X-57 Static Structural Requirements and Airworthiness Approach

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The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) (Edwards, California, U.S.A.) has been flying various types of aircraft, including experimental ones requiring structural modifications. Many of these aircraft aren't typically certified by the Federal Aviation Administration (FAA) or the Department of Defense (DoD), but NASA can provide its own airworthiness certification utilizing a risk-based approach. The AFRC has established review processes and procedures to identify hazards, manage risks associated with flight programs, ensure safe flight operations, and satisfy programmatic requirements. The Aerostructures Branch at AFRC developed guidelines for the structural safety of flight, covering experimental aircraft, new components, payloads, and modifications. These guidelines detail structural design, analysis, instrumentation, ground testing, and flight-test operational aspects. The guidelines are followed for defining the airworthiness plan throughout the life cycle of a project. The guidelines can be tailored to the risk posture of each individual project. This paper documents the details of the structural airworthiness plan for the X-57 aircraft, including existing, modified, and newly developed structures. Additionally, it covers the design requirements and load cases specific to the X-57 aircraft.

I. Nomenclature

FS = factor of safety
F_x = force in x-direction
F_y = force in y-direction
F_z = force in z-direction
g = acceleration of gravity
M_x = moment about the x axis
M_y = moment about the y axis
M_z = moment about the z axis
N_x = load factor in x-direction
N_y = load factor in y-direction
N_z = load factor in z-direction
Va = design maneuvering speed
Vc = cruise speed
Vd = dive speed
Vs = stall speed

II. Background

The National Aeronautics and Space Administration (NASA) Armstrong Flight Research Center (AFRC) (Edwards, California, U.S.A.) has been involved in flying various aircraft types, including experimental ones requiring structural modifications. Many of these aircraft aren't typically certified by the Federal Aviation Administration (FAA) or the

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Department of Defense (DoD), but NASA, and thus AFRC, has the authority to certify experimental aircraft for "Public Use."

These experimental manned or unmanned aircraft require structural modifications to accommodate unique flight experiments. Sometimes, a completely new, one-of-a-kind experimental aircraft is built. Over the years, AFRC has established review processes and procedures to identify any hazards, manage risks associated with flight programs, ensure safe flight operations, and ensure that flight objectives satisfy programmatic requirements. The goal is to provide a flexible review system based on risk management that identifies airworthy aircraft. These aircraft can then be operated safely with the highest probability of mission success. There is no exception that the X-57 aircraft would follow the typical AFRC airworthiness review process.

The X-57 project began as a small effort in 2014 called LEAPTech [1]. It involved a ground testing concept that distributed 18 small electric motors along the leading edge of the wing. The motors optimized wing performance as the airflow from the distributed motors generated more than double the lift of the unblown wing. The project then transitioned into an experimental aircraft called the X-57 aircraft by modifying the Tecnam [2] P2006T airplane. This aircraft was developed to demonstrate distributed electric propulsion technology and serve as a research platform for exploring more energy-efficient and environmentally friendly methods of aviation.

The overview of the transformation of the P2006T airplane into the X-57 aircraft is shown in Fig. 1. This aircraft underwent conversions into an electric aircraft by replacing its two gas engines with electric motors and incorporating over 860 lb of batteries, systems, and instrumentation. This modification, referred to as the Mod II configuration, was carried out by Empirical Systems Aerospace, Inc. (ESAero) (San Luis Obispo, California, U.S.A.) [3]. The primary contractor, ESAero, along with several subcontractors, were responsible for the aircraft modification and initial integration. Most of the Mod II airframe modifications took place at Scaled Composites in Mojave, California. The Modification (Mod) III and IV modifications plans were to replace the original Tecnam wing with a new high-aspect-ratio composite wing. Additionally, two cruise motors were to be relocated to the wingtips with 12 small electric high-lift motors installed along the leading edge of the wing.

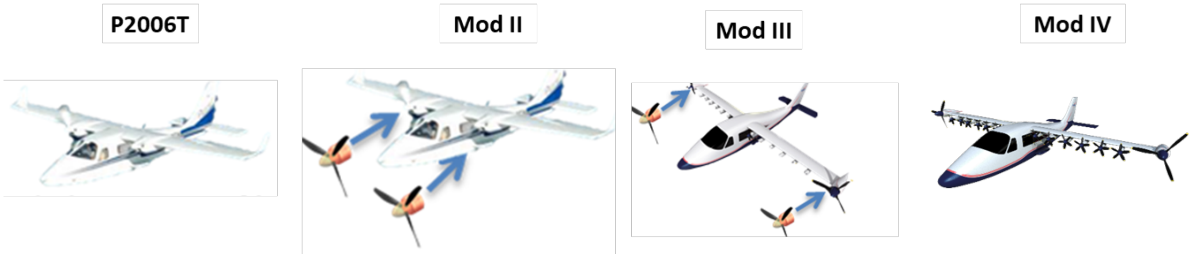

Fig. 1 Overview of the modification phases of the X-57 aircraft.

III. Static Structure Design and Analysis Process

The Aerostructures Branch at AFRC is responsible for providing airworthiness assessment of aircraft from a structural perspective. The Structural Safety of Flight guidelines, AFG-7123.1-001 [4], was developed by the Aerostructures Branch to provide guidance on demonstrating the structural airworthiness of an aircraft before beginning ground and flight tests. These guidelines offer several options including different combinations of design, analysis, instrumentation, ground testing, and flight-test operation. The guidelines can be tailored individually based on the safety risk posture of each project. The design criteria and airworthiness plan for the X-57 aircraft were developed based on these guidelines, as well as industry standards.

The overview of the static structure analysis process developed for the X-57 aircraft is shown in Fig. 2. The AFRC is responsible for providing structural design criteria and load requirements. Personnel at the NASA Langley Research Center (LaRC) (Hampton, Virginia, U.S.A.), the Glenn Research Center (GRC) (Cleveland, Ohio, U.S.A.), and ESAero played a significant role in design and analysis. They performed structural analysis of the new and modified structures as well as of the new composite wing. The AFRC is responsible for overseeing all structural design and analyses and providing the structural assessment of the components and aircraft. Independent analyses were performed and reviewed by AFRC when necessary. The findings of the assessment are documented in an Airworthiness Assessment Memo (AAM), which provides recommendations to the X-57 project team and the Airworthiness and Flight Safety Review Board (AFSRB), chaired by the Center Chief Engineer. The Chair of the AFSRB then formulates a recommendation letter to the Center Director regarding the adequacy of project preparation, paying close attention to quantifying residual risks and identifying Accepted Risk hazards.

