Structural Requirements for Design and Analysis of 25% Scale Subsonic Single Aft Engine (SUSAN) Research Aircraft

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The purpose of this paper is to define a set of structural requirements that can be used for conceptual design studies of the Subsonic Single Aft eNgine (SUSAN) aircraft and the early design phases of a 25%-scale flight research aircraft. SUSAN presents an architecture for a subsonic regional jet transport aircraft that couples a single turbofan engine to an electrified aircraft propulsion system (EAP). Presented within this paper are a consolidated set of requirements drawn from NASA, FAA (FAR, Federal Aviation Regulation), and nongovernment structural standards with a focus on loads. An example application of the breakout load tables and the approach for applying existing standards to those configurations are presented for the SUSAN 25%-scale flight research vehicle. Positioning of the turbofan, electric engines, battery, and the requirement for the 25%-scale vehicle to be shippable in a cargo box are atypical structural design requirements. Particular focus is given to the primary aircraft structural elements such as the engine/tail mount, fuselage structure, and wing structure.

I. Nomenclature

FoS = factor of safety
H_C = cruise altitude
MoS = margin of safety
n = positive maneuvering load factor
SL = sea level
S_{ref} = reference surface area
V_A = design maneuvering speed
V_C = design cruise speed
V_D = design diving speed
V_F = design flap speed
V_{MC} = speed below which aircraft control cannot be maintained if critical engine fails
V_{ref} = reference speed
V_S = stalling speed with flaps retracted at design weight
V_{SF} = stalling speed with flaps fully extended at design weight
W = maximum takeoff weight
ρ_{ref} = reference air density

II. Introduction

The purpose of this paper is to define a set of structural requirements that can be used for conceptual design studies of aircraft and the early design phases of experimental aircraft. An extensive set of references for structure loading exists from the Federal Aviation Administration (FAA) and NASA standards for experimental research aircraft. When conducting conceptual design of a commercial aircraft, a simplified subset of the FAA structural information is useful. In order to conduct conceptual and early-stage design of a research aircraft at NASA, a simplified subset of the NASA structural standards is useful. Presented within this paper are a consolidated set of requirements drawn from NASA, FAA (FAR, Federal Aviation Regulation), and non-government structural standards with a focus on loads.

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This paper identifies the load requirements for the full-scale 180-passenger SUSAN concept aircraft and the loads for the 25%-scale SUSAN flight research vehicle. Additionally, an example application of consolidated loads cases is provided for the SUSAN 25%-scale flight research vehicle. Particular focus is given to the primary aircraft structural elements such as the engine/tail mount, fuselage structure, and wing structure.

A. Relevant Documents

The FAA governs aircraft operating in the United States under Title 14 of the Code of Federal Regulations (CFR). We draw commercial aircraft structural requirements for this paper from Title 14 CFR Part 23 Airworthiness Standards: Normal Category Airplanes [1] and from Title 14 CFR Part 25 Airworthiness Standards: Transport Category Airplanes [2]. These standards must be met for aircraft to receive an airworthiness certificate. Part 23 focuses on general aviation aircraft, which ranges from a small two-piston engine aircraft to a turbine-powered jet. Similarly, Part 25 standards apply to large aircraft that typically fall into the category of commercial aviation. These include transport cargo aircraft and large passenger/commuter aircraft. Title 14 CFR Part 23 enumerates the standards for normal, utility, acrobatic, and commuter category airplanes, and Part 25 determines standards for transport category airplanes. Load standards for these categories of airplanes have been organized this way because, for example, an acrobatic airplane will not undergo the same loading as an airplane in another category.

NASA Armstrong AFG-7123.1-001 Aircraft Structural Safety of Flight Guidelines [3] governs the structural requirements of experimental aircraft within the scope of aircraft either modified for experimental use or unique aircraft being used for research. “The [Armstrong] Center is engaged in flying many varied and unique aircraft. Frequently, these aircraft require structural modifications in order to accommodate unique flight experiments, and sometimes a completely new one-of-a-kind experimental airplane is built” (Ref. [3], p. 4), with requirements drawn from Section 4.1, Static Structural Design. It is important to contextualize these requirements within the testing and research environment they regulate. These aircraft are atypical compared with typical civil, commercial, and military aviation because they are unique test and research-oriented aircraft.

B. Loads Analysis Approach

At a high level, loads can be broken down into limit loads and ultimate loads. Limit loads are the maximum loads anticipated to act on the aircraft—typically based on flight conditions and maximum accelerations the aircraft is expected to experience in different directions. Ultimate loads are determined by multiplying limit loads by a prescribed factor of safety, FoS.

At different points in the aircraft’s flight regime there are different loads being applied, we divide these flight regime regions into mission points. At each mission point it is essential to identify the controlling load cases and evaluate their structural impacts against the aircraft’s minimum margin of safety, MoS. We have identified five mission points in the SUSAN 25% flight research vehicle: takeoff, landing, cruise, loitering, and maneuvering. This paper identifies individual load requirements at specific components and flight conditions and groups these together in the 25%-scale SUSAN flight research vehicle example application to represent the key mission-point loading.

III. Design Loads

A. Type of Loads

The definitions below of the types of loads provide context for the referenced load requirements in the following Table 1 to Table 15:

1) Aerodynamic loads: Loads induced by outside air onto the aircraft. These take the form of a pressure load and include loads from lift, drag, crosswind, side force, moments, etc.
2) Balancing loads: Loads necessary to maintain equilibrium in any specified aircraft flight condition where there is no intended change to pitch.
3) Control surface loads: Loads that include the air loads, forces, and deflections on moveable surfaces due to pilot input.
4) Gust loads: Loads resulting from atmospheric phenomena, which can be described as the aircraft penetrating a rising or sinking column of air.
5) Inertial loads: Loads resulting from accelerating or decelerating the mass of an aircraft. These loads act in the opposite direction as the aircraft acceleration vector.
6) Maneuver loads: Loads resulting from pilot commands such as pitch, roll, or yaw.
7) Symmetric loads: Loads typically seen in steady level flight and are an equal distribution of loads across surfaces.

8) Asymmetric loads: Loads that occurs outside of steady, level flight and during different maneuvers and flight profiles, resulting in an unequal distribution of loading.
9) Brake loads: Loads resulting from deceleration on landing with sources such as the landing gear, thrust reverses, and air brakes.
10) Crash loads: Loads resulting from an aircraft crash landing.
11) Landing loads: Loads resulting from the aircraft touching down during descent.

Table 1 below summarizes the flight maneuvers that typically produce high loading on the aircraft [3]. Additional load references have been added to this table; they map the load table references from the FAA to the specific condition prescribed to typically produce significant loading. This table is important in narrowing down the many load cases an aircraft undergoes to the main maneuvers/mission profiles producing high flight loads. This information can be used to identify controlling load cases at different component levels of the aircraft.

The assumptions made in this section follow that the full-scale 180-passenger SUSAN aircraft concept will adhere to 25 CFR requirements [2], and the 25%-scale SUSAN flight research vehicle concept will be guided by 23 CFR requirements [1]. Table 2 to Table 15 outline some of the main loading requirements each of these aircraft concepts will observe.

