



X-57 Static Structural Requirements and Airworthiness Approach

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Outline



- NASA AFRC Aircraft Structural Safety of Flight Guidelines
- Static Structure Design and Analysis Process
- Static Structure Airworthiness Approach
- Mod II Structural Modification
- Mod III Wing Airworthiness Approach
- X-57 Aircraft Operating Limits
- Conclusions



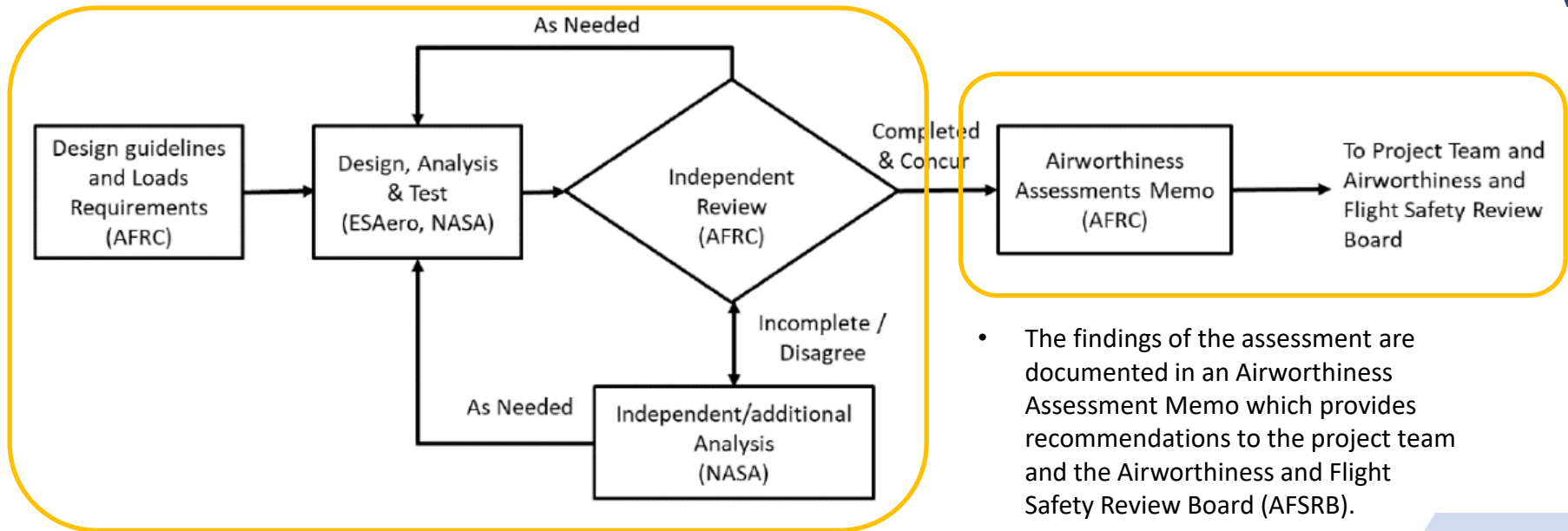
Aircraft Structural Safety of Flight Guidelines



- X-planes and NASA research aircraft are not normally FAA or DOD certified aircraft
 - NASA provides own airworthiness certification utilizing a risk-based approach
 - Organization can determine airworthiness are FAA, DoD and NASA
- The Aerostructures Branch at AFRC has developed an Aircraft Structural Safety of Flight Guidelines (AFG-7123.1-001)
 - Describe the airworthiness approaches and options are available for designing, testing, and operating "one-of-a-kind" aircraft as well as for modifying certified aircraft at AFRC.
 - Consider a combination of design, analysis, testing, monitoring techniques, and inspection plans
 - Flexible - can be tailored based on the risk posture of an individual project



Static Structure Design and Analysis Process



- The AFRC is responsible for overseeing all structural design and analyses and providing the structural assessment of the components and aircraft.