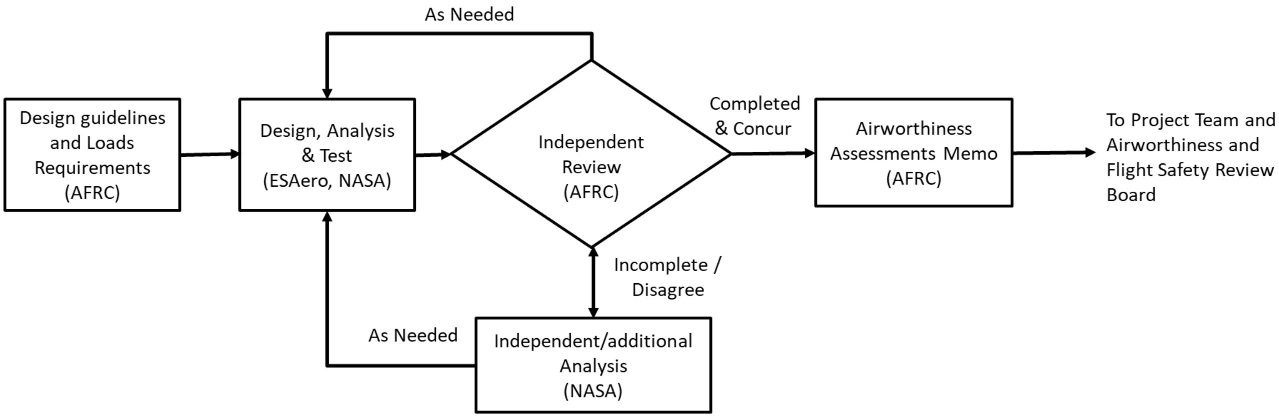

Fig. 2 The static structure design and analysis process for the X-57 aircraft.

IV. The Airworthiness Approach for the X-57 Structure

The Aerostructures Branch at AFRC developed guidelines (AFG-7123.1-001) for the structural safety of flight, covering experimental aircraft, new components, payloads, and modifications. These guidelines detail the options of the combination of structural design, analysis, instrumentation, ground testing, and flight-test operational aspects. The airworthiness approach requires a balance of those five aspects to ensure an acceptable level of confidence that the aircraft is ready for flight. The AFRC G-7123.1-001 document, along with industry standards, were used as guidelines to develop the airworthiness plan for the X-57 aircraft.

All static structural designs require a factor of safety to reduce the probability of in-flight structural failures. Different materials, structural analyses, and testing are components of determining the minimum factor of safety required for a structure to be suitable for flight. All structures must maintain a positive margin of safety. The calculation of the margin of safety is defined in Eq. (1). The ultimate load is defined as being equal to the factor of safety (FS) multiplied by the design limit load (DLL). The allowable load is defined as the maximum load that a structure or structural component can sustain before resulting in a failed condition. The DLL is defined as the worst possible loading conditions the aircraft structure or structural component is expected to encounter while operating within its allowable flight envelope. The ultimate load is checked against ultimate strength; the design limit load should be checked against yield strength.

When abbreviated or no ground testing is conducted, the increased risk of unexpected structural failure modes is mitigated by employing higher safety factors in the analysis. The factor of safety can be determined to balance the risk and cost. The overall static structure airworthiness approach and the factor of safety for the X-57 aircraft are summarized in Table 1.

$$Margin\ of\ Safety = \frac{Allowable\ (Load\ or\ Stress)}{Ultimate\ Limit\ (Load\ or\ Stress)*FS} - 1.0 \tag{1}$$

For all existing metallic structures, the 1.5 FS used in the FAA certification was maintained and applied in the analysis for the original structure and verified by analysis only. For any new and modified metallic structures, a 2.25 FS is employed in the design and analysis if structural design is verified by analysis only.

In composite structures, mechanical performance is highly dependent on materials and fabrication processes. A factor of safety of 2.25 to 3.00 is utilized if structural design is verified by analysis along with building block approach defined in MIL-HDBK-17 [5] (CMH-17) for testing. For example, 2.25 FS can be used when using well established composite processes and materials, plus the full utilization of building block approach. Higher FS such as 3.0 is used when a limited building block approach is employed.

The material strength of additive manufacturing parts, including 3D-printed and injection molded parts, also heavily depends on both the raw materials and the fabrication process. These materials must undergo verification through analysis using a factor of safety of 3.0 and proof testing to ensure they can withstand no less than 120 percent of the DLL. A 20 percent reduction in material allowable is applied for B-Basis statistical reliability when material testing has been conducted, and the test results are used. In cases where no material testing is performed, a rule of thumb of 50 percent reduction in material allowable is applied to be conservative and cover the uncertainty. All hardware must undergo qualification testing to ensure it can withstand 105 percent of operational loads to be deemed acceptable for flight.

For the Mod III composite wing design, in order to balance structural weight, manufacturing cost and project risk, the factor of safety 1.8 instead of 3.0 is used along with a limited building block approach is employed. The structures must be proof tested to 120% of DLL. Furthermore, instrumentation and load calibration for in-flight load monitoring are required for safety of flight perspective.

Table 1. The airworthiness approach for the X-57 aircraft.

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

V. Loads Requirements

This section outlines the loads requirements for the primary structure. Code of Federal Regulations (CFR) 14, Part 23 [6] along with the Tecnam aircraft Pilot's Operating Handbook, which contained valuable flight envelope data, was used to develop the load requirements for the X-57 aircraft. Although the Tecnam P2006T was certified as a 3.8-g aircraft, due to the maximum gross weight of the aircraft increasing from 2712 lb to 3000 lb, all of the new and modified structures were designed to a reduced Nz (load factor in the z direction) of 3.4 g at the early phase of the X-57 project. The corresponding structures were designed to meet the load requirements referenced in Table 2.

