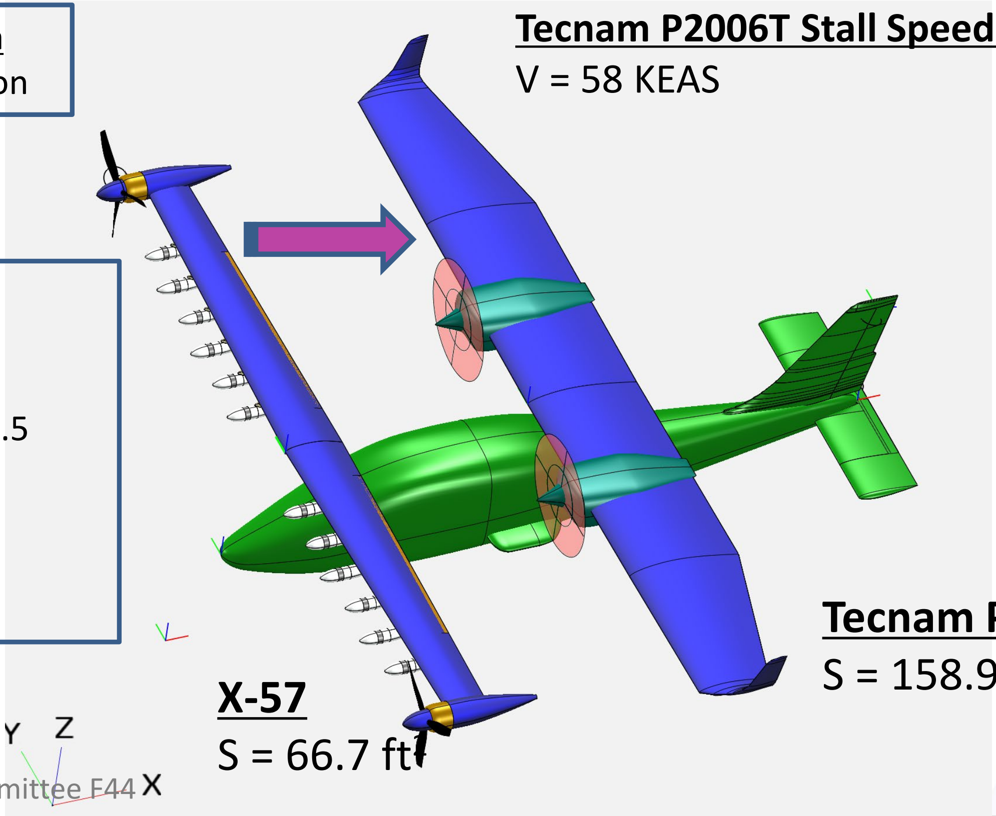
Stall Speed Comparison

Replace Wing: Tecnam P2006T → X-57

Wing Planform Area
X-57: 58% reduction

X-57 Stall Speed
- Cruise $C_{L,max}$ = 1.7
  - 89 KEAS
- Unpowered 30° flap $C_{L,max}$ = 2.5
  - 73 KEAS