Table 1. Flight Maneuvers That Produce Significant Flight Loads

Aircraft component	Maneuvers that normally produce high external loads	Loads reference	Notes
Wing	Symmetric pull-up	Table 2 and Table 4	As the primary lift creating device of the aircraft, the wing is subject to numerous complex loads that change throughout the flight regime. Attention must be given to the lift-creating devices that are typically mounted to the wing such as slats and flaps. These will have anywhere from a negligible load condition to one that is responsible for significant lift and drag at different mission points.
	g-loaded rolling conditions	Table 2 and Table 3	
	Landing	Table 4, Section III.F	
	Symmetric vertical gust	Table 7, Fig. 2	
	Head-on gust	Table 4, Fig. 2	
Horizontal surfaces	Symmetric pullup	Table 2, Table 4, and Table 9	Horizontal control surfaces include ailerons and elevators. In some aircraft these may include hybrid devices such as flaperons and spoilerons. At different mission points different loads are developed, typically dependent on speed, altitude, and maneuvering. It is recommended to document the maximum magnitude of loads at each mission point and then create a load envelope.
	Symmetric vertical gust	Table 7, Fig. 2	
	Head-on gust	Table 4, Fig. 2	
	Landing	Table 4, Section III.F	
Vertical surfaces	Abrupt rudder maneuver	Table 2, Table 5, Table 6, and Table 9	The rudder is responsible for aircraft yaw and can develop significant loads during low-speed takeoff and landing conditions in significant cross winds, where the high density of the air and relatively low speed requires significant rudder deflection.
	Lateral gust	Table 7, Fig. 2	
	One engine inoperative	Table 10	
	Unsymmetric gust	Table 6 and Table 7	
	Headon gust	Table 4, Fig. 2	
	Landing	Table 4, Section III.F	
Fuselage	Most wing and empennage load cases	General	The fuselage itself must translate the aircraft’s mass to the lift-generating devices and thus the propulsive elements. Simultaneously, this must also maintain internal pressure for pressurized cabins.
	Pressurized cabin loads	Table 11	
	Landing	Table 4, Section III.F	

B. Maneuvering Loads

Load factors are g-loads that represent different flight conditions such as straight level flight or maneuvering. Table 2 outlines both positive and negative limit maneuvering load factors for different category airplanes. Table 3 defines the unsymmetrical semispan-wing air loads acting on each side of the airplane due to rolling maneuvers.

1. High-Lift Devices

If flaps or similar high-lift devices are to be used for takeoff, approach, or landing the airplane, with the flaps fully extended at V_F, high-lift devices are assumed to be subjected to symmetrical maneuvers and gusts within the range determined by Table 4.

Table 2. Limit Maneuvering Load Factors (23 CFR 337 [1]; 25 CFR 337 [2])

Category	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
Positive Limit Maneuvering Load Factors		
Normal and commuter airplanes	$2.1 + \frac{24{,}000}{W + 10{,}000}$ (not to exceed 3.8)	$2.1 + \frac{24{,}000}{W + 10{,}000}$ (not to exceed 3.8)
Utility airplane	4.4	$2.1 + \frac{24{,}000}{W + 10{,}000}$ (not to exceed 3.8)
Acrobatic airplane	6.0	$2.1 + \frac{24{,}000}{W + 10{,}000}$ (not to exceed 3.8)
Negative Limit Maneuvering Load Factors		
Normal, utility, and commuter airplanes	0.4× positive load factor	May not be less than –1.0
Acrobatic airplane	0.5× positive load factor	May not be less than –1.0

Table 3. Rolling Conditions[*] (23 CFR 349 [1]; 25 CFR 349 [2])

Category	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
Acrobatic, Conditions A and F	100% of semispan-wing air load acts on one side of airplane 60% of semispan-wing air load acts on other side	-------------
Normal, utility, and commuter, Condition A	100% of semispan-wing air load acts on one side of airplane 75% of semispan-wing air load acts on other side	100% of semispan-wing air load acts on one side of airplane 80% of semispan-wing air load acts on other side

[*] Rolling conditions include loads resulting from aileron deflections and speeds in combination with an airplane load factor of at least 2/3 the positive maneuvering load factor used for design.

Table 4. High-Lift Devices Operational Loads (23 CFR 345 [1]; 25 CFR 345 [2])

Condition	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
Positive limit load factor	2.0	2.0
Gust (acting normal to flight path in level flight)	±25 ft/s	±25 ft/s
V_F (design flap speeds)	Not less than $1.4V_S$ or $1.8V_{SF}$, whichever is greater (to be conservative) In addition to above loads, the following conditions are to be taken separately: 1. Head-on gust of 25 ft/s equivalent airspeed (EAS) combined with propeller slipstream, corresponding to 75% of maximum continuous power 2. Effects of propeller slipstream, corresponding to maximum takeoff power	Not less than $1.4V_S$

2. *Vertical Surface Maneuver Loads (Yaw)*

The airplane must be designed for loads resulting from the yaw maneuver conditions outlined in Table 5 and Fig. 1 at speeds from V_{MC} to V_D.

With the airplane in unaccelerated flight at zero yaw it is assumed that the cockpit rudder control is suddenly displaced to achieve the resulting rudder deflection as limited by the control system on control surface stops.

3. *Unsymmetrical Loads*

Horizontal surfaces (other than the main wing) and their supporting structures must be designed for gust loads and unsymmetrical loads arising from yaw and slipstream effects in combination with balancing. In the absence of more rational data for airplanes that are conventional (with regard to the location of engines, wings, planform, and horizontal surfaces other than the main wing), the requirements in Table 6 can be followed. For airplanes that are nonconventional, the surfaces and supporting structures must be designed for combined vertical and horizontal surface loads resulting from each prescribed flight condition taken separately.

Table 5. Limit Pilot Forces

Speed	Normal, Utility, and Acrobatic Category Airplanes	Commuter Category Airplanes	Transport Category Airplanes
V_{MC} to V_A	At speeds up to V_A, vertical surfaces must be designed to withstand sudden displacement of rudder control to maximum deflection. Airplane yaws to overswing sideslip angle of 22.5°. Aeronautic loads are determined from this maneuver.	See Fig. 1	300 lb
V_C/M_C to V_D/M_D	--------------	See Fig. 1	200 lb
V_A to V_C/M_C	--------------	See Fig. 1	Linear variation

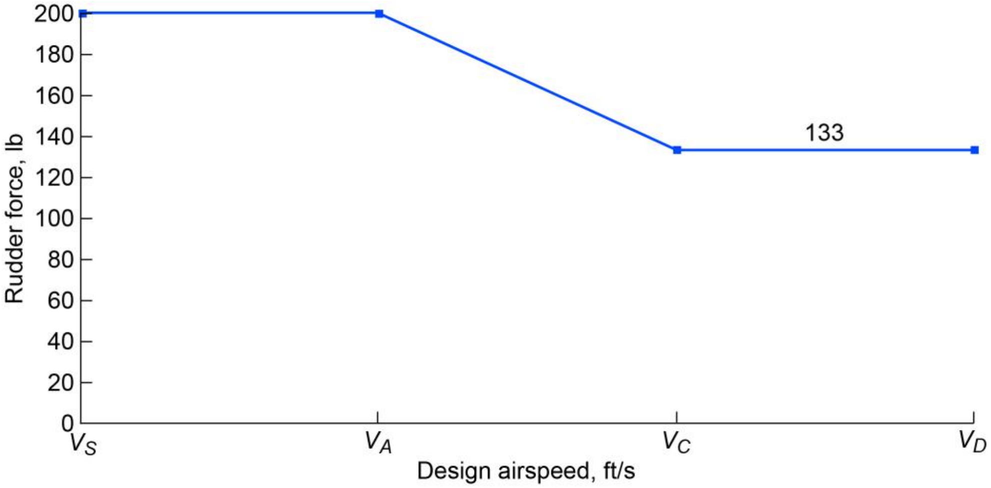

Fig. 1. Pilot rudder force (from 23 CFR 441 [1]). Force in diagram referencing 23 CFR 397(b).