- The findings of the assessment are documented in an Airworthiness Assessment Memo which provides recommendations to the project team and the Airworthiness and Flight Safety Review Board (AFSRB).
- The Chair of the AFSRB formulates a recommendation letter to the Center Director regarding the adequacy of project preparation, quantifying residual risks and identifying Accepted Risk hazards.



Static Structure Airworthiness Approach



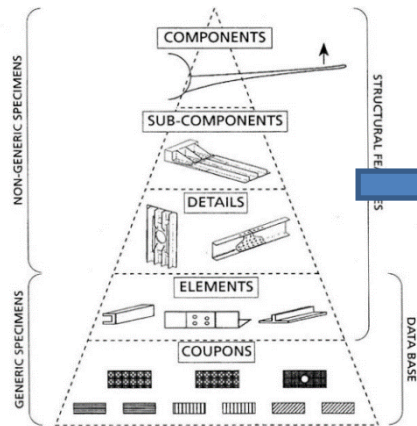
- Our primary motivation is to do everything we can to ensure mission success, but with no compromise to human safety. Design requirements are essentially risk mitigations.
- The overall static structure airworthiness approach for X-57 is summarized below

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
	Metallic	2.25	Verified by analysis only
Mod III Wing	Composite	1.80	Required well established composite processes and materials Proof tested to 120% design limit loads Allowed to flight to 100% proof tested loads Instrumented and loads calibrated for in-flight loads monitoring

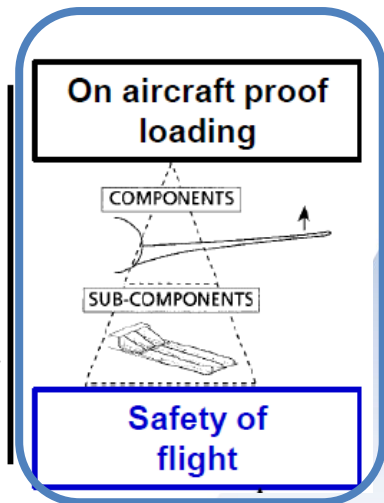
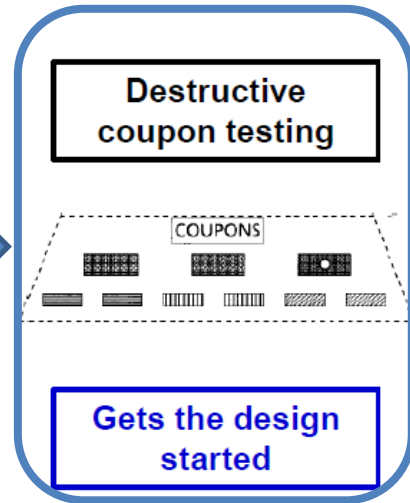


Composite Structures

- 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 tested for safety of flight



MIL-HDBK-17-1F (2002)



Additive Manufacturing Structures



- Additive manufacturing (3D-printed and injection molded) are relatively new and first use for flight at NASA AFRC (e.g. high-lift blade)
- Equivalence coupon testing is required to verify the material and fab. processes
 - Test results usually don't match or not available on the material datasheets → pose a higher risk to the flight project
 - Test at the extreme environmental conditions expected in operation (hot and cold)
 - e.g. LCF40-PPA Tensile strength: 45 ksi (spec at room temp), 47 ksi @ 0° F, 37 ksi @ 165° F
- A more conservative approach is adapted for X-57
 - Designs are verified by analysis AND proof tested to 120% design limit loads
 - 20 percent material allowable knock down for B-Basis statistical reliability
 - 50 percent material allowable knock down if no material testing
 - All flight hardware are qualification tested to 105% operational loads

