Aircraft Structural Considerations

Frank Sauer

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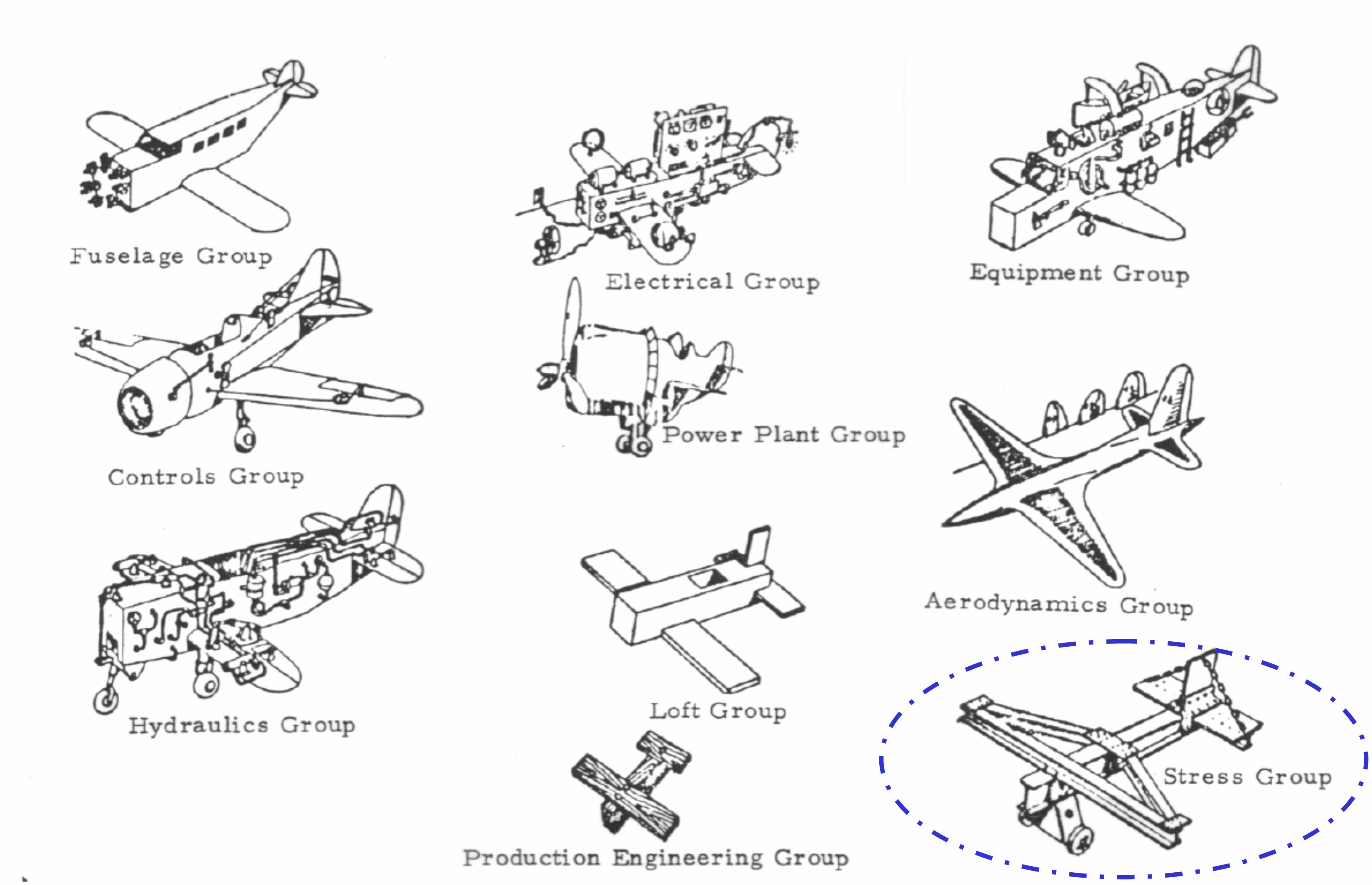
One of Many Considerations