- **Powered High-Lift Stall Speed**
  - **58 KEAS → $C_{L,max}$ = 3.95**



Tecnam P2006T Stall Speed at W_g = 3,000 lbs
V = 58 KEAS

X-57
S = 66.7 ft²

Tecnam P2006T
S = 158.9 ft²

Comparison of CFD High-Lift Analysis

Three different grid topologies and solvers used in the analysis

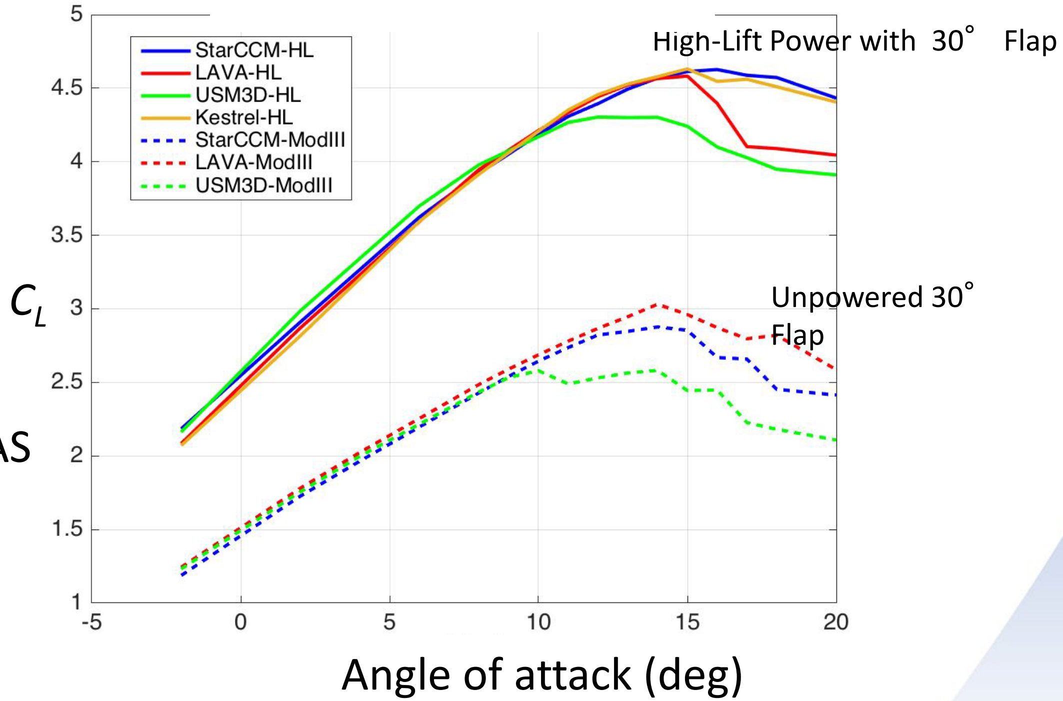
- ARC – **LAVA** solver with structured overset grid
- AFRC – **StarCCM+** solver with unstructured polyhedral grid
- LaRC – **USM3D** and **Kestrel** solvers with unstructured tetrahedral grids