Thermal stresses, resulting from surface color of the components, temperature differentials, varying coefficients of thermal expansion (CTEs), and operating temperatures are considered in the design process. The specific temperature requirements depend on the materials used and the surface color of the components. For example, during the summer, temperatures can soar to nearly 200 °F on dark surfaces exposed to the sun on the Edwards Air Force Base flight line. As such, it is imperative for the composite matrix to possess a glass transition temperature well above 200 °F to prevent softening or degradation of the composite laminate structure. As a general practice it is recommended that all composite surfaces be painted white to mitigate surface temperatures. The X-57 wing, painted in gloss white, is designed to operate within a temperature range of 0 °F and 165 °F.

Table 2. X-57 Loads requirements document numbers.

Components	Document number
Fuselage and equipment support	REQ-CEPT-007 revision D
Mod II motor mount	REQ-CEPT-008 revision E
Cruise motor	REQ-CEPT-010 revision A
Mod III/IV wing	SPEC-CEPT-003 revision A
Mod III wingtip cruise nacelle	REQ-CEPT-015 revision A
Mod IV high-lift structure	REQ-CEPT-006 revision B

A. Fuselage and Equipment Support

The new primary structures, including fuselage modifications and all support structures for instrumentation and equipment, are designed to meet the REQ-CEPT-007 document (see Table 2). The inertial load requirements consider flight maneuver loads, ground loads, taxi bumps, landings, and ground handling load conditions. Items within the cabin that could injure the pilot must be secured to the fuselage structure to withstand crash load conditions. The critical DLLs are summarized in Table 3. The original aircraft was certified to comply with the FAR Part 25.303 requirement for a safety factor of 1.5 applied to the prescribed limit load. The maneuver loads are treated as limit loads, while crash loads are considered as ultimate loads. When a loading condition is prescribed in terms of ultimate loads, a factor of safety need not be applied unless otherwise specified.

Table 3. Mod II fuselage and equipment support design limit loads.

Condition		Design Limit Load Factor (g)	Factor of Safety	
			New metallic structure	Existing structure
Maneuver loads	Upward, Nz	3.4	2.25	1.5
Maneuver loads	Downward, Nz	-1.4	2.25	1.5
Crash loads	Forward, Nx	-18.0	1.0	1.0
Crash loads	Sideward, Ny	+/- 4.5	1.0	1.0
Crash loads	Downward, Nz	-6.0	1.0	1.0

B. The Mod II Motor Mount and Cruise Motor

The Mod II motor mount and cruise motor are designed to withstand various flight conditions, including flight maneuvers, gusts, ground loads, and powerplant loads. The powerplant loads include thrust loads produced by the motor, torque loads resulting from rotational motion, P-factor loads induced by propeller asymmetry loading, and gyroscopic loads influenced by motor and propeller dynamics. These powerplant loads are applied simultaneously with the inertia loads. Seven flight and ground conditions, listed in Table 4, were analyzed. The cruise motor powerplant design limit loads are listed in Table 5. The motor mount structure is designed for 200 h of flight.

Initially, before the motor design was matured, the maximum torque and thrust loads for structural analysis were estimated using NACA report WR-3G26 [7], which provided data for an engine with 2250 RPM, 66 kW (89 hp), a propeller diameter of 5.5 ft, and three blades at sea level air density. The estimated maximum static thrust at sea level was 475 lbf (2113 N) and was expected to be higher than the motor selection for conservatism. Later, as the motor was built, the torque and thrust loads were adjusted based on dynamometer test data, and the design limit requirements were revised for designing the Mod III cruise motor support structures and nacelle. The P-factor loads were estimated considering various flight conditions, including a 15-deg angle of attack and a 15-deg sideslip. Imbalance loads were considered as radial loads and were estimated based on a maximum imbalance displacement of 0.02 in along the shaft centerline at the maximum rpm. Gyroscopic loads were estimated to comply with FAR 23.371(a).

Table 4. Cruise motor structure design limit loads.

Condition	**Design Limit Load Factor**			**Thermal Stress**	**Thrust, Torque & P-factor**	**Gyroscopic Loads**	**Engine Torque**
	Nx	**Ny**	**Nz**				
Flight	0	+/-1.33	3.4	x	x	x	
Flight	0	+/-1.33	-2.0	x	x	x	
Flight	0	+/-1.33	3.4	x	x		x
Flight	0	+/-1.33	-2.0	x	x		x
Flight	0	+/-1.33	3.4	x	x	x	x
Flight	0	+/-1.33	-2.0	x	x	x	x
Ground	-3.0	+/-1.33	-2.0	x			

Table 5. Mod II cruise motor powerplant design limit loads.

Loads	**Fx (lbf)**	**Fy (lbf)**	**Fz (lbf)**	**Mx (in-lbf)**	**My (in-lbf)**	**Mz (in-lbf)**
Maximum thrust, regen, and P-factor	+/- 637.8	+/- 74.83	+/- 89.46		+/- 2634.33	+/- 3229.64
Maximum torque				+/- 4159.85		
Gyroscopic					+/- 1389.57	+/- 3469.49

C. The Mod III Wing

A non-linear vortex-lattice model [8] was used to calculate the aerodynamic loads distribution over the wingspan. Wing aerodynamic loads were calculated based on an aircraft weighing 3000 lb maximum gross at altitudes of above sea level (ASL) and 15,000 ft. A total of 19 load cases, listed in Table 6, were analyzed. External loads and aerodynamic loads acted simultaneously with inertial limit load conditions. The structure was designed to withstand maximum aerodynamic loads within the flight envelope, as well as various extreme flight conditions resulting from sideslip and angle of attack. Asymmetric and rolling load cases included an additional 0.98g Nz vertical acceleration. The structures, especially the wing and nacelle interface, were designed to include the maximum preload. Airspeed is measured in knots calibrated airspeed (KEAS).

Table 6. Mod III wing design limit load cases.