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What does a structural analyst do? 4 Questions

1. *What is the load path?*
   – Where is load coming from, where does it "want" to go? Perhaps more basic: What is the load?
2. *How do structural members carry the load?*
   – Tension, compression, bending, shear, torsion. How do you arrange the members efficiently?
3. *How do those structural members, carrying those loads, fail?*
   – Many different failure modes - strength, stability, attachments, interactions…
4. *How do you calculate the failing load for those members, those loads?*

- Getting the answer wrong on the first or third questions is most common cause of unexpected structural failure

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Engineering

One of the Great Laws of Engineering…and Life

- ***Good*** **Judgment comes from Experience**

- **Experience comes from *Bad* Judgment**
  - **If We Are Clever, We Try To Learn From Other's Experience**
    - **The Aviation Community Has Tried To Codify Its Experience**

Structural Considerations

- **The Structure Will Not Fail!**
  - Not Under Any Static Design Ultimate Load Case
    - Ultimate Load Is Typically 1.5 * Limit Load
      - Limit Load Is Most Severe Condition Expected To Be Encountered In Life Of The Fleet
    - Safety Factor Covers Part Tolerances, Statistical Allowables, Load Exceedance, Environmental Degradation
  - Not After Repeated Loads Within The Lifetime Of The Vehicle
- **The Structure Will Not Deflect Such That Something Does Not Work Anymore!**
  - Control Surfaces Will Move Through Expected Range
  - Doors Will Open When They Are Supposed To
  - Nothing Will Yield
  - No Unexpected Shock Waves Will Form
- **Structure Will Meet Specified Durability/ Damage Tolerance/ Fail Safety Requirements.**
  - No Failures With Specified Damage Within Allowed Inspection Intervals

What Do You Need to Consider?

You are responsible for assuring that the vehicle complies with all structural criteria and requirements. What would it take to convince you that the design was safe and should be certified?

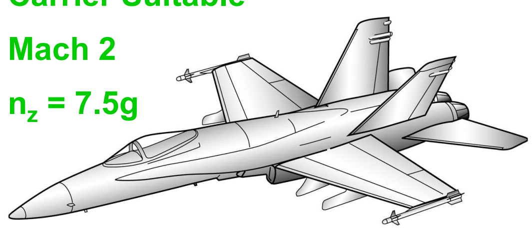
- **Are The External Loads Accurate And Complete?**
- **Are Good Internal Load Paths Provided? Load Paths Control Weight Efficiency of Structure**
  - **Well Defined, Properly Placed Members Carry Load Efficiently**
  - **Indirect, Poorly Defined Load Paths Not So Efficient**
    - **Structural Arrangement (Load Paths) Are Not Always Optimum, Compromises Necessary to Meet All Requirements**
- **Are The Internal Loads Balanced For Each Component And Part? (Free Body Diagrams Are Best Way to Show This)**
- **Do The Material Allowables Meet The Criteria/Requirements? (Static Strength, D&DT, Thermal, Manufacturing/Processing Considerations)**
- **Does The Certification Basis Demonstrate Compliance With Criteria & Requirements**
  - **Detail Analysis Notes**
  - **Tests**
  - **Reports**