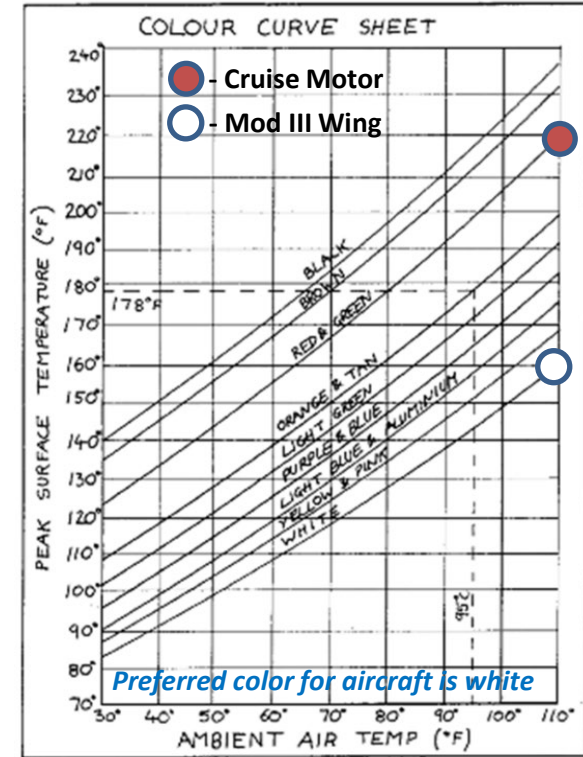


Temperature Considerations



- 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 motor's surface temperature at startup due to the adhesive strength of the magnet.

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



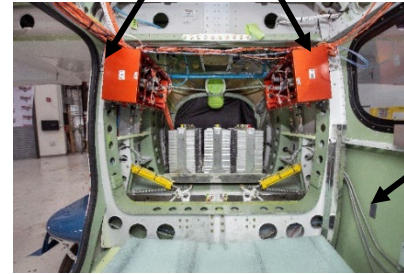
Colour - Temperature relationship.

Mod II 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

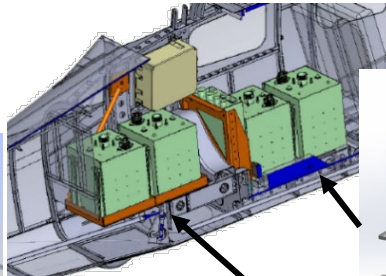
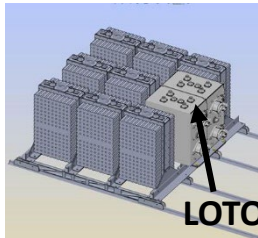
Contactor pallet (left and right)



Battery Control Module



Equipment Pallet



Fwd Battery Tray

Aft Battery Tray



Battery Venting Assembly



Battery Venting (3" dia)



Mod II Aircraft Modification

- For flight instrumentation and pilot safety enhancement
 - Air data probe added
 - 3-point seat belts with inertia reel upgraded to 4-point harness
 - Passenger window modified to become secondary egress
 - New motor cowling fabricated

Mod II Cruise Motor Cowling



Secondary Egress



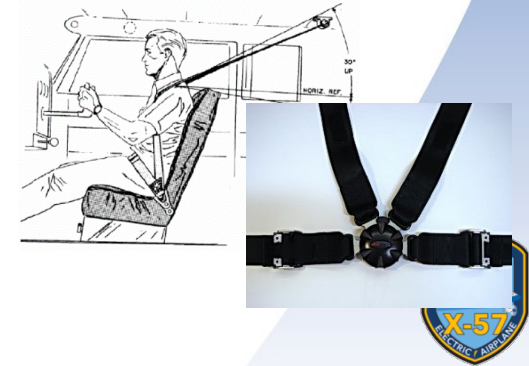
Nose cone composite structure proof tested