Case No.	Airspeed (KEAS)	Load Factor	Altitude (ft)	Description
1	89	1.00	0	Vs – 1g ASL
2	152	2.91	0	Vc max nz due stall ASL
3	164	3.42	0	Va – positive maneuver ASL
4	190	3.42	0	Vd – positive maneuver ASL
5	190	-1.37	0	Vd – negative gust ASL
6	89	1.00	15000	Vs – 1g high altitude
7	152	2.91	15000	Vc max nz due stall high alt.
8	164	3.42	15000	Va – positive maneuver high alt.
9	190	3.42	15000	Vd – positive maneuver high alt.
10	190	-1.71	15000	Vd – negative gust high alt.
11	164	2.99	0	Asym – 100/75
12	164	2.28	0	Rolling at Va
13	164	2.28	0	Rolling at Va – max roll rate
14	190	2.28	0	Rolling at Vd
15	190	2.28	0	Rolling at Vd – max roll rate
16	130	2.00	0	Flap
17	164	2.57	0	Fx=433 lbf, Mx=3330 in-lbf
18	164	3.42	0	Fx=314.7 lbf, Mx=2821.2 in-lbf
19	164	2.50	0	Fx=346.7 lbf, My=2314.5 in-lbf, Mz=925.8 in-lbf

D. The Mod III Wingtip Cruise Nacelle

The motor torque and thrust loads for the Mod III cruise motor nacelle were refined based on measured dynamometer test data. The following 21 load cases listed in Table 7 were defined for the Mod III wingtip support structures and nacelle. The taxi bump load case was addressed in case 17. The motor powerplant loads were applied simultaneously with the inertia loads. The critical wing structures, including motor mounts, were designed for no less than 100 h of flight.

Table 7. Mod III wingtip nacelle design limit load 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	-3.0	+/-1.33	-1.00	X	-531	-171	185	2820	-690	1250
2	Vc max nz due to stall	X	-3.0	+/-1.33	-2.91	X						
3	Va - Positive maneuver ASL	X	-3.0	+/-1.33	-3.42	X						
4	Vd - Positive maneuver ASL	X	-3.0	+/-1.33	-3.42	X						
5	Vd - Negative maneuver ASL	X	-3.0	+/-1.33	1.37	X						
6	Vs-1g high altitude	X	-3.0	+/-1.33	-1.00	X						
7	Vc max nzdue to stall high altitude	X	-3.0	+/-1.33	-2.91	X						
8	Va - Positive maneuver high altitude	X	-3.0	+/-1.33	-3.42	X						
9	Vd - Positive maneuver high altitude	X	-3.0	+/-1.33	-3.42	X						
10	Vd - negative gust high altitude	X	-3.0	+/-1.33	1.71	X						
11	Asym - 100/75	X	-3.0	+/-1.33	-3.97	X						
12	Rolling at Va	X	-3.0	+/-1.33	-3.26	X						
13	Rolling at Va - max roll rate	X	-3.0	+/-1.33	-3.26	X						
14	Rolling at Vd	X	-3.0	+/-1.33	-3.26	X						
15	Rolling at Vd - max roll rate	X	-3.0	+/-1.33	-3.26	X						
16	Flap	X	-3.0	+/-1.33	-2.00	X						
17	Max Takeoff & P-Factor (23.361.a.1)	X	-2.25	+/-1.00	-2.57	X	-590					
18	Max Continuous & P-Factor (23.361.a.2)	X	-3.0	+/-1.33	-3.42	X	-531					
19	Max Continuous & P-Factor & Gyroscopic (23.371)	X	0.0	0.0	-2.50	X		150	150		2315	925
20	Ground Loads (Landing)		-3.0	+/-1.33	-3.00	x						
21	Ground Loads (Landing)		-3.0	+/-1.33	2.75	x						

E. The Mod IV High-Lift Motor and Nacelle Structure

The high-lift motor and nacelle structure were designed for flight conditions including flight maneuvers, gusts, ground loads, and powerplant loads [9], listed in Table 8 and Table 9. These powerplant loads were applied simultaneously with the inertia loads. Structural fatigue and dynamic loads due to motor vibration were addressed as well.

Table 8. Mod IV high-lift motor and nacelle design limit loads.

Condition	Aircraft Design Limit Load Factor (g)			Thermal Stress	Thrust, Torque & P-factor Loads	Gyroscopic Loads	Propeller Imbalance Loads	Ground Handling /Abuse Loads	External Loads (for Nacelle)
	Nx	Ny	Nz						
Flight	0	+/-1.33	3.4	x	x	x	x		x
Flight	0	+/-1.33	-2.0	x	x	x	x		x
Flight	0	+/-1.33	3.4	x	x		x		x
Flight	0	+/-1.33	-2.0	x	x		x		x
Ground	-3.0	+/-1.33	-2.0	x					
Ground				x				x	

Table 9. Mod IV high-lift motor and nacelle powerplant design limit loads.

Loads	Fx (lbf)	Fy (lbf)	Fz (lbf)	Mx (in-lbf)	My (in-lbf)	Mz (in-lbf)
Maximum thrust and torque	-77.56	0	0	+/- 214.42	0	0
Maximum thrust and torque with P-factor	-93.07	+/- 15.51	+/- 15.51	+/- 214.42	+/- 168.16	+/- 168.16
Propeller imbalance loads	0	+/- 11.24	+/- 11.24	0	0	0
Gyroscopic loads	0	0	0	0	+/- 88.5	+/- 221.27
Ground handling loads	+/- 50.58	+/- 50.58	+/- 50.58	0	0	0

F. The Mod IV Blade and Hub

The blade and hub structure were designed for the worst load condition based on the estimated performance with a rotation speed of 5460 rpm, a maximum thrust load of 60.7 lbf (270 N), and a maximum torque load of 191.18 in-lbf (21.6 Nm). These loads acted simultaneously with 100 percent of the inertial limit load which included gust loads, imbalance loads, and ground handling. Thermal loads due to temperature differentials were also addressed, along with structural fatigue. Four flight and ground conditions, listed in Table 10, were analyzed.

The maximum thrust loads and torque loads were estimated based on aerodynamic load distribution determined by computational fluid dynamics (CFD) and airfoil theory. The maximum loads per blade were estimated by dividing the maximum thrust by the number of blades. Rotating centrifugal limit loads and rotational drag loads were considered in the blade and hub retention system design. The hub, blade retention system, and counterweights were tested to comply with FAR 35.35(a) for a period of one hour at a load equivalent to 200 percent of the maximum centrifugal DLL.