Table 6. Unsymmetrical Loads on Horizontal Surfaces (23 CFR 427 [1]; 25 CFR 427 [2])

Load	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
Horizontal loads assumed on the surface on one side of the plane of symmetry	100% of maximum loading from symmetrical flight conditions	100% of maximum loading from symmetrical flight conditions and the vertical gust conditions acting separately
Horizontal loads assumed on the surface on the opposite side of plane of symmetry	% of maximum loading from symmetrical flight conditions* (= 100 – 10(n – 1))	80% of maximum loading from symmetrical flight conditions and the vertical gust conditions acting separately

*n is the specified positive maneuvering load factor (this value cannot be more than 80%).

C. Gust Loads

1. *Gust Envelope*

The airplane is assumed to be subjected to symmetrical vertical and lateral gusts in level flight (Table 7). Fig. 2 displays vertical, head-on and lateral gust types and their loading directionality.

Table 7. Gust Envelope Load Factors (23 CFR 333 [1]; 25 CFR 341 [2])

Condition[*]	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Category	Transport Category Airplanes
At V_C (altitude between sea level and 20,000 ft)	Gust of ±50 ft/s	At V_C (altitude at sea level)	Gust of ±56 ft/s
At V_C (altitude at 50,000 ft)	Gust of ±25 ft/s	At V_C (altitude at 15,000 ft)	Gust of ±44 ft/s
At V_D (altitude between sea level and 20,000 ft)	Gust of ±25 ft/s	At V_C (altitude at 50,000 ft)	Gust of ±26 ft/s
At V_D (altitude at 50,000 ft)	Gust of ±12.5 ft/s	At V_D (altitude at sea level)	0.5 × ±56 ft/s
[†]At V_B (altitude between sea level and 20,000 ft)	Rough air gust of ±66 ft/s	At V_D (altitude at 15,000 ft)	0.5 × ±44 ft/s
[†]At V_B (altitude at 50,000 ft)	Rough air gust of ±38 ft/s	At V_D (altitude at 50,000 ft)	0.5 × ±26 ft/s

[*] Gust velocity may be reduced linearly between altitudes.

[†] Additional requirement for commuter category airplanes.

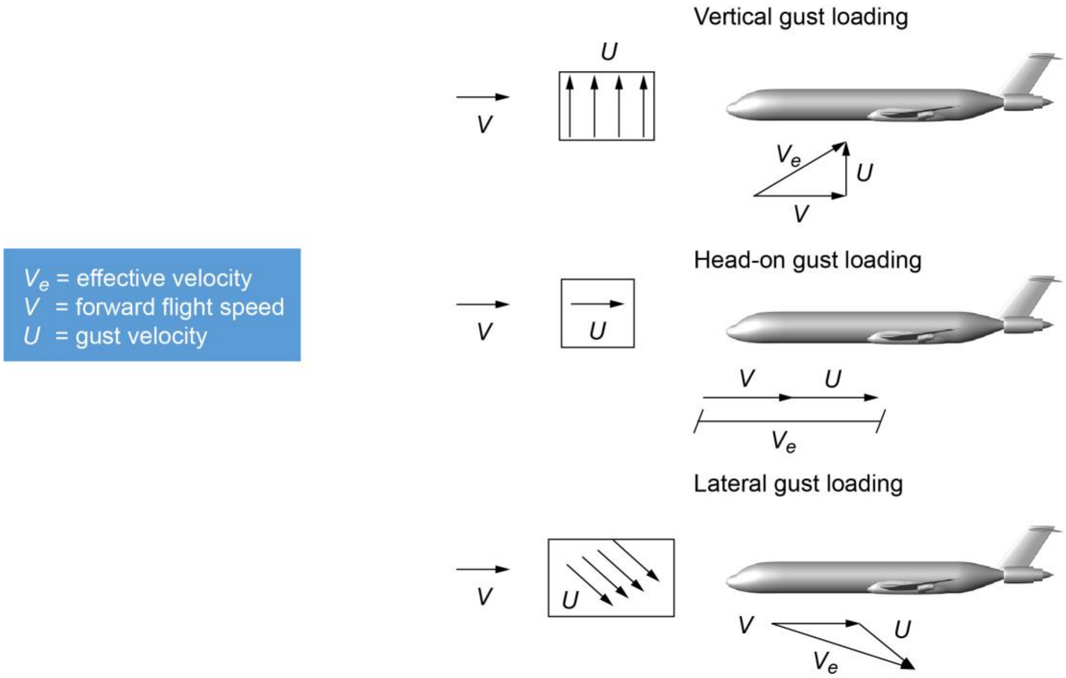

Fig. 2. Gust types and their directionality.

D. Engine Mount Loading

1. Side Load on Engine Mount

Each engine and auxiliary power unit mount and its supporting structure must be designed for side loads (see Table 8). Note: the side load applied may be assumed to be independent of other flight conditions.

2. Gyroscopic and Aerodynamic Loads

Each engine mount and its supporting structure must be designed for the gyroscopic, inertial, and aerodynamic loads that result—with the engines and propellers, if applicable—at maximum continuous revolutions per minute under each separate condition in Table 9. For airplanes approved for aerobatic maneuvers, each engine mount and its supporting structure must meet the requirements in the above table and be designed to withstand the load factoring expected during combined maximum yaw and pitch velocities. For airplanes certificated in the commuter category, each engine mount and its supporting structure must meet the requirements in the above table, and the gust conditions specified in Table 7.

3. Engine Failure

The airplane must be designed for the unsymmetrical loads resulting from the failure of the critical engine. Turbo-propeller airplanes must be designed for the conditions in Table 10 in combination with a single malfunction of the propeller drag limiting system, considering the probable pilot corrective action on the flight controls. Pilot corrective action may be assumed to be initiated at the time maximum yawing velocity is reached, but not earlier than 2 s after the engine failure. The magnitude of the corrective action may be based on the control forces specified in Table 5 as well as 23 CFR 397 [1] and 25 CFR 397 [2]. However, lower forces may be assumed where it is shown by analysis or test that these forces can control the yaw and roll resulting from the prescribed engine failure conditions.

Table 8. Side Load on Engine Mount (23 CFR 363 [1]; 25 CFR 363 [2])

Limit load factor	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
In lateral direction	Not less than 1.33	At least equal to the maximum load factor obtained in the yawing conditions but not less than 1.33
	Not less than 1/3 of limit load factor for flight condition A	Not less than 1/3 of limit load factor for flight condition A

Table 9. Gyroscopic and Aerodynamic Loads (23 CFR 371 [1]; 25 CFR 371 [2])

Load conditions	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
Yawing conditions	See Table 5	See Table 5
Maneuvering loads	See Table 2	See Table 2
All possible combinations of the following:	Yaw velocity of 2.5 rad/s	--------------
	Pitch velocity of 1.0 rad/s	--------------
	Normal load factor of 2.5	--------------
	Maximum continuous thrust	--------------
Landing conditions	--------------	See Section III.F, “Landing Loads”
Gust loads	--------------	See Table 7

Table 10. Unsymmetrical Loads Resulting from Engine Failure (23 CFR 367 [1]; 25 CFR 367 [2])

Condition	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
At speeds between V_{MC} and V_D	Limit loads = loads resulting from power failure because of fuel flow interruption	
At speeds between V_{MC} and V_C	Ultimate loads = loads resulting from the disconnection of the engine compressor from the turbine or from the loss of the turbine blades	
Time history of the thrust decay and drag buildup occurring as a result of prescribed engine failures	Must be substantiated by test or other data applicable to the particular engine-propeller combination	
Pilot corrective action	Timing and magnitude of the probable pilot corrective action must be conservatively estimated, considering the characteristics of the particular engine-propeller-airplane combination	

E. General Loads

1. *Pressurized Cabin Loads*

For each pressurized compartment, the conditions in Table 11 apply.