Cockpit Display



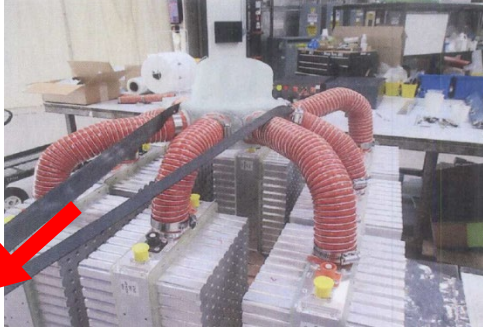
Upgraded 4-point Harness



Proof Testing

- Proof Tested Items
 - Low mass items mount (GoPro, Data recorders)
 - Battery venting assembly
 - Nosecone air data probe cutout
 - GoPro camera mount
 - 3D printed parts

Battery Venting Assembly Test



GoPro Mount Test



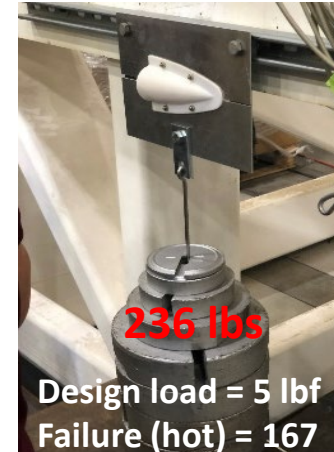
Nosecone Test



HL Blade Test
(Injection molding)



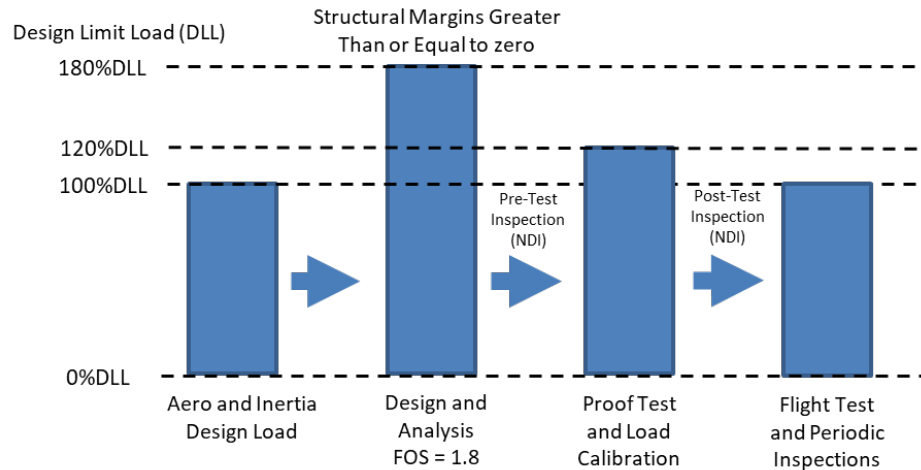
Cowling Air Scoop Test





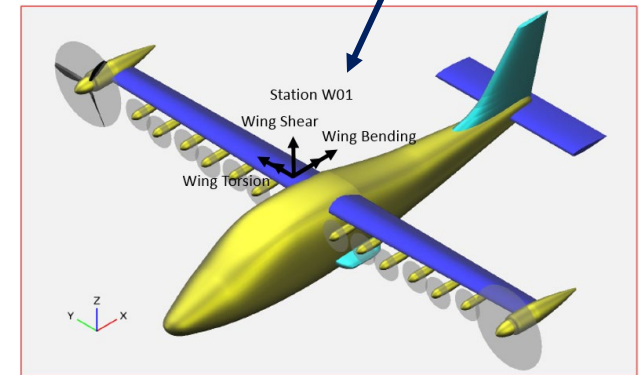
X-57 Mod III Wing Airworthiness Approach

- Demonstrate and validate the structural integrity of the wing for flight
- Approach: Designed to 1.8 FS, proofed to 120% flight limit, full flight instrumentation, allowed to fly to 100% with real-time loads monitoring