Table 10. Mod IV hub and blade limit load.

Condition	Aircraft Design Limit Load Factor (g)			Thermal Stress	Centrifugal Loads	Thrust Loads	Torque & Rotation drag Loads	Imbalance Loads	Ground Handling /Abuse Loads
	Nx	Ny	Nz						
Flight	0	+/-2.0	5.0	x	x	x	x	x	
Flight	0	+/-2.0	-3.0	x	x	x	x	x	
Ground	-3.0	+/-1.33	-2.0	x					
Ground				x					x

VI. Overview of the Structure of the X-57 Aircraft

This section provides an overview of the structural modifications made to the Tecnam P2006T aircraft in the Mod II configuration. Additionally, it discusses the airworthiness approach for the Mod III Wing and the additive manufacturing structures prepared for the Mod IV configuration.

A. Overview of the Mod II Airframe Modification

Extensive modifications were required for Mod II on the fuselage structure to transform the aircraft into an electric aircraft. This transformation involved replacing the two gas engines with electric motors, and installing 860 lb of batteries as well as battery systems and instrumentation. An air data probe was added to measure various air data parameters for the safe and efficient operation of the aircraft. A cutout with composite reinforcement was made in the original nose cone to accommodate this new air data probe. An overview, closeup view, and inside view of the air data probe are shown in Fig. 3. A new motor mount adapter and new truss were designed for the electric cruise motor and are shown in Fig. 4. The firewall interface structure remained unchanged. The fuselage floor, including the rear passenger and cargo area, was reinforced to carry the batteries. The aft and the front and battery trays are shown in Fig. 5. The equipment pallet was installed on the co-pilot seat, and the contactor pallet and battery control modules were mounted on the side of the fuselage. Figure 6 shows the battery control module. Due to the battery installation, the original egress was not accessible by the pilot in case of an emergency. Therefore, the passenger side window was modified to serve as an emergency exit. This secondary egress window is shown in Fig. 7. The entire window can be dropped by lifting a handle and lever and pushing it outward.

The majority of the new and modified structures for the Mod II structure modifications were metallic and had been designed and analyzed using a factor of safety of 2.25 and verified by analysis. Certain modified or new components were proof-tested rather than analyzed, because testing proved to be a more cost-effective and expedient method for ensuring airworthiness. These components included lightweight components such as the data acquisition units (DAUs) mounted within the wing and the camera mount on the cockpits. Components that posed analytical challenges, such as the modified nose cone with the cutout, the battery venting adapter, and the final assembly required more extensive analysis and were instead validated for airworthiness through load testing. The battery venting adapter and assembly are shown in Fig. 8.

Fig. 3 The air data probe (left to right: overview, closeup view, inside view).

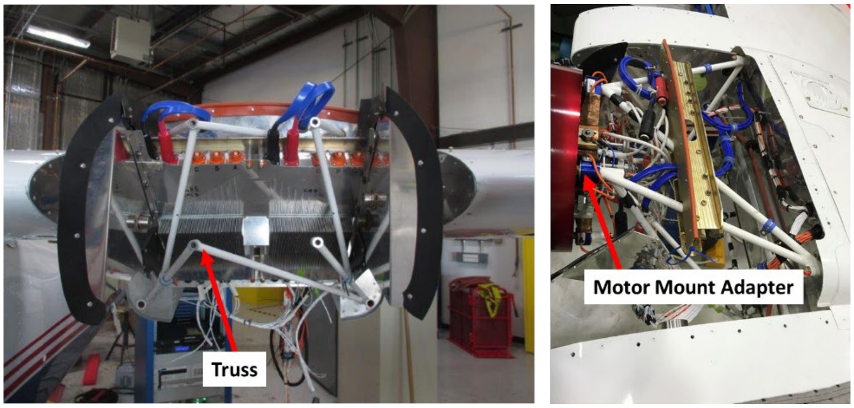

Fig. 4 The motor mount truss and adapter.

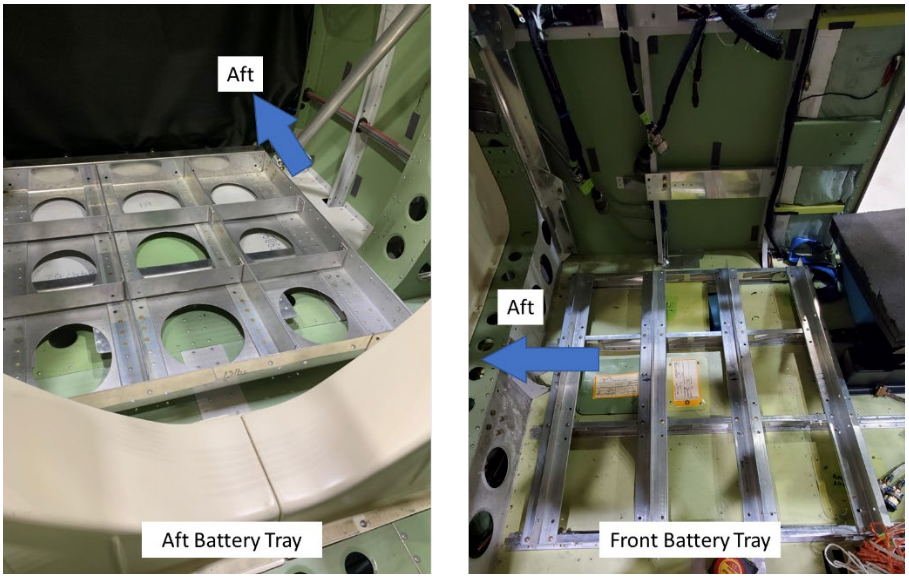

Fig. 5 The aft and the front battery trays.