2. *Crash Loads*

Crash loads make up the ultimate inertia forces that an aircraft occupant experiences in emergency landing conditions. The crash loads in Table 12 act separately relative to the surrounding structure.

F. Landing Loads

1. *Level Landing Conditions*

The level landing condition is a normal level flight attitude for airplanes with tailwheels. For airplanes with nose wheels it is considered when the nose and main wheels contact the ground simultaneously, when the main wheels contact the ground, and when the nose wheel is just clear of the ground. The following load conditions must be considered under level landing conditions:

a. The wheel spin-up load must be combined with the corresponding instantaneous vertical ground reactions.
b. The wheel spring-back must be combined with vertical ground reactions at the instant of the peak forward load, assuming wing lift and a tire-sliding coefficient of 0.8 (23 CFR 479 [1]; 25 CFR 479 [2]).

2. *One-Wheel Landing Conditions*

Airplane is assumed to be in level attitude and in contact with the ground on one side of the main landing gear. In this attitude the ground reactions must be the same as those obtained on that side under Section III.F.1, "Level Landing Conditions" (23 CFR 483 [1]; 25 CFR 483 [2]).

3. *Side Load Conditions*

For the side load conditions to apply (Table 13), the airplane is assumed to be in a level attitude with only the main wheels contacting the ground and with the shock absorbers and tires in their static positions.

Table 11. Pressurized Compartment Considerations (23 CFR 365 [1]; 25 CFR 365 [2])

Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
The airplane structure must be strong enough to withstand flight loads combined with pressure differential loads from 0 to the maximum relief valve setting.	The normal operating differential pressure combined with the expected external aerodynamic pressures applied simultaneously with the flight loading conditions, if they have a significant effect (these include maneuvering, limit gust, limit rolling, limit yaw, and limit unsymmetrical conditions)
External pressure distributions in flight and any stress concentrations must be accounted for.	--------------
If landings are made with the cabin pressurized, landing loads must be combined with pressure differential loads from 0 up to maximum allowed during landing.	--------------
Airplane structure must be strong enough to withstand the pressure differential loads corresponding to the maximum relief valve setting ×1.33 factor (omitting other loads)	Maximum value of normal operating differential pressure (including the expected external aerodynamic pressures during 1g level flight) ×1.15 factor (omitting other loads)
If the pressurized cabin has greater than two compartments separated by bulkheads or a floor, the primary structure must be designed for the effects of sudden release of pressure in any compartment with external doors or windows (condition investigated for the effects of failure of the largest opening in the compartment).	--------------

Table 12. Crash Load Factors (DO-160G [4]: Environmental Conditions and Test Procedures for Airborne Equipment, 25 CFR 561 [2])

Aircraft Type	Up	Down	Forward	Aft	Side
Fixed-wing transport	3.0	6.0	9.0	1.5	4.0

4. *Braked Roll Conditions*

Table 14 outlines the load conditions acting on the landing gear during a braked roll of the aircraft. Shock absorbers and tires are in their static positions under braked roll conditions.

a. Attitudes and ground contacts follow those described for level landing conditions.
b. Drag reaction must be applied at the ground contact point of each wheel with brakes. The drag reaction need not exceed the maximum value based on limiting brake torque (23 CFR 492 [1]).

For airplanes with a steerable nose wheel that is controlled by hydraulic or other power, at design takeoff weight with the nose wheel in any steerable position the application of 1.33× the full steering torque combined with a vertical reaction equal to 1.33× the maximum static reaction on the nose gear must be assumed. If a torque-limiting device is installed, the steering torque can be reduced to the maximum value allowed by that device. For airplanes with a steerable nose wheel that has a direct mechanical connection to the rudder pedals, the mechanism must be designed to withstand the steering torque for the maximum pilot forces specified in Table 5 as well as 23 CFR 397 [1] and 25 CFR 397 [2].

5. *Ground Loads on Nose Wheels*

Table 15 contains the load conditions acting on the nose wheel landing gear. For airplanes with a steerable nose wheel that is controlled by hydraulic or other power, at design takeoff weight with the nose wheel in any steerable position the application of 1.33× the full steering torque combined with a vertical reaction equal to 1.33× the maximum static reaction on the nose gear must be assumed. If a torque-limiting device is installed, the steering torque can be reduced to the maximum value allowed by that device. For airplanes with a steerable nose wheel that has a direct mechanical connection to the rudder pedals, the mechanism must be designed to withstand the steering torque for the maximum pilot forces specified in Table 5 as well as 23 CFR 397 [1] and 25 CFR 397 [2].

Table 13. Side Load Conditions* (23 CFR 485 [1]; 25 CFR 485 [2])

Category	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
Limit vertical load factor	1.33 (Vertical ground reaction divided equally between the main wheels)	--------------
Limit side inertia factor*	0.83 where side ground reaction is divided between the main wheels as: • 0.5 × W acting inboard on one side • 0.33 × W acting outboard on the other side	0.8× vertical reaction acting inward on one side 0.6× vertical reaction acting outward on the other side These loads must be combined with 0.5× maximum vertical ground reactions obtained in level landing conditions

*Side loads are assumed to be applied at the ground contact point and the drag loads may be assumed to be zero.

Table 14. Braked Roll Conditions (23 CFR 493 [1]; 25 CFR 493 [2])

Category	Normal, Utility, Acrobatic, and Commuter Category Airplanes	Transport Category Airplanes
Limit vertical load factor	1.33	1.2 at design landing weight
		1.0 at design ramp weight
Drag reaction	Vertical reaction × 0.8	Vertical reaction × 0.8

Table 15. Ground Loads on Nose Wheels (CFR 23 Part 499 [1])

Category	Normal, Utility, Acrobatic, and Commuter Category Airplanes
For aft loads the limit force components at the axle	Vertical component 2.25× the static load on the wheel
	A drag component 0.8× the vertical load
For forward loads the limit force components at the axle	A vertical component of 2.25× the statics load on the wheel
	A forward component of 0.4× the vertical load
For side loads the limit force components at ground contact	A vertical component of 2.25× the static load on the wheel
	A side component of 0.7× the vertical load

IV. Structural Safety Margin

This section of the paper covers factors of safety outlined by 14 CFR Parts 23 [1] and 25 [2] as well as NASA standard factors of safety [5].

A. Methodology for Applying Factors of Safety

Factors of safety are typically applied to the limit load of the structure and can be prescribed in terms of a yield *FoS* or ultimate *FoS*. They can be applied to a load case prior to analysis, or in the post processing calculations of margins of safety. NASA standards prescribe for *MoS* to be calculated by the following equation, as detailed in NASA-STD-5001b [5]:

$$MoS = \frac{Allowable\ load\ \text{(yield or ultimate)}}{Limit\ load * FoS\ \text{(yield or ultimate)}} - 1 \tag{1}$$

Following this equation, positive margins of safety must be met on all components in both yield and ultimate load conditions.

B. Factors of Safety Defined for SUSAN 180PAX

The full-scale 180-passenger SUSAN concept aircraft will adhere to FAA FoS requirements and utilize an ultimate *FoS* of 1.5. Per 25 CFR 303 [2],

> Unless otherwise specified, a factor of safety of 1.5 must be applied to the prescribed limit load which are considered external loads on the structure. When a loading condition is prescribed in terms of ultimate loads, a factor of safety need not be applied unless otherwise specified.

C. Factors of Safety Defined for SUSAN 25% Scale Concept

NASA Armstrong AFG-7123.1-001, “Aircraft Structural Safety of Flight Guidelines,” [3] governs the structural requirements of experimental aircraft, aircraft structural components, and structural modifications to existing experimental aircraft. The 25%-scale SUSAN flight research vehicle aligns closely with the scope and requirements of AFG-7123.1-001 and will adhere to the higher factors of safety outlined in Table 16.