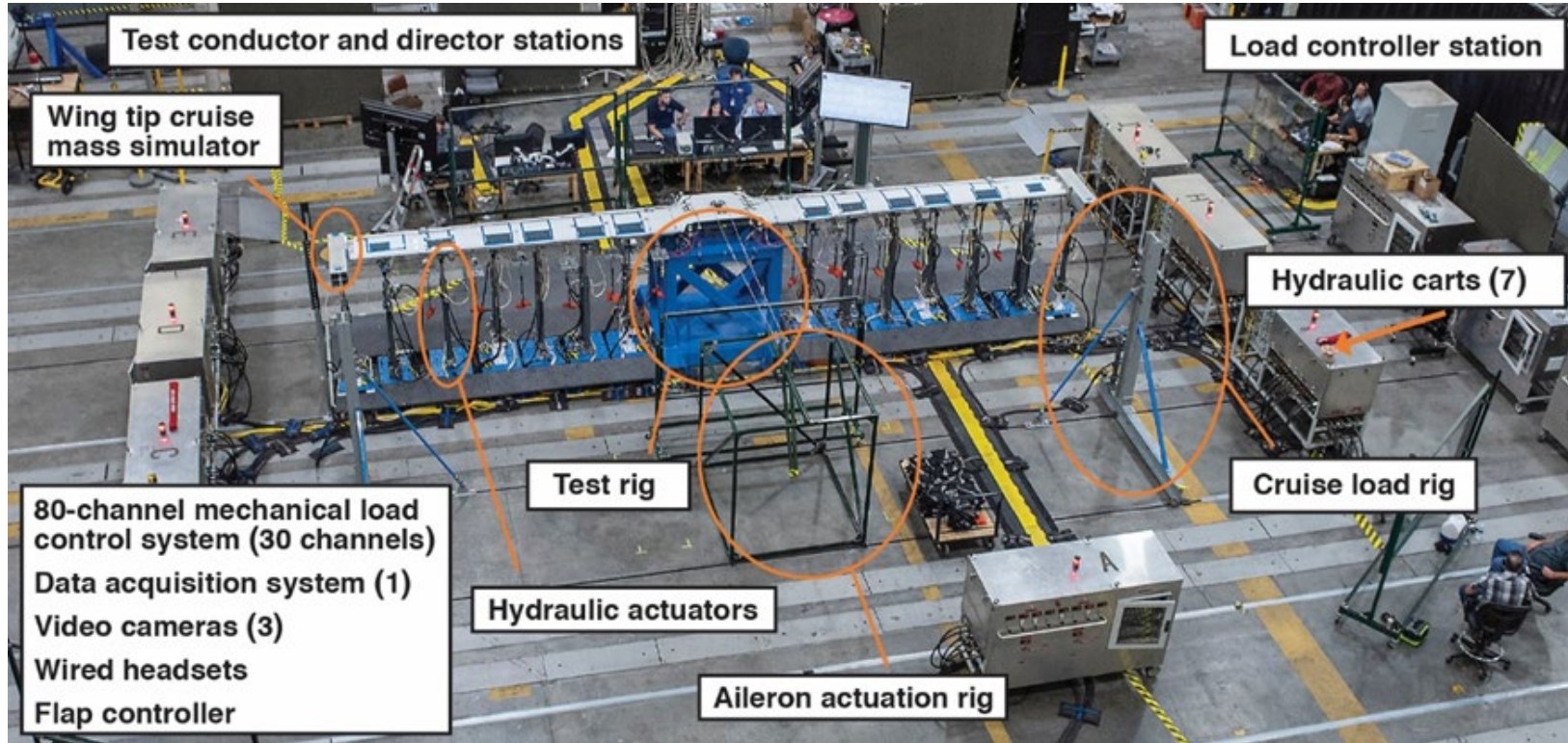
Flight Test Loads Monitoring

Monitor loads at root inboard station



X-57 Mod III Wing Proof Load Test

Armstrong Flight Loads Lab



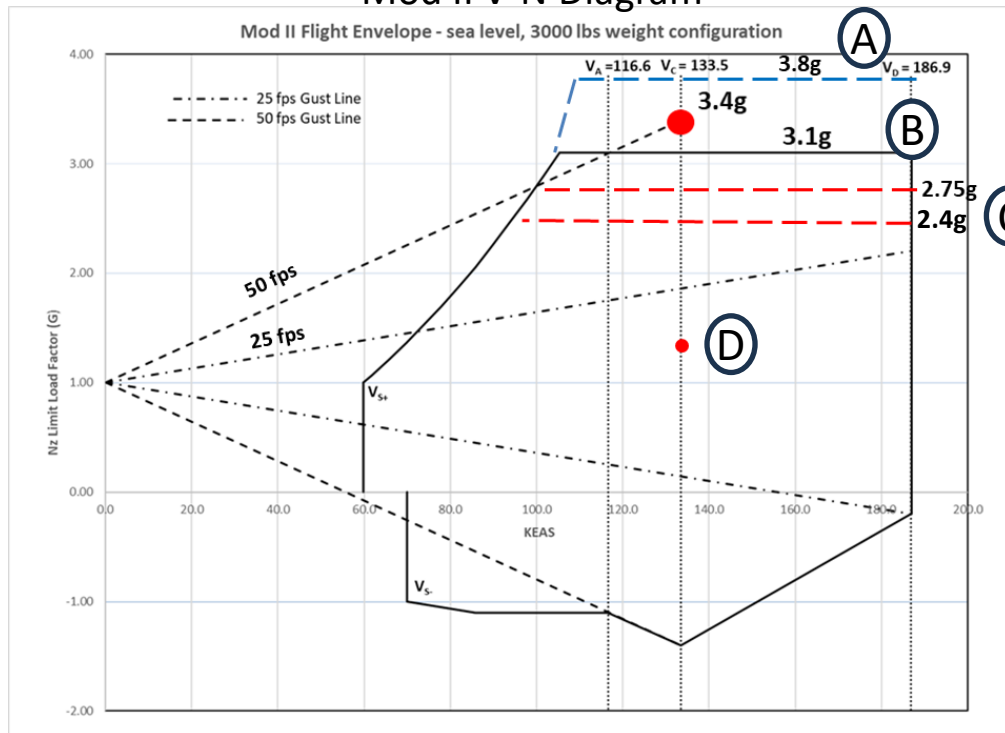
Reference: Miller, Li et al. X-57 Wing Structural Load Testing, AIAA 2020-3090, 2020



Mod II Aircraft Operating Limits



Mod II V-N Diagram



- The increase in gross weight required to reduce the maneuver and landing load factor by scaling the N_z and gross weight
 - Standard Tecnam P2006T is certified for 2712 lbs and +3.8 / -1.7g N_z (A)
 - X-57 is a retrofit aircraft (Mod II ~3000 lbs and Mod III/IV ~3200 lbs). N_z reduced to +3.4/-1.4g (Mod II) and +3.1/-1.4g (Mod III/IV) (B)
 - 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 (<2.75g), fuselage (<2.4g), and landing gear. (C)
- Gust load (3.4g due to 50 fps gust) is higher than the maneuver N_z
 - Limited the operation - Not allowed to operate in conditions of above "light" turbulence (D)



Lessons Learned



- 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.
- Unexpected increase in 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 (T_g) of a polymer.



Conclusions



- NASA provides own airworthiness certification utilizing a risk-based approach
- Aircraft Structural Safety of Flight Guidelines (AFG-7123.1-001) is flexible and can be tailored based on the risk posture of an individual project
- The airworthiness approach requires a balance of design, analysis, testing, inspections and monitoring techniques to ensure an acceptable level of confidence in the structural integrity of aircraft components and modifications.
- AFRC Aerostructures Branch oversees all structural design and analyses, providing the structural evaluation of components and aircraft.
- Our primary motivation is to do everything we can to ensure mission success, but with no compromise to human safety.