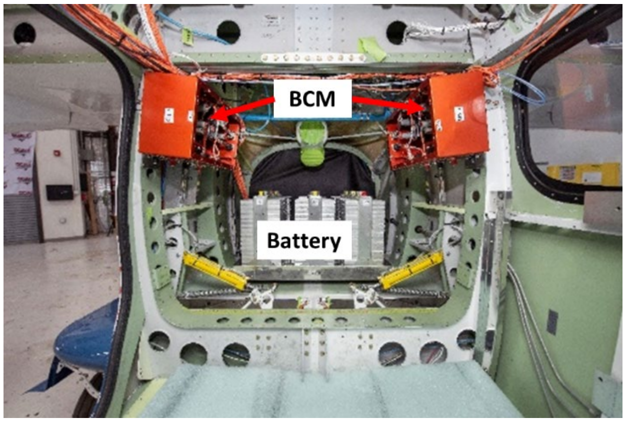

Fig. 6 The battery control module.

Fig. 7 The secondary egress window.

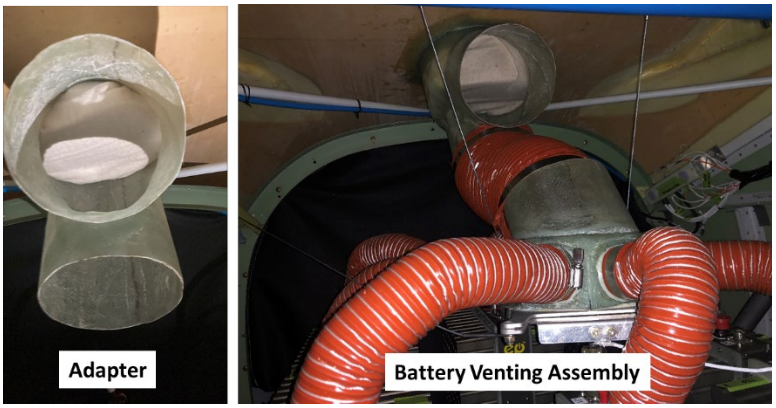

Fig. 8 The battery venting adapter and assembly.

B. The Mod III X-57 Wing

The Mod III Wing was a new high-aspect-ratio composite wing. This wing was a 379-in span carbon-epoxy wing designed and manufactured by Xperimental LLC, (San Luis Obispo, California U.S.A). The wing had a reference chord of 25.5 in and a total surface area of approximately 9,600 in^2. The test article was a straight taper wing with 0-deg sweep at 70-percent chord. The wing box consisted of a main spar, forward spar, and rear spar that extended the full length of the wing. There was an aft secondary spar located in the root section that extended from the aft wing section to the fuselage attachment points. Figure 9 shows the wing inverted in the shipping container upon arrival at AFRC. The fuselage was attached to the wing with an aluminum H-frame structure. The H-frame contained four pinned connection points for attaching to the fuselage.

Validation of the composite structures design and analysis is performed by utilizing a building-block approach and testing, which requires time and money. Every aspect cannot be tested, but this approach helps reduce risk. A balance between analysis and actual testing must be struck. In the case of the X-57 Mod III Wing, coupon testing was performed to support analysis, and proof-testing was conducted to ensure the safety of flight and to strike a good balance between risk and cost. Destructive testing of design features was omitted. This approach was found to be the most suitable for the X-57 project A conventional airworthiness approach was used for this wing, as shown in Fig. 10. The wing was designed and analyzed using a 1.8 FS on ultimate and qualification tested to 120 percent DLL to confirm the structural strength beyond the expected flight loads. The proof test focused on five of the 19 design cases presented in Table. These cases are critical load cases for shear, bending, and torsion. An additional set of load cases was selected to calibrate the strain-gage instrumentation at the inboard wing station. The strains and deflections of the wing were monitored during testing to verify that the structure was behaving as expected as the results from the pretest analysis indicated. Inspections were essential for determining the health of the wing prior to and after testing.

The wing proof-test was conducted at the AFRC Flight Loads Laboratory (FLL) in 2019 [10]. A conservative loading and monitoring methodology were employed, resulting in a successful test that met all the testing objectives. In this testing, a total of 28 hydraulic cylinders were utilized to apply combinations of shear, bending, and torsional loads to the wing. Additionally, two hydraulic cylinders applied axial thrust loads to the wingtips. The upward load was applied simultaneously with a downward force on the wingtips to simulate cruise nacelle inertial loads. Shot bags were used for the down-load test case. Figure 11 illustrates the hydraulic up-load testing of the wing, and Fig. 12 shows the shot-bag down-load testing of the wing at maximum load. The wing was proof tested to 120 percent of DLL. The proof test confirmed the strength of the wing for flight and provided an opportunity to calibrate the wing strain gages for in-flight load monitoring. The wing presented no observable or audible problems during load testing. Ultrasonic inspections of the wing were conducted to assess its condition before and after testing and to determine whether any damage occurred during testing. The tests and inspections confirmed the structural integrity of the wing, rendering it airworthy.

As part of the airworthiness approach, in-flight shear, bending moment, and torsional loads will be monitored during the flight phase at the inboard root station as shown in Fig. 13 to confirm that the design load cases are within the expected design range. Figure 14 shows the locations of wing inboard flight-test strain gages. Periodic inspections will be performed to confirm the health of the wing throughout the flight phase.

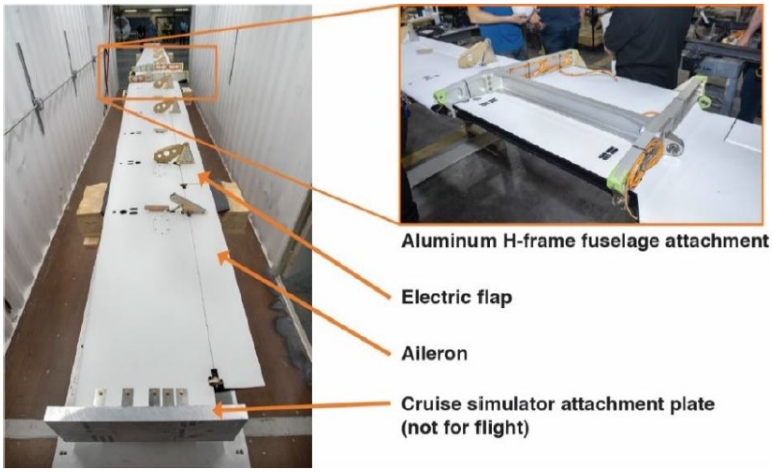

Fig. 9 The X-57 wing inverted in the shipping container.