D. Fitting Factor

For each fitting (a part or terminal used to join one structural member to another) whose strength is not proven by limit and ultimate load tests in which actual stress conditions are simulated in the fitting and surrounding structures, a fitting factor of at least 1.15 (see Table 17) must be applied to the fitting, the means of attachment, and the bearing on the joined members.

Table 16. NASA Armstrong Factors of Safety ([3] Revision A)

Factor of Safety	Material	Condition
2.25 ~ 3.00	Composite	Structure verified by analysis along with building-block approach* (2.25 with well-established building block approach, higher *FoS* for limited building-block approach employed).
2.25	Metal	Structures verified by analysis only
1.80	Metal or composite	Structure verified by proof tests up to 120% design limit load
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

*Building-block approach employs testing of certain design features at each of the complexity levels (starting with coupons, elements to design, detailed design locations, subcomponents, and components), which is then used to validate the design.

Table 17. Fitting Factors Comparisons

NASA Fitting Factor [6]	CFR Part 23 [1] Fitting Factor	CFR Part 25 [2] Fitting Factor
1.15	1.15	1.15

E. Fatigue and Creep

For NASA spaceflight structures made of well-characterized materials and with sufficient load cycle data that account for all in-service environments, a minimum service life factor of 4.0 shall be applied to the service life for fatigue and creep life assessments [5].

F. Buckling

All structural items subjected to significant in-plane stresses (compression and/or shear) under any combination of ground, flight, or thermal loads shall be analyzed for buckling failure [5].

- Design loads for buckling shall be ultimate loads.
- If a loading condition tends to alleviate buckling, then the unfactored load shall be used in combination with other factored loading conditions.
- Buckling evaluation shall address general instability, local or panel instability, crippling, and creep.
- Analyses of thin-walled shell structures subject to buckling load conditions during the service life shall account for the differences between idealized model geometry and the physical structure, including boundary conditions.

V. SUSAN Electrofan Aircraft Concept

A. Overview of SUSAN Structural Approach

The SUbsonic Single Aft eNgine (SUSAN) Electrofan aircraft concept is a subsonic regional jet transport aircraft that utilizes a single-turbofan engine mounted in an aft nacelle and an electrified aircraft propulsion (EAP) system under the wings. This design concept enables propulsive and aerodynamic benefits that aim to reduce fuel usage, emissions, and cost. History has shown jet aviation progress from the utilization of four- to three- to two-engine setups, which are driven by market factors and per-mile operating cost. In an effort to find a practical and effective evolution of these designs, SUSAN seeks to use an aft-mounted turbofan in addition to wing-mounted distributed electric engines. Boundary layer ingestion into the turbofan has been investigated as a method of increasing efficiency when the engine is located at the aft end of the aircraft. The unique challenge of this airframe from a structural perspective is how fundamentally the powertrain and propulsion systems are integrated into the structure of the aircraft to minimize weight and fully realize efficiency benefits. This results in novel force vectors and primary load paths over those traditionally seen in tube and wing constructions both in the mass loading of critical subsystems (battery, generator, etc.) and propulsive loading through the distributed wing motors and tailcone engine.

B. Aircraft Concept Features

The full-scale 180-passenger SUSAN aircraft concept and 25%-scale flight research vehicle are typical tube-and-wing designs with a mix of metallic and composite structures. One of the main unique features of this concept is the aft-mounted turbofan jet engine in line with the fuselage. This feature will be unique from other aft-mounted engine cases because it will be mounted via a pylon structure where the tail structure shares this mounting location. Because of battery pack storage in the wings, this concept will have a different ratio of maximum to empty weights because of the battery mass. Typical landing loads assume that the aircraft has ejected most of its propellant as exhaust from the engines. In an electric aircraft with both fuel and electric packs in the wings, the landing weight is closer to the takeoff weight than with an aircraft having only fuel load in the wings. Additional unique features include the wing-mounted electric engines, which will impact the control surfaces and the loads they will see. The loads on the engine mounts will be more distributed across the wings as opposed to single nacelles of typical aircraft.

The above features are applicable to both the full and 25%-scale aircraft concepts; however, the 25%-scale vehicle will include additional constraints. There is a requirement for the 25%-scale vehicle to be transportable; that is, the wings will need to be removed and reattached and thus able to carry aerodynamic loads across a separatable joint. There is also the constraint that the vehicle must be low cost and quick to manufacture. Finally, the 25%-scale vehicle will not need to be as structurally efficient as the full-scale aircraft as it will not have passenger payload.

VI. Example Application: SUSAN 25%-Scale Vehicle

Because of the implementation of multiple novel technologies with the SUSAN vehicle, it is necessary to reduce technical risk through incremental validation of design concepts. In support of the full-scale SUSAN flight research vehicle the SUSAN team is formulating a 25%-scale flight research vehicle to serve as a remotely piloted flying research testbed for the integrated flight, propulsion, and controls architecture of the SUSAN aircraft. The 25%-scale flight research vehicle is a direct scaledown of the existing full-scale 180-passenger vehicle outer mold line (OML) (Fig. 3). Table 18 summarizes the vehicle’s design targets and flight conditions. This scaled-down vehicle will maintain relevant primary force and moment effectors for controls architecture development and allows for further development of the powertrain and power system integration approach. The three main structural components being analyzed on the vehicle are broken up into the engine mounting structure, the fuselage, and the wing. This section provides an example application of key load elements for the 25%-scaled vehicle based on the approach defined in the load's tables earlier in the paper.

C. Aerodynamic Loads

Computational fluid dynamics (CFD) simulations were used to determine initial approximation of aerodynamic loads at each main component location. All cases were run through steady Reynolds-averaged Navier–Stokes (RANS) calculations using Launch Ascent and Vehicle Aerodynamics (LAVA) curvilinear solver [7].

Flight conditions are summarized in Table **19**. Eight load scenarios were chosen for initial analysis where line loads were computed for each case. The following load scenarios were simulated:

1) Symmetric maneuver: +3.75g at W, V_C, SL
2) Symmetric maneuver: +3.75g at W, V_C, H_C
3) Symmetric maneuver: –1.5g at W, V_C, SL
4) Symmetric maneuver: –1.5g at W, V_C, H_C
5) Vertical gust: +1g at W, V_C, H_C, +50 ft/s vertical gust
6) Vertical gust: +1g at W, V_C, H_C, –50 ft/s vertical gust
7) Lateral gust: +1g at W, V_C, H_C, +50 ft/s lateral gust
8) Lateral gust: +1g at W, V_C, H_C, –50 ft/s lateral gust

Fig. 4 shows the output force and moment line load locations across the span of each main component geometry from the CFD simulations. The different colors shown here divide the force and moment loads across each component into separate "bins," or locations where line loads are to be applied.

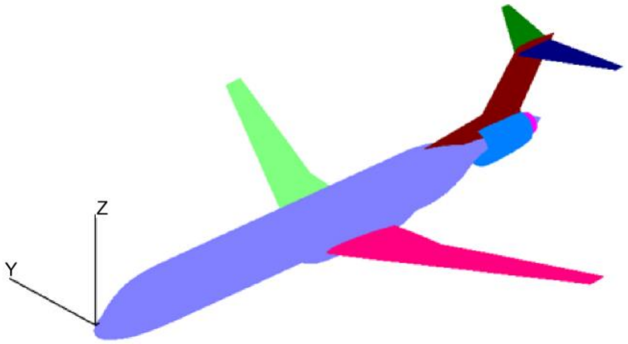

Fig. 3. 25%-scale SUSAN flight research vehicle OML.