Backup



Design Criteria, Requirements and Reports



- NASA AFRC Aircraft Structural Safety of Flight Guidelines, AFG-7123.1-001
- REQ-CEPT-006 – Structural loads requirements for High-Lift Structure
- REQ-CEPT-007 - Structural loads requirements for Floor and Equipment Support
- REQ-CEPT-008 - Structural loads requirements for Mod II Wing Motor Mounts
- REQ-CEPT-010 - Structural loads requirements for Cruise Motor
- REQ-CEPT-015 - Structural Loads Requirements for Mod III Cruise Nacelle Structure
- SPEC-CEPT-003 Rev A - Mod III/IV Wing Structural Specifications
- SPEC-CEPT-004 - High-lift Propeller Specification
- ANALYS-CEPT-007 (Rev B) - X-57 Landing Gear and Mod II Wing Loads
- ANALYS-CEPT-021 - Mod II fuselage and Mod III wing/fuselage attachment stress analysis



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



Loads for Mod II Cruise Motor and Motor Mount



- Documented in REQ-CEPT-008 and -010
- Inertial Loads
 - Flight Maneuver Loads
 - Ground Loads
- Powerplant Loads
- Thermal stress
- Fatigue
- Blade-out condition was not considered
 - MT propeller is a certified component
- Motor failure and bearing seizing load condition was not considered
 - Motors are qual and endurance tested on the ground test fixture (Airvolt)

<i>Powerplant Loads</i>	F_x, N	F_y, N	F_z, N	$M_x, N-m$	$M_y, N-m$	$M_z, N-m$
Max Thrust & Regen & P-factor	+/-2837.05	+/-332.86	+/-397.96		+/-297.64	+/-364.90
Max Torque				+/- 470.0		
Gyroscopic					+/-157.0	+/-392.0

- Max torque and thrust
 - Initially, the max torque and thrust were higher than motor selection but were later adjusted based on the test results
 - NACA report WR-3G26: 2250 RPM, 66kW=89 hp, prop dia=5.5 ft, 3 blades, at SL density (Max SL Static thrust = 475 lbf (2113N))
- P-factor loads
 - Considered at various extremes flight conditions including 15deg angle of attack and 15deg sideslip
- Imbalance loads (Radial)
 - Max imbalance displacement of 0.02" from shaft centerline at max RPM
- Gyroscopic load (FAR 23.371 (a))



X-57 Mod III Wing V-N Diagram



Configuration

Cruise (Mod III/IV)