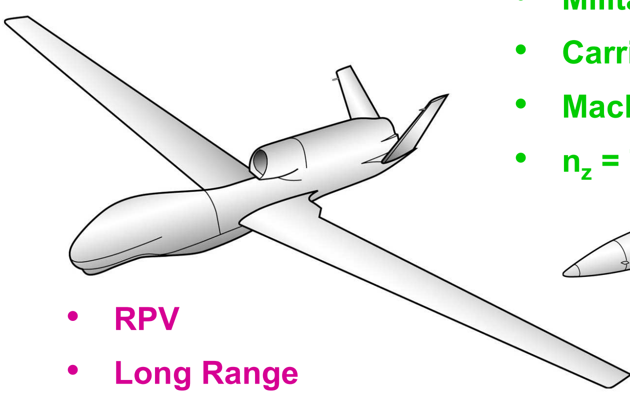
Aircraft Structural Considerations

Different Objectives - Different Configurations - Similar Process

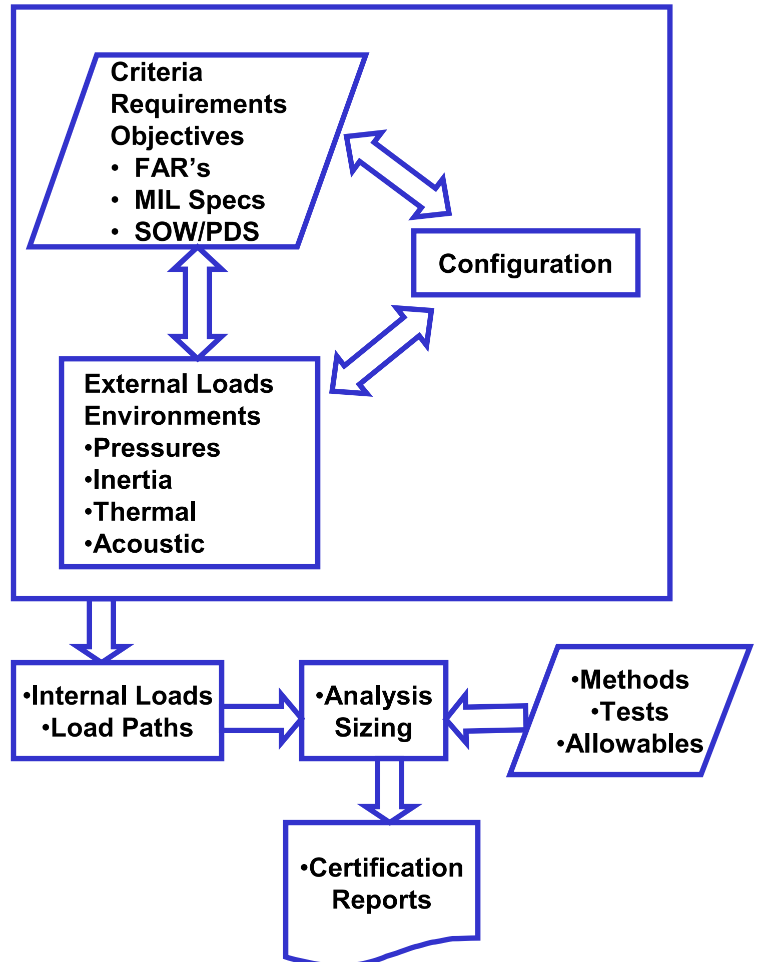
- 400 passengers
- 40 year service life
- All weather
- Maintainable
- Reliable
- Damage Tolerant

- Military Fighter/Attack
- Carrier Suitable
- Mach 2
- n_z = 7.5g





- RPV
- Long Range
- Loiter XX Hours w/o refueling



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Aircraft Loads, Conditions & Requirements

Requirements Have Evolved With Experience/Lessons Learned

Flight Loads:
- **Maneuver**
- **Gust**
- **Control Deflection**
- **Buffet**
- **Inertia**
- **Vibration**

Ground Loads:
- **Vertical Load Factor**
- **Braking**
- **Bumps**
- **Turns**
- **Catapult**
- **Arrested Landing**
- **Aborted Takeoff**
- **Spin-Up**
- **Spring Back**
- **One Wheel/Two Wheel**
- **Towing**
- **Ground Winds**
- **Break Away**

Other Loads & Conditions:
- **Jacking**
- **Pressurization**
- **Crash**
- **Actuation**
- **Bird Strike**
- **Lightning Strike**
- **Hail**
- **Power Plant**
- **Thermal**
- **Fatigue**
- **Damage Tolerance**
- **Fail Safety**
- **Acoustics**
- **Ground Handling**

Specific Conditions are defined per:
- **CFR14 Parts 23 and 25…(FAR)………….*Commercial (Subpart C = Structures)***
- **Mil-A-8860-8870 and SD-24L……………. *Military***

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Aircraft Loads, Conditions & Requirements