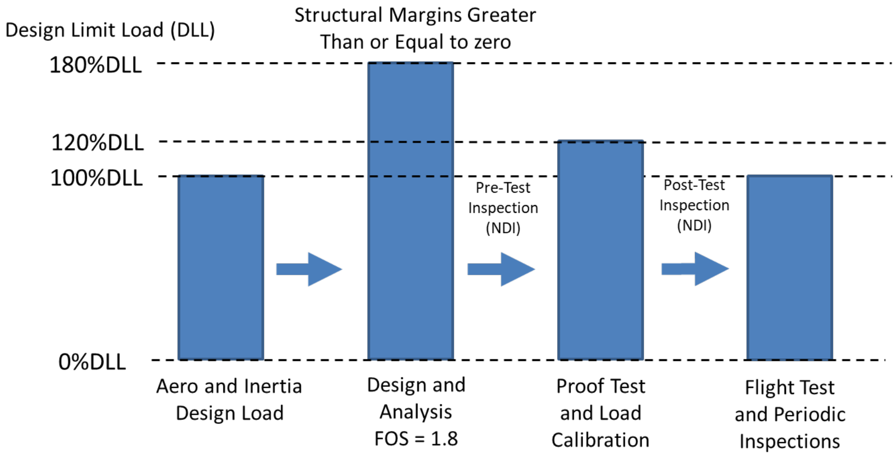

Fig. 10 The X-57 wing conventional airworthiness approach.

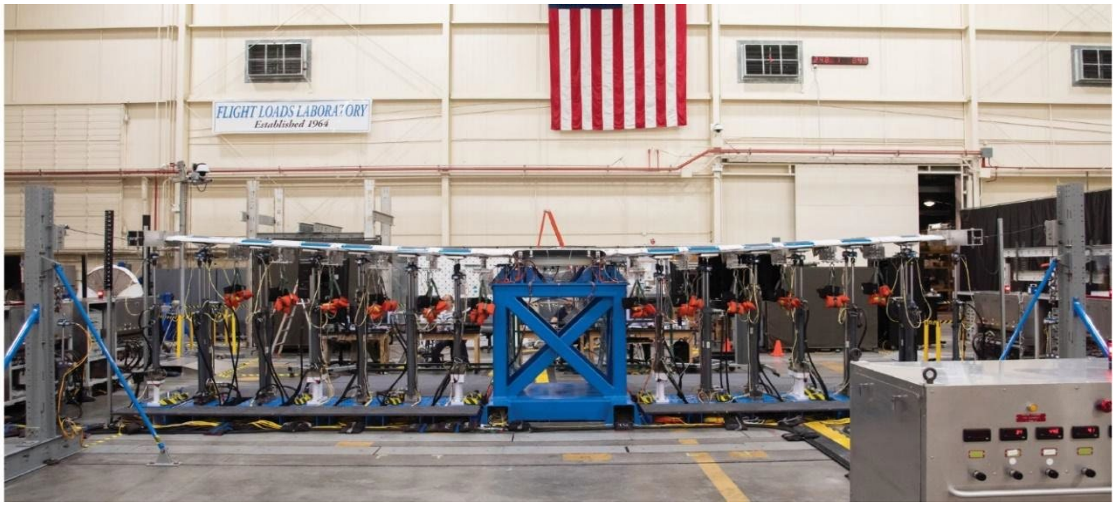

Fig. 11 The X-57 wing hydraulic upload testing.

Fig. 12 The X-57 wing shot-bag download testing at maximum load.

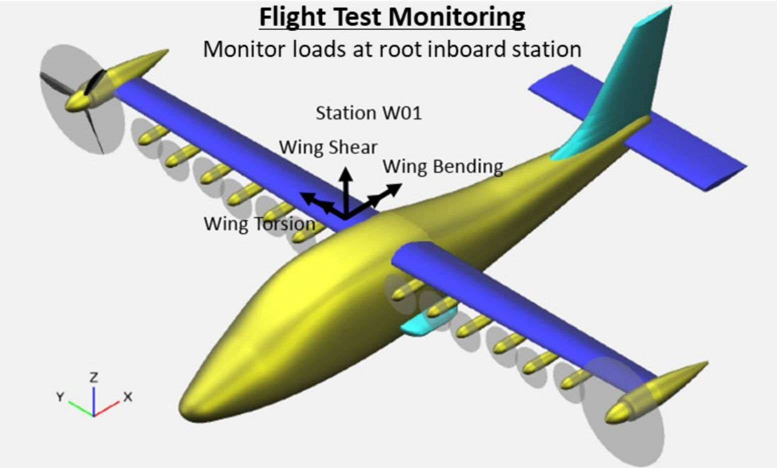

Fig. 13 Flight-test monitoring at the root inboard station.

Fig. 14 Wing inboard flight-test strain gages.

C. Additive and Injection-molded Manufacturing Structures

In the case of additive manufacturing, including 3D-printed and injection-molded parts, material strength greatly depends on the raw materials and the fabrication process, posing a higher risk to the X-57 flight project. A more conservative approach thus was adopted when working with structures made from these materials. The X-57 aircraft utilized these materials in mounting brackets for the lightweight sensors and cowling air scoops employed in the Mod II and Mod III cruise nacelles. Equivalence coupon testing must be performed to verify the material properties and fabrication processes. It is often the case that the test results do not match or are not available on the material datasheets. Also, it is critical to test the extreme environmental conditions expected in operation, including hot and cold environments. For example, according to the datasheet provided by the manufacturer, the tensile strength of LCF40-PPA tensile is 45 ksi at room temperature; however the test results indicated that the tensile strength is 47 ksi and 37 ksi at 0 and 165 °F, respectively. Components also undergo proof tests to 120-percent design limit to verify that the design can withstand the required design loads. Additionally, all hardware is required to undergo qualification testing for 105 percent of operational loads to be flightworthy. The Mod II cruise motor cowling scoop and the Mod IV high-lift blade follow this airworthiness approach. Proof tests of the cowling scoop and high-lift blade are shown in Fig. 15 and Fig. 16. Several cowlings were tested at cold, room, and elevated temperatures. All of the cowlings passed the required proof-test loads and were continuously loaded until failure. The test results indicated that the cowling design is adequate with a significant structural margin. The results from the high-lift blade test were used to update the design, and, eventually, the design matured to meet the structural requirements.