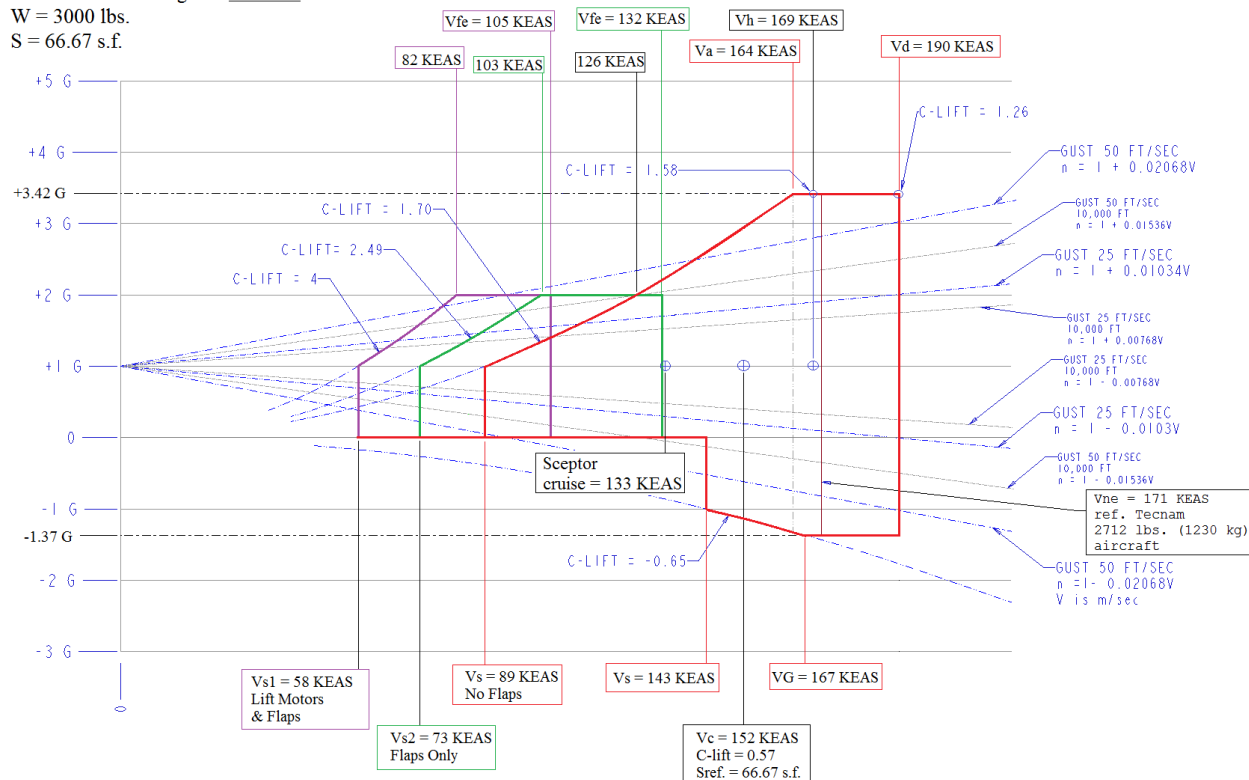
Flap 30° No HL Power
(Mod III/IV)

Flap 30° With HL Power
(Mod IV)

X-57 mod-4 v-n diagram 20161207

W = 3000 lbs.

S = 66.67 s.f.



V_d = dive speed
V_c = cruise speed = (0.9)(V_h)
V_a = maneuvering speed
V_h = max. speed, level flight, max. cont. power
V_{ne} = never exceed speed



X-57 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)	High Lift Devices [§ 23.345] ± 25 ft/sec vertical 25 ft/sec head-on Wing Flaps [§ 23.457(a)]	Vertical Surfaces Lateral gust: ± 50 fps @ V_C [§ 23.443(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		
	Horizontal Stabilizing and Balancing Surfaces [§ 23.425] Clean airplane and with high lift devices		[§ 23.373]	[§ 23.445]	Horizontal Stabilizing and Balancing Surfaces [§ 23.427] Loads from gusts combined with yawing and slipstream effects, clean airplane and with high lift devices
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.	Balancing Horizontal Tail Load [§§ 23.331, 23.421]	Speed Control Devices	[§ 23.445(d)]	Vertical Surfaces [§ 23.441] - @ V_A Yaw, sideslip, and rudder deflection
				Outboard Fins or Winglets	Ailerons [§ 23.445] Abrupt maximum control movement @ V_A . Control deflection requirements @ V_C and V_D
	Pitching: Checked and Unchecked Applies to horizontal stabilizing and balancing surfaces [§ 23.423] Abrupt maximum control input @ V_A	High Lift Devices [§ 23.345] $n = 2.0$ g Wing Flaps [§ 23.457(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		
ENGINE			Engine Torque [§ 23.361] – Combined with symmetrical limit loads @ V_A		
			Side Load on Engine Mount [§ 23.363]		
			Gyroscopic and Aerodynamic Loads [§ 23.371] – Pitching and yawing, applies only to turbine installations		
			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]		
	Rear Lift Truss , reverse air flow [§ 23.369]		Canard or Tandem Wing Configurations [§ 23.302]		



- X-57 Wing Design Load Case



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

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

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

Maximum Take-off Torque
Maximum Continuous Torque
Gyroscopic Moment