Requirement: Bird Strike (Parts 23, 25, 29, 91)

Commercial Transport

- **Wings/Body/Windscreen-Windows**

  The airplane must be capable of successfully completing a flight during which likely structural damage occurs as a result of - Impact with a **4-pound bird** when the velocity of the airplane relative to the bird along the airplane's flight path is equal to Vc at sea level or 0.85Vc at 8,000 feet, whichever is more critical;

- **Empennage**

  The empennage structure must be designed to assure capability of continued safe flight and landing of the airplane after impact with an **8-pound bird** when the velocity of the airplane (relative to the bird along the airplane's flight path) is equal to V_C at sea level

Military

Specifications typically require that catastrophic structural failure or loss of control of aircraft be prevented after a defined limit of structural damage has occurred as a result of in-flight bird strike.

⇨

No penetration of cockpit
- **Danger to crew**

No penetration of fuel tanks:
- **In-flight fire hazard**
- **Fuel loss**

No damage to control surface actuation/controls

Is this really necessary?

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Aircraft Loads, Conditions & Requirements

Every Requirement and Condition is There for a Reason!

747/767/777 Daily Highlight Report
03 April 2001

Multiple Bird Strike - One Bird Entered Flight Deck 767 (L/N 447)
American Airlines reported that on April 2nd during climb from Paris, at 12,000 feet, the reference airplane struck multiple birds impacting various locations on the aircraft. One bird entered the flight deck via the P1-1 panel on the captain's left side. All flight controls and systems functioned normally. The crew elected to return to Paris where an uneventful landing was made. The airplane is currently AOG in Paris.

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Aircraft Loads, Conditions & Requirements

Requirement: 8 lb. Bird Strike Empennage

**Apparent
Pterodactyl Strike**

RH Horizontal Stabilizer of Navy T-44A
aircraft out of Corpus Christi, TX
(October 2002)

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Small Airplanes Hit Birds, Too

McKinney, TX, 8 July 2003

NTSB Identification: FTW03FA182

14 CFR Part 91: General Aviation

Aircraft: Cessna 172S

Registration: N166ME

Injuries: 2 Fatal

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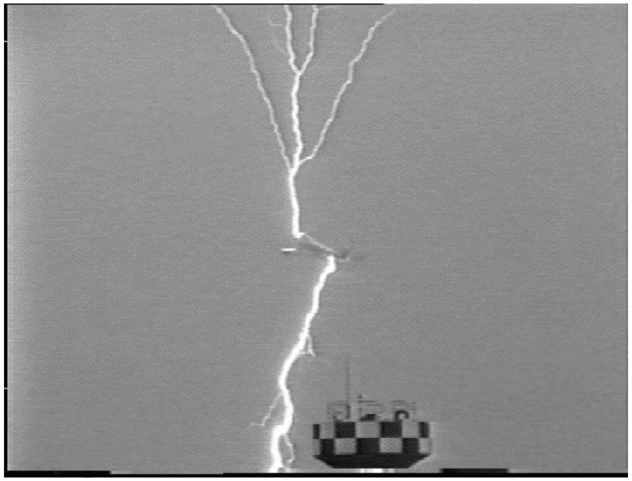
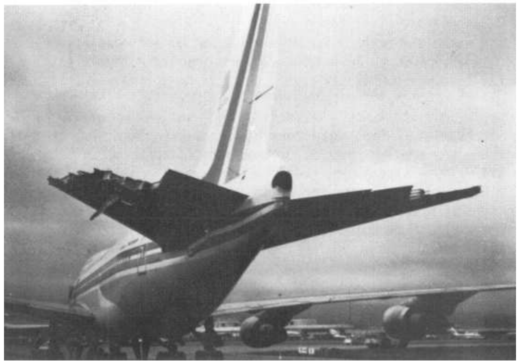
Aircraft Loads, Conditions & Requirements

Design Criteria Evolved with Performance/Goals and from Aircraft incidents

Uncontained Engine Blade Failure



Lightning



Engine Windmilling

Ballistic Damage

In Flight Hail

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Aircraft Loads, Conditions & Requirements