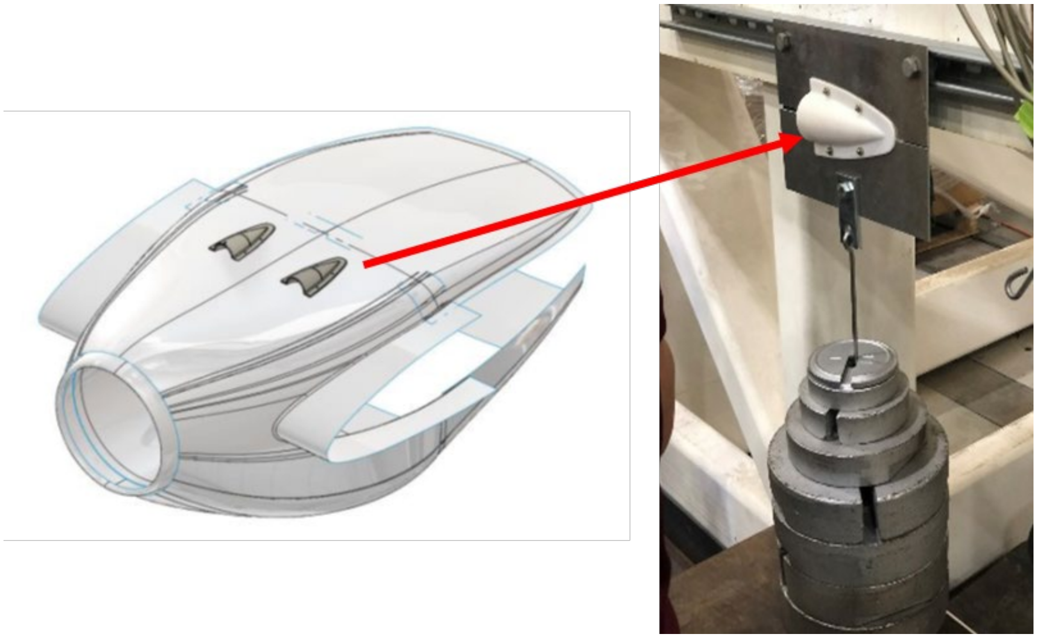

Fig. 15 The X-57 Mod II cowling air scoop proof test.

Fig. 16 The X-57 Mod IV high-lift blade proof test.

VII. Conclusion

The authority of the National Aeronautics and Space Administration to self-certify aircraft allows the Armstrong Flight Research Center (AFRC) (Edwards, California, U.S.A.) to conduct flight tests. The airworthiness assessment process at AFRC is flexible, tailorable, and risk-management based to determine if an aircraft and its systems meet minimum design criteria, standards, and configuration for safe flight operations at AFRC.

Over time, the Aerostructures Branch at AFRC has developed guidelines for the structural safety of flight, covering experimental aircraft, new components, payloads, and modifications. This Branch oversees all structural design and analyses, providing the structural evaluation of components and aircraft. Various approaches exist for aircraft design and operation at AFRC. The airworthiness approach requires a balance of design, analysis, testing, and monitoring techniques to ensure an acceptable level of confidence in the structural integrity of aircraft components and modifications.

The airworthiness plan for the static structures of the X-57 aircraft presented in this paper met the intent of the Aircraft Structural Safety of Flight Guidelines. Additionally, this paper documents the X-57 structural design criteria and load requirements.

References

[1] N. Borer, M. Moore, A. Turnbull, “Tradespace Exploration of Distributed Propulsors for Advanced On-Demand Mobility Concepts’” AIAA Paper 2014-2850, June 2014.
doi: 10/2514.6.2014-2850

[2] Costruzioni Aeronautiche TECNAM S.p.A, URL: https://tecnam.com/ [retrieved 18 June 2024].

[3] Empirical Systems Aerospace, URL: https://www.esaero.com/ [retrieved 17 June 2024].

[4] Armstrong Flight Research Center Research Engineering Directorate, “Aircraft Structural Safety of Flight Guidelines,” AFG-7123.1-001, Rev. A, September 2020.

[5] United States Department of Defense, “Composite Materials Handbook, Volume 1, Polymer Matrix Composites Guidelines for Characterization of Structural Materials,” MIL-HDBK-17-1F, June 2002.

[6] Federal Aviation Administration, Code of Federal Regulations Title 14, FAR Parts 23 and 35, URL: https://www.ecfr.gov/ [retrieved 18 June 2024].

[7] Desmond, G. L., and Freitag, R. F. “Working Charts for the Computation of Propeller Thrust Throughout the Take-Off Range,” ARR 3G26, July 1943.

[8] de Vargas, L. A. T., and de Oliveira, P. H. I. A, “A Fast Aerodynamic Procedure for a Complete Aircraft Design Using the Know Airfoil Characteristics,” SAE Technical Paper 2006-01-2818, 2006.
doi:10.4271/2006-01-2818.

[9] Li, W., “X-57 Maxwell Structural Loads Requirements for High-Lift Structure, REQ-CEPT-006, Rev. B, October 2020.

[10] Miller, E. J., Li, W. W., Jordan, A., and Lung, S-F., “X-57 Wing Structural Load Testing,” AIAA 2020-3090, June 2020.
doi: 10.2514/6.2020-3090

[11] Li, W., “.SCEPTOR X-57 Maxwell Structural Loads Requirements for Floor and Equipment Support,” REQ-CEPT-007, Rev. D, November 2016.

[12] Li, W., “SCEPTOR X-57 Maxwell Structural Loads Requirements for Mod II Wing Motor Mounts,” REQ-CEPT-008, Rev. E, August 2017.

[13] Li, W., “SCEPTOR X-57 Maxwell Structural Loads Requirements for Cruise Motor,” REQ-CEPT-010, Rev. A, August 2017. -

[14] Li, W., “X-57 Maxwell Structural Loads Requirements Loads Analysis for Cruise Nacelle Structure,” REQ-CEPT-015, Rev. A, September 2022.