Table 18. 25%-Scale Flight Research Vehicle Summary

Powerplant: hybrid	Single aft fan in addition to 16 wing-mounted distributed electric thrusters
Target system weight (fueled)	<1,500 lb
Airspeed	130 kt
Maximum altitude	10,000 ft

Table 19. Flight Conditions

Condition	**Value**
SL	0 ft
H_C	10,000 ft
V_C	130 kt (150 mph)
W	1,500 lb
S_{ref}	81.125 ft^2
V_{ref}	225.61 ft/s

ρ_{ref}	0.001755 slugs/ft^3

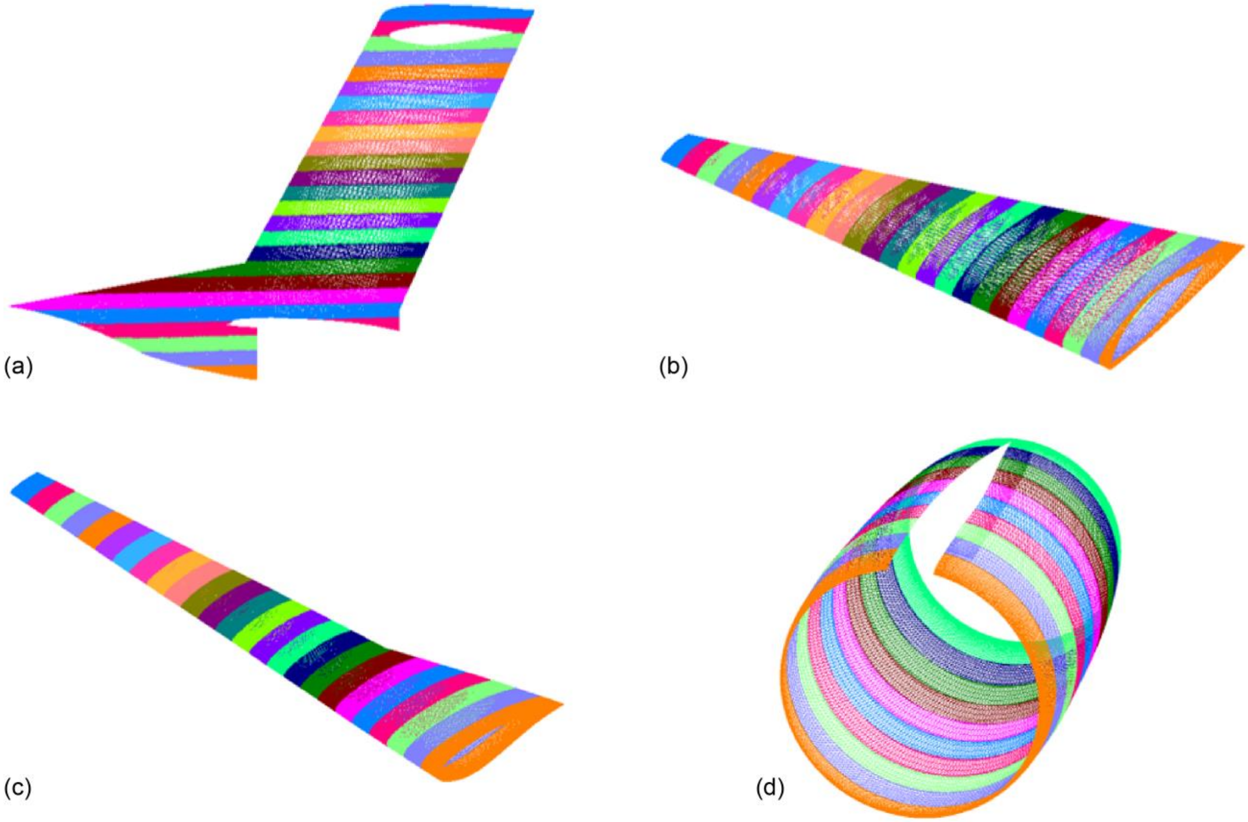

Fig. 4. Example force and moment line loads provided at "bins" across the span of each listed component geometry. (a) Vertical tail. (b) Horizontal tail. (c) Wing. (d) Nacelle.

D. Engine Mounts

This section summarizes some of the main load requirements for the engine mount. This case is unique, as our engine is mounted at the aft location of the aircraft and shares mounting structure with the T-tail as well as shown in Fig. 5. This structural layout is unique because it adds additional loading from the tail structure to the engine mount beam that a typical engine mount would not have otherwise seen. Additionally, with the engine and tail mounted off the aft end of the fuselage by a pylon-like beam, the loads seen here will also transfer into the tail cone of the fuselage. Considerations for potential tail strike will also be included here. Table 20 below expands upon the engine mount loads referenced in Section III of this paper, "Design Loads," for the 25%-scale SUSAN aircraft concept. Table 21 combines the individual load requirements defined in Table 20 to encompass the full range of load cases on the engine mount structure for specific mission profiles.

Loads referenced from 14 CFR Part 23 [1] in Table 20 to Table 25 are based on a normal category airplane. These airplanes are those which have nine or less seats, excluding those of the pilot. Their maximum takeoff weight is less than 12,500 lb, and they are intended for nonacrobatic operations. The loads prescribed for each of these components can each be checked within finite element models of the respective components, and the controlling load case can be determined. Table 20 to Table 25 of this section show an example application of consolidated loads and requirement standards for the unique 25%-scale hybrid SUSAN aircraft concept. Note that the tables don't represent all loads the components will see, but rather they highlight some of the major requirements assessed from the standards referenced here.

E. Fuselage

This section summarizes the load requirements for the fuselage structure shown in Fig. 6. This structure mostly follows typical fuselage layouts and will undergo all similar loading requirements. The unique feature to this structure is the aft mounted engine at the tailcone location of the fuselage. The tailcone structure will see additional loading induced by the shared engine-/tail-mounting structure that a typical aircraft configuration would not. It is assumed here that the landing gear mounting structure is part of the fuselage assembly. Table 21 expands upon the fuselage loads referenced across multiple subparts of Section III of this paper, "Design Loads," for the 25%-scale SUSAN aircraft concept. Table 22 combines the individual load requirements defined in Table 21 to encompass the full range of load cases on the fuselage for specific mission profiles.

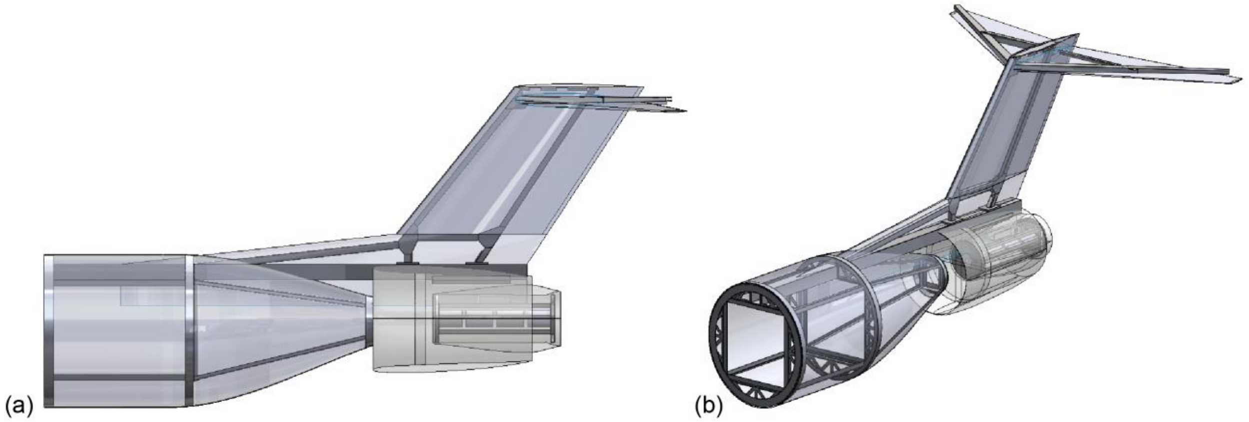

Fig. 5. SUSAN 25%-scale concept. (a) Aft-mounted engine. (b) Tail structure.