At design stall speed

$V_{\text{powered high-lift}}$ = 58 KTAS

$V_{\text{unpowered}}$ = 73 KTAS

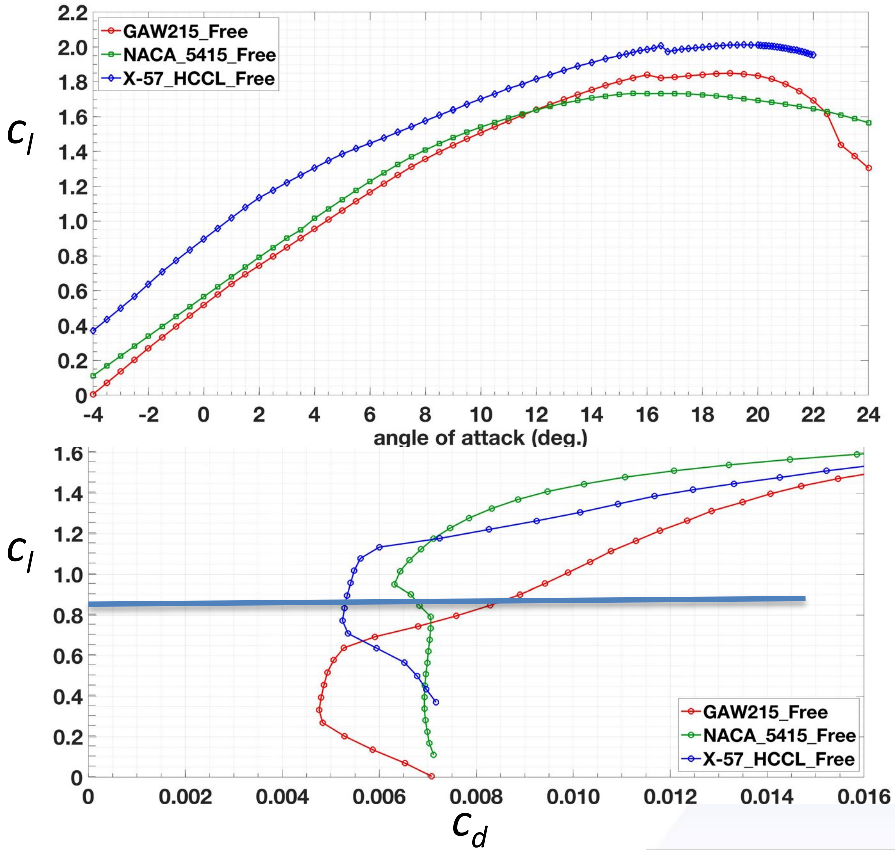
Altitude = 2500 ft



Airfoil Performance Comparison – Free Transition

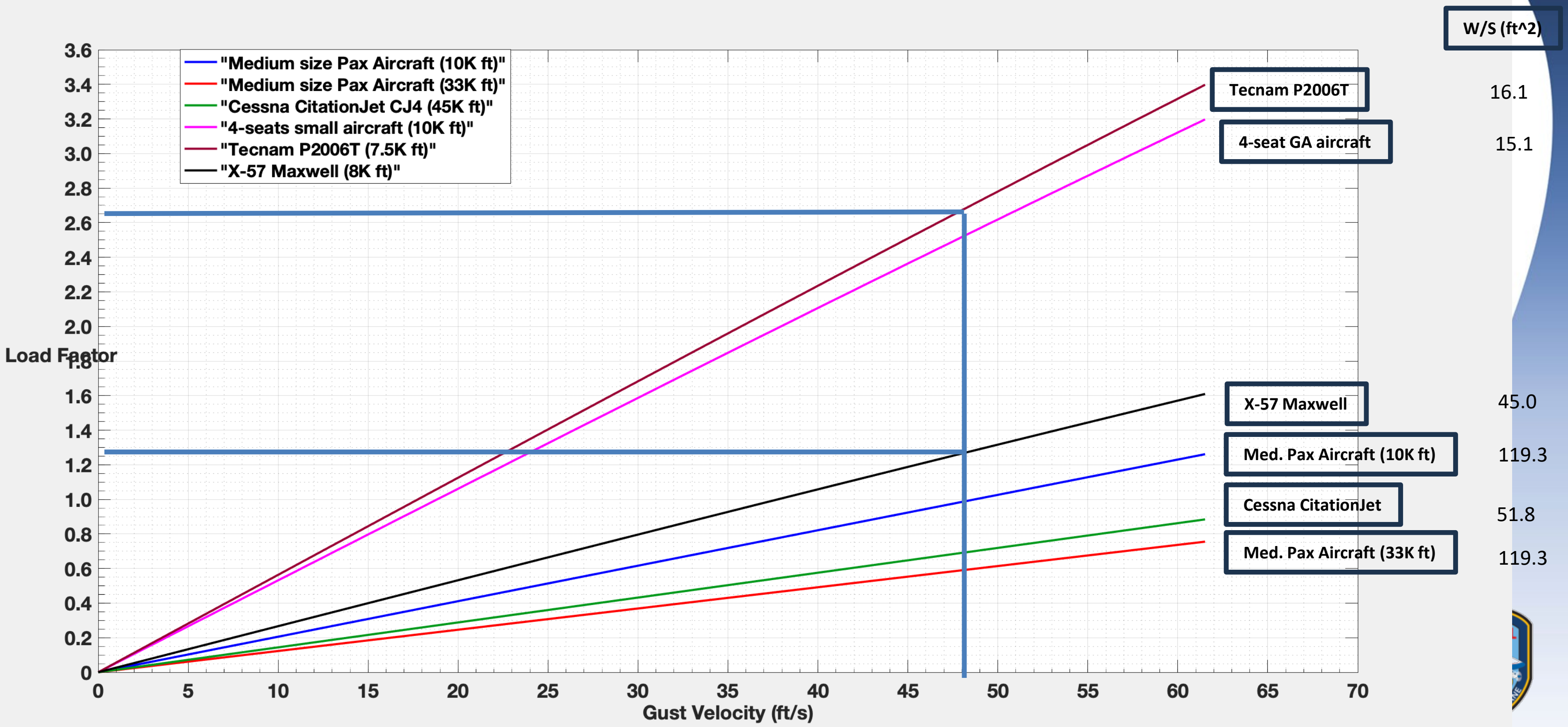
X-57, GAW215, and NACA 5415 Airfoils

- X-57 Airfoil
- $c_{l,max}$ = 2.05 (free transition)
- Drag of 55 counts at c_l = 0.9
- Low drag bucket for maneuvering capability w/o large increase in drag



Backup – Ride Quality

Load Factor Versus Gust Velocity



Backup –Material Testing

Coupon Test

- ASTM D3039 – Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials
- ASTM D6641 – Standard Test method for Compressive Properties of Polymer Matrix Composite Materials Using a Combined Loading Compression (CLC) Test Fixture
- ASTM D5379 – Shear Properties of Composite Materials by the V-Notched Beam Method
- ASTM D5766 – Open-Hole Tensile Strength of Polymer Matrix Composite Laminates

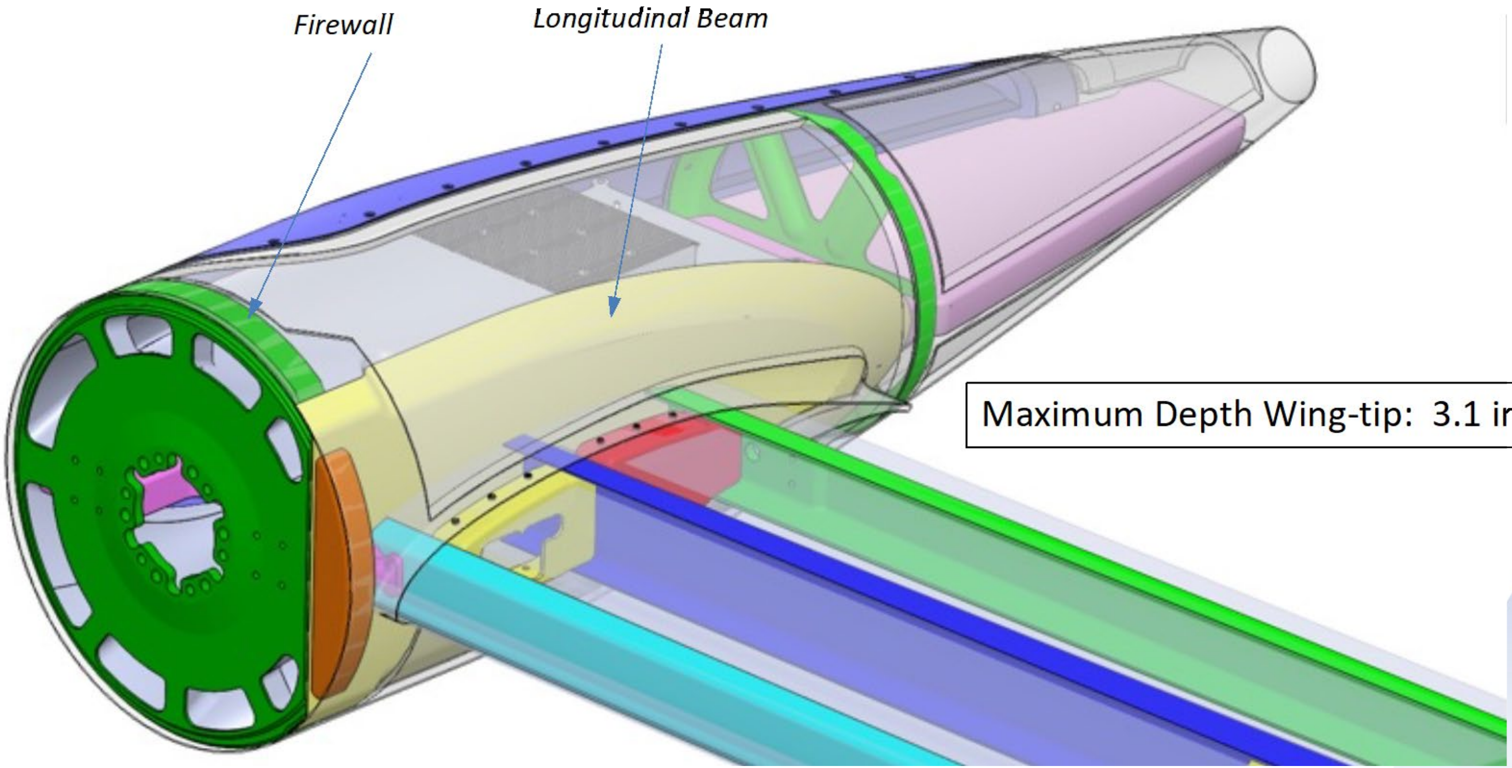
	Material	PMT-F4/IM2C UDP			PMT-F4/IM2C UDP			PMT-F4/IM2-2T			PMT-F4/IM2-2T			CHM12K			CHM12K			HexForce 282		
	Cure	250F OOA			250F OOA			250F OOA			250F OOA			Wet Lay			Wet Lay			Wet Lay		
	Condition	RTD 70±10F			ETD 165±5F			RTD 70±10F			ETD 165±5F			RTD 70±10F			ETD 165±5F			RTD 70±10F		
Method Reference	Test	Batch	Panel	Sample	Batch	Panel	Sample	Batch	Panel	Sample	Batch	Panel	Sample	Batch	Panel	Sample	Batch	Panel	Sample	Batch	Panel	Sample
ASTM D3039	0° (warp) Tensile Modulus, Strength, and Poisson's Ratio	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
				2			2			2			2			2			2			
				3			3			3			3			3			3			
				4			4			4			4			4			4			
				5			5			5			5			5			5			
ASTM D3039	90° (fill) Tensile Modulus & Strength	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
				2			2			2			2			2			2			
				3			3			3			3			3			3			
				4			4			4			4			4			4			
				5			5			5			5			5			5			
ASTM D6641	0° (warp) Compressive Modulus, Strength, and Poisson's Ratio	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
				2			2			2			2			2			2			2
				3			3			3			3			3			3			3
				4			4			4			4			4			4			
				5			5			5			5			5			5			
ASTM D6641	90° (fill) Compressive Strength	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
				2			2			2			2			2			2			2
				3			3			3			3			3			3			3
				4			4			4			4			4			4			
				5			5			5			5			5			5			
ASTM D5379	V-Notch Beam Shear Strength and Modulus – G12Plane	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
				2			2			2			2			2			2			
				3			3			3			3			3			3			
				4			4			4			4			4			4			
				5			5			5			5			5			5			
ASTM D5379	V-Notch Beam Shear Strength and Modulus – G21Plane	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1			
				2			2			2			2			2			2			
				3			3			3			3			3			3			
				4			4			4			4			4			4			
				5			5			5			5			5			5			
ASTM D5766	0° (warp) Open Hole Tension							1	1	1	1	1	1	1	1	1	1	1	1			
										2			2			2			2			
										3			3			3			3			
										4			4			4			4			
										5			5			5			5			