Design Criteria are Still Evolving

November 12, 2001 - Commercial transport lost vertical fin shortly after takeoff from Kennedy International Airport. The airliner crashed into a neighborhood in Belle Harbor, New York. 265 Fatalities. <u>Pilot control input caused fin load to exceed ultimate capability.</u>

1 Center and 2 Aft Attach Points

Right Side Forward and Center Attach Points

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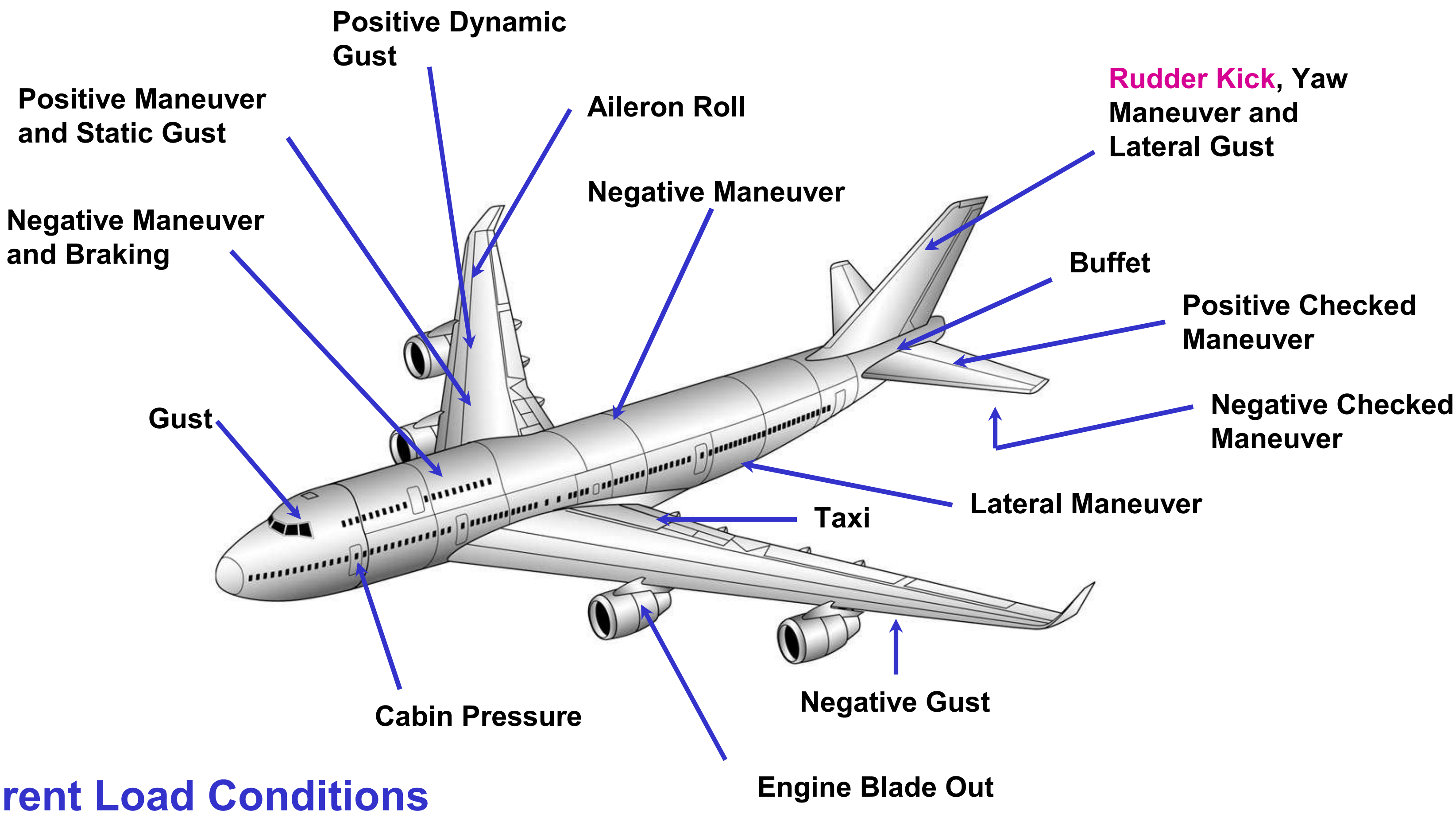
Aircraft Loads, Conditions & Requirements

Typical Commercial Transport Critical Static Load Conditions



Different Load Conditions are Critical for Different Areas

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How Does a Load Get from Here to There?

- Structure Carries Load In:
  - Tension
  - Compression
  - Shear
  - Bending
  - Or Combinations of The Above
- Typical Means To Carry Load
  - Columns – Tension, Compression
  - Beams – Bending, Shear, Tension, Compression
  - Plates - All
  - Shells - All
  - Combinations of Those Types
- Structural Analysis – Idealize Structure
  - Defines Loads in Member
  - Determines Whether Member Can Carry Load Without Failing
    - Comparison of Above Is Quantified as "Margin of Safety"

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Aircraft Structure

- How Does Aircraft Structure Differ from Other Typical Structure?
- Weight Efficiency
  - Weight is Important to Everyone, Material Costs $
  - But, In Flight Vehicles, Weight is $ & <u>Performance</u>, We Usually Operate Structure Near Buckling or in Post-Buckled Regime
- Columns, Beams, Plates, Shells Made From Thin Members in Flight Vehicle Structure
  - Buckling Due to Shear and/or Compression Loading May Be Allowed at Very Low Load Levels
  - Post-Buckled Behavior, Failure is the Realm of Aircraft Stress Analysis

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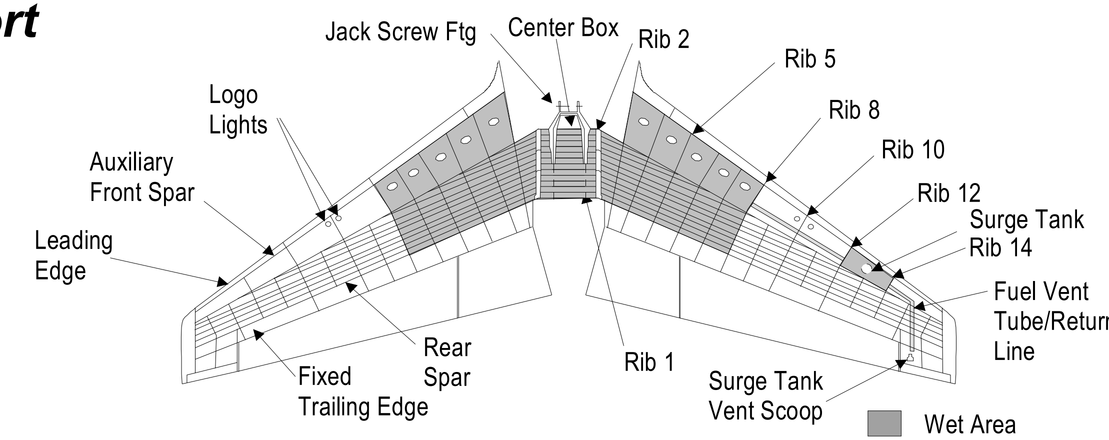
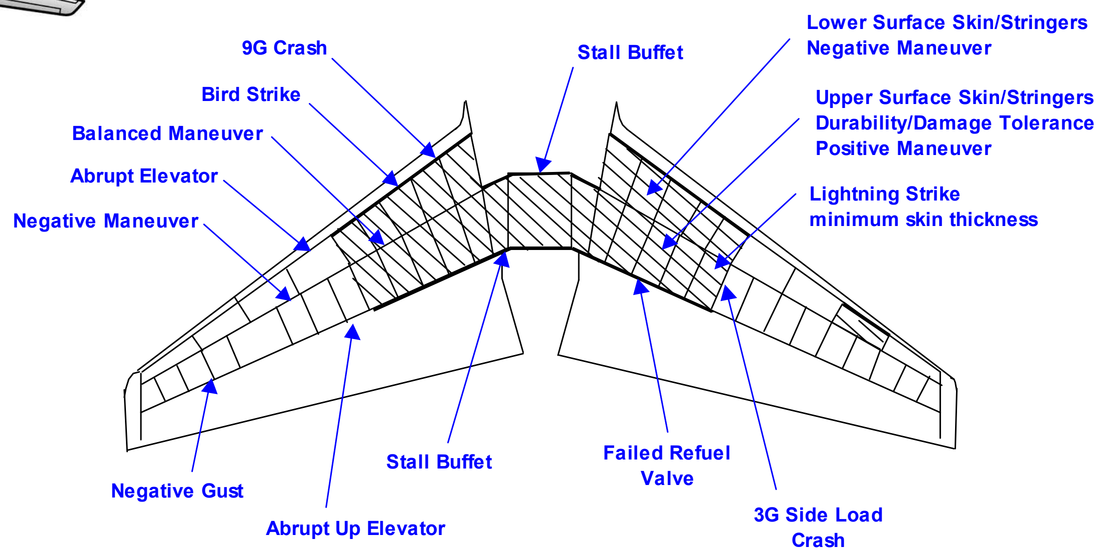
Aircraft Loads, Conditions & Requirements

Typical Commercial Transport Critical Load Conditions



Structural Considerations

- External loads (pressures/inertia)
- Durability/Damage Tolerance
- Crash
- Failed Refueling Valve
- Hail and bird strike
- Lightning strike
- Material utilization



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Internal Loads/Load Paths

- **Aircraft structure is designed to be light weight => Typically very thin gage**
- **Members are arranged to carry loads efficiently (in-plane)**
  - **shear webs**
  - **axial members**
- **Out-of-plane loads are carried to redistribution members where the loads are converted to in-plane components**

Stiffened Skin Panel

Body Panel

Built-Up Spar

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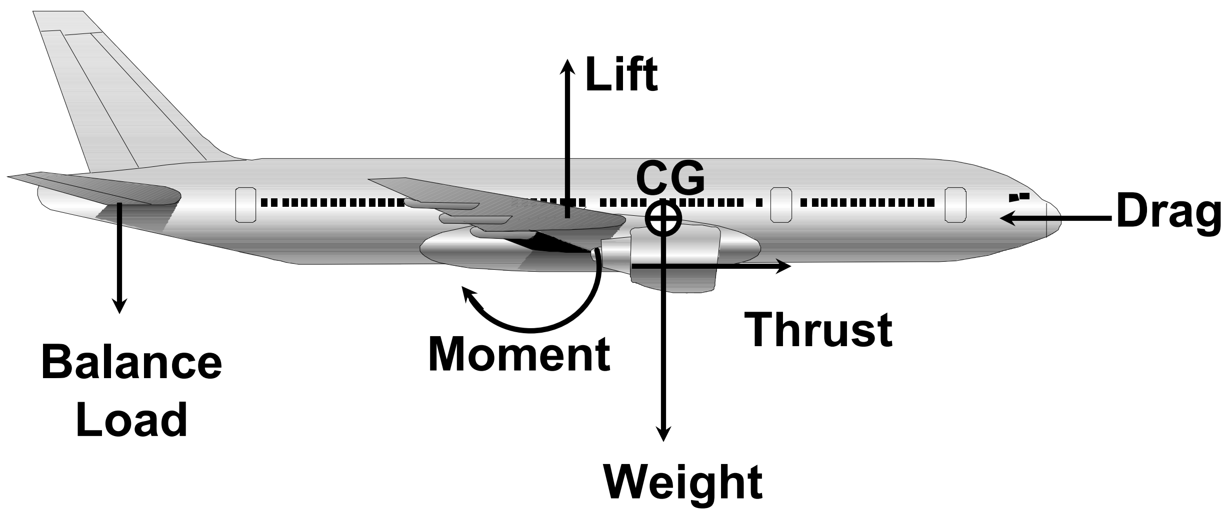
Internal Loads/Load Paths

So how do we get internal members to carry loads efficiently?