Table 20. Individual Load Requirements for Engine Mount

Load Case	Load or Load Factor Applied	Reference
Engine mount side load	Limit load factor of 1.33g in lateral direction (assumed to be independent of other flight conditions)	23 CFR 363 [1]
Aerodynamic loads	These include horizontal and vertical gust loads of ±50 ft/s, symmetric maneuvering loads on vertical tail, air loads on rudder and elevators, and aerodynamic loads at the nacelle.	Combined requirements, CFR Part 23
Engine thrust	300 lb maximum thrust estimate	Project specification
Engine torque	Limit engine torque corresponding to maximum continuous power and propeller speed acting simultaneously with the limit loads (+3.8/–1.5)	23 CFR 361
Combination of thrust with vertical and side loads	300 lb engine thrust, side limit load factor = 1.33g, vertical load factor = 3.8g (from maximum maneuvering load factor)	CFR Part 23
Gyroscopic and aerodynamic loads	Combination of 2.5 rad/s yaw velocity, 1.0 rad/s pitch velocity, normal load factor of 2.5g, maximum continuous thrust force, and aerodynamic loads that result from engine operation	23 CFR 371
Unsymmetrical loading on horizontal tail (maneuvering)	100% of maximum loading from symmetrical flight conditions on one side; opposite side follows: $\% = 100 - 10(n - 1)$ where value may not be more than 80%.	23 CFR 427
Maneuvering load on vertical tail surface	Yaw velocity assumed to be zero and airplane in unaccelerated flight; at speeds up to V_A, vertical surfaces must be designed to withstand sudden displacement of rudder control to maximum deflection. Airplane yaws to overswing sideslip angle of 22.5°. Aeronautical loads are determined from this maneuver.	23 CFR 441

Table 21. Specific Cases/Mission Profile Loading for Engine Mount

Load Case	Load or Load Factor Applied	Reference
Crash condition	3g, 6g, 9g, 1.5g, 4g loads applied up, down, forward, aft, and side, respectively. g-loads applied separately.	DO-160G [4], 25 CFR 561 [2]
Engine-out condition	Does not lead to typical unsymmetric loads detailed in CFR Part 23 [1]. In the event of turbofan engine failure, primary batteries will provide electrical power to wing propulsors and allow for limited continuation of flight.	General
Takeoff/landing	Aerodynamic loads, engine thrust and torque, considerations for tail strike at aft engine (must check different angles of attack at landing)	Combined requirements
Cruise	Symmetrical vertical gusts in level flight (gust of ±50 ft/s), thrust, engine torque, aerodynamic loads, 1g load factor	Combined requirements
Maneuvering (this will include load cases for airplane loitering)	Aerodynamic loads, engine thrust and torque, side loads on engine mount, gyroscopic loads, unsymmetrical loading, and maneuvering conditions on empennage	Combined requirements

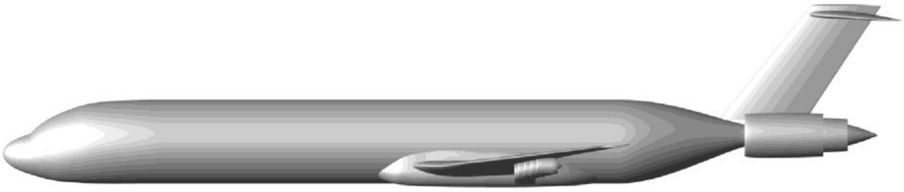

Fig. 6. SUSAN 25%-scale concept fuselage structure.

Table 22. Individual Load Requirements for Fuselage

Load Case	Load or Load Factor Applied	Reference
Pressurized cabin loads	Three load cases: Flight loads combined with pressure differential loads from 0 to maximum relief valve setting; take into account external pressure distributions in flight; if landing with pressurized cabin, combine landing loads with pressure differential loads from 0 up to maximum allowed during landing. Separate load case: pressure differential loads corresponding to maximum relief valve setting × 1.33 load factor	23 CFR 365 [1]
Level landing	Vertical ground reaction force and drag (drag loads may not be less than 0.25× maximum vertical ground reaction)	23 CFR 479
One-wheel landing	Aircraft contacts the ground on one side of main landing gear; ground reactions are the same as those obtained on that side under level landing conditions	23 CFR 483
Landing side load condition	This can be combined/checked with level landing condition: limit vertical load factor = 1.33 (vertical ground reaction divided equally between the main wheels); limit side inertia factor = 0.83 with the side ground reaction divided between the main wheels so that $0.5 \times W$ acts inboard on one side and $0.33 \times W$ acts outboard on the other side. Drag loads are assumed to be zero in this condition.	23 CFR 485
Braked roll	Level landing conditions + vertical load factor = 1.33; drag reaction = vertical reaction at wheel ×0.8 (applied at wheels with brakes)	23 CFR 493
Unequal tire loads	Established loads must be applied in a 60/40 percent distribution to the dual wheels and tires in each dual-wheel landing gear unit	23 CFR 511
Deflated tire loads	60% of the limit drag and side loads, and 100% of the limit vertical load	23 CFR 511
Ground turn	1.33× the full steering torque combined with a vertical reaction equal to 1.33× the maximum static reaction on the nose gear	23 CFR 499
Taxiing	Use shock/vibration requirements + ground gusts + ground turn case	DO-160G [4], CFR Part 23
Symmetrical vertical gust (level flight)	At V_C (altitude between sea level and 20,000 ft), gust of ±50 ft/s	23 CFR 333
Symmetrical lateral gust (level flight)	At V_C (altitude between sea level and 20,000 ft), gust of ±50 ft/s	23 CFR 443
Positive/negative limit maneuvering load factor	+3.8g/–1.5g	23 CFR 337
Ground loads on nose wheels	For aft loads: vertical component 2.25× static load on wheel; drag component 0.8× vertical load	23 CFR 499
	For forward loads: vertical component 2.25× static load on wheel; drag component 0.4× vertical load	
	For side loads: vertical component 2.25× static load on wheel; drag component 0.7× vertical load	
Loads induced on fuselage by wings	See wing load cases	Combined
Loads at tailcone induced by engine/tail mount	See engine-mount load cases	Combined
Jacking at landing gear	Vertical: 1.35× static reaction; fore: 0.4× static reaction; aft: 0.4× static reaction; lateral: 0.4× static reactions. Vertical static reaction based on weight + gravity divided by number of support points	23 CFR 507
Aerodynamic loads	Include maneuvering, gusts, and g-loads	Combined requirements, CFR Part 23

Table 23. Specific Cases/Mission Profile Loading for Fuselage

Load Case	Load or Load Factor Applied	Reference
Crash condition	3g, 6g, 9g, 1.5g, 4g loads applied up, down, forward, aft, and side, respectively. g-loads applied separately.	DO-160G [4], 25 CFR 561 [2]
Takeoff/landing	Pressurized cabin loads, all landing conditions to be checked, taxiing and brake conditions, ground turn, aerodynamic loads, impact from wing load cases	Combined
Cruise	Pressurized cabin loads, aerodynamic loads, loads at tailcone from engine cases, impact from wing load cases	Combined
Maneuvering (this will envelope load cases for airplane loitering as well)	Aerodynamic loads (includes gust and maneuvering g-loads), and pressurized cabin loads, impact from wing load cases	Combined