Backup-Final

Cruise Nacelle Loads Cases

Load Case	Description	Aerodynamic & External Loads	Inertial Loads (g's)			Thermal Stress	Motor Loads (Right Nacelle) (lbs, in-lbs)					
			Nx	Ny	Nz		Fx	Fy	Fz	Mx	My	Mz
1	Vs-1g ASL	X	-1.0	+/-1.33	-1.00	X	-531	-171	185	2820	-690	1250
2	Vc max nz due to stall	X	-1.0	+/-1.33	-2.91	X	-531	-171	185	2820	-690	1250
3	Va - Positive maneuver ASL	X	-1.0	+/-1.33	-3.00	X	-531	-171	185	2820	-690	1250
4	Vd - Positive maneuver ASL	X	-1.0	+/-1.33	-3.00	X	-531	-171	185	2820	-690	1250
5	Vd - Negative maneuver ASL	X	-1.0	+/-1.33	1.37	X	-531	-171	185	2820	-690	1250
6	Vs-1g high altitude	X	-1.0	+/-1.33	-1.00	X	-531	-171	185	2820	-690	1250
7	Vc max nzdue to stall high altitude	X	-1.0	+/-1.33	-2.91	X	-531	-171	185	2820	-690	1250
8	Va - Positive maneuver high altitude	X	-1.0	+/-1.33	-3.00	X	-531	-171	185	2820	-690	1250
9	Vd - Positive maneuver high altitude	X	-1.0	+/-1.33	-3.00	X	-531	-171	185	2820	-690	1250
10	Vd - negative gust high altitude	X	-1.0	+/-1.33	1.71	X	-531	-171	185	2820	-690	1250
11	Asym - 100/75	X	-1.0	+/-1.33	-3.48	X	-531	-171	185	2820	-690	1250
12	Rolling at Va	X	-1.0	+/-1.33	-2.98	X	-531	-171	185	2820	-690	1250
13	Rolling at Va - max roll rate	X	-1.0	+/-1.33	-2.98	X	-531	-171	185	2820	-690	1250
14	Rolling at Vd	X	-1.0	+/-1.33	-2.98	X	-531	-171	185	2820	-690	1250
15	Rolling at Vd - max roll rate	X	-1.0	+/-1.33	-2.98	X	-531	-171	185	2820	-690	1250
16	Flap	X	-1.0	Horizontal (Value) Axis Major Gridlines			-531	-171	185	2820	-690	1250
17	Max Takeoff+P-Factor (23.361.a.1)+Taxi Bump	X	-1.0	+/-1.00	-2.57	X	-590	-171	185	2820	-690	1250
18	Max Continuous+P-Factor (23.361.a.2)	X	-1.0	+/-1.33	-3.00	X	-531	-171	185	2820	-690	1250
19	Max Continuous+P-Factor+Gyroscopic (23.371)	X	0.0	0.0	-2.50	X	-531	150	150	2820	2315	925
20	Ground Loads (Landing)		-3.0	+/-1.33	-3.00	x						
21	Ground Loads (Landing)		-3.0	+/-1.33	2.75	x						

Cruise Motor Tip Nacelle



Maximum Depth Wing-tip: 3.1 inches

High-Lift Motor/Controller/Prop – Initial Structure