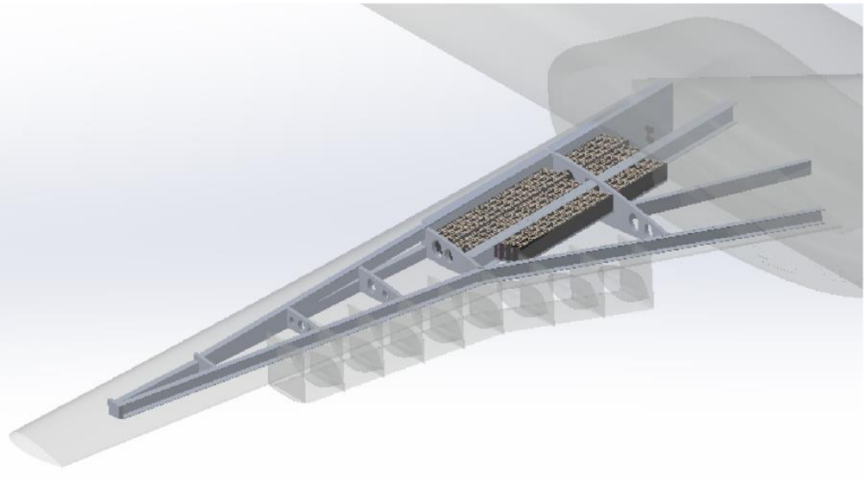

Fig. 7. SUSAN 25%-scale concept wing structure.

F. Wing

This structure mostly follows typical wing layouts and will undergo all similar loading requirements. The unique features to this structure are the 16 under-wing distributed electric thrusters and the mounting of batteries in the wings as shown in Fig. 7. These distributed electric thrusters present a unique wing layout and will induce additional loading through their mounting structure. The batteries and power system in the wing result in added weight, thermal, and electrical loading requirements. It is assumed here that the landing gear mounting structure is part of the fuselage assembly and not the wing structure. It is also assumed that fuel/oil will not be housed in the wing structure. Table 23 expands upon the wing loads referenced across multiple subparts of Section III of this paper, “Design Loads,” for the 25%-scale SUSAN aircraft concept. Table 24 combines the individual load requirements defined in Table 23 to encompass the full range of load cases on the wing for specific mission profiles.

Table 20 to Table 25 demonstrating loads for the engine mount structure, fuselage, and wing serve to capture both the individual load cases on the structure as well as the combined cases that encompass the mission profiles. Table 1 of this paper outlined the flight maneuvers that typically produce high loads at varying aircraft component locations. The feedback of Table 1 along with the mission profile loading for each main component location can be used to identify the controlling loads cases at each component location and greatly reduce the analysis iterations run at the early sizing stages of aircraft conceptual design studies.

Table 24. Wing Loading

Load Case	Load or Load Factor Applied	Reference
Positive limit maneuvering load factor	3.8g	23 CFR 337 [1]
Negative limit maneuvering load factor	–1.5g	23 CFR 337
High-lift devices (flaps fully extended) at V_F (takeoff, approach, or landing)	Positive limit maneuvering load factor = 2.0; Gust of ±25 ft/s acting normal to flight path in level flight; Design flap speeds not less than $1.4V_S$ or $1.8V_{SF}$, whichever is greater (in determining external loads on airplane as a whole, thrust, slipstream, and pitching acceleration may be assumed to be zero). In addition to these loads, must check head-on gust of 25 ft/s (EAS), combined with propeller slipstream corresponding to 75% maximum continuous power; considered separately are effects of propeller slipstream corresponding to maximum takeoff power	23 CFR 345
Taxiing	Use shock/vibration requirements + ground gusts	DO-160G [4], CFR Part 23
Symmetrical vertical gust (level flight)	At V_C (altitude between sea level and 20,000 ft), gust of ± 50 ft/s	23 CFR 333
Symmetrical lateral gust (level flight) on vertical surfaces (motor mounts)	At V_C (altitude between sea level and 20,000 ft), gust of ± 50 ft/s	23 CFR 443
Rolling conditions (aileron (stick control))	Take Worst Case: Aeronautical surface loads on ailerons in neutral position during symmetrical flight; Aeronautical surface loads during sudden maximum displacement of aileron control at V_A and during sufficient deflection at V_C; also, aeronautical loads at sufficient deflection at V_D where the rate of roll is not less than 1/3 that at sudden maximum displacement of aileron. (Maximum pilot force: 67 lb)	23 CFR 397
Rolling conditions (unsymmetrical loading condition)	100% of wing air load acts on one side of airplane, 75% of this load acts on other side. In addition to loads resulting from aileron deflections and speeds in combination with a load factor of 2.53	23 CFR 349
Yawing conditions affecting any vertical surfaces (motor mounts on wing)	2.5 rad/s	23 CFR 351
Maneuvering load on vertical surface (motor mounts on wing)	Yaw velocity assumed to be zero and airplane in unaccelerated flight; at speeds up to V_A, vertical surfaces must be designed to withstand sudden displacement of rudder control to maximum deflection. Airplane yaws to overswing sideslip angle of 22.5°. Aeronautical loads determined from this maneuver.	23 CFR 441
Motor thrust	15 lb thrust estimate per motor (16 motors total)	Project specification
Motor torque	Limit engine torque corresponding to maximum continuous power and propeller speed acting simultaneously with the limit loads (+3.8/–1.5)	23 CFR 361
Motor mount side load	Limit load factor of 1.33g in lateral direction (assumed to be independent of other flight conditions)	23 CFR 363
Gyroscopic and aerodynamic loads on motor mounts	Combination of 2.5 rad/s yaw velocity, 1.0 rad/s pitch velocity, load factor of 2.5g, maximum continuous thrust force, and aerodynamic loads that result with motor operation	23 CFR 371

Table 25. Specific Cases/Mission Profile Loading for Wing

Load Case	Load or Load Factor Applied	Reference
Crash condition	3g, 6g, 9g, 1.5g, 4g loads applied up, down, forward, aft, and side, respectively. g-loads applied separately.	DO-160G [4], 25 CFR 561 [2]
Failure of distributed electric thrusters (one wing); unsymmetrical loads	Limit loads = loads resulting from power failure because of power flow interruption; ultimate loads = loads resulting from disconnection of engine compressor or from loss of fan blades	Loosely based on 23 CFR 267 [1]
Takeoff/landing	High-lift device load requirements, aerodynamic loads, taxiing, motor thrust/torque	Combined
Cruise	Case to include gust, motor thrust/torque, aerodynamic loads on wing, 1g load factor	Combined
Maneuvering (this will envelope load cases for airplane loitering as well)	Gust, motor thrust/torque, aerodynamic loads on wing, maneuvering loads on vertical and horizontal surfaces, unsymmetrical loading on wings	Combined

VII. Conclusion

In order to provide a solid foundation for the conceptual design of the SUSAN concept aircraft and related 25%-scale flight research vehicle, we consolidated structural requirements from the FAA and NASA. This set of consolidating applicable aircraft design loads and standards structural requirement enables rapid informed iterations on the structural design of the SUSAN aircraft. The 25%-scale SUSAN flight research example case highlighted unique loading conditions of this configuration. This paper evaluated key elements of the SUSAN 25%-scale flight research vehicle based on the approach defined in the first section of the paper. The breakout load tables for each of the main components of the SUSAN flight research vehicle highlight the application of typical FAA, military, and nongovernment standards to an atypical aircraft configuration.

VIII. Acknowledgements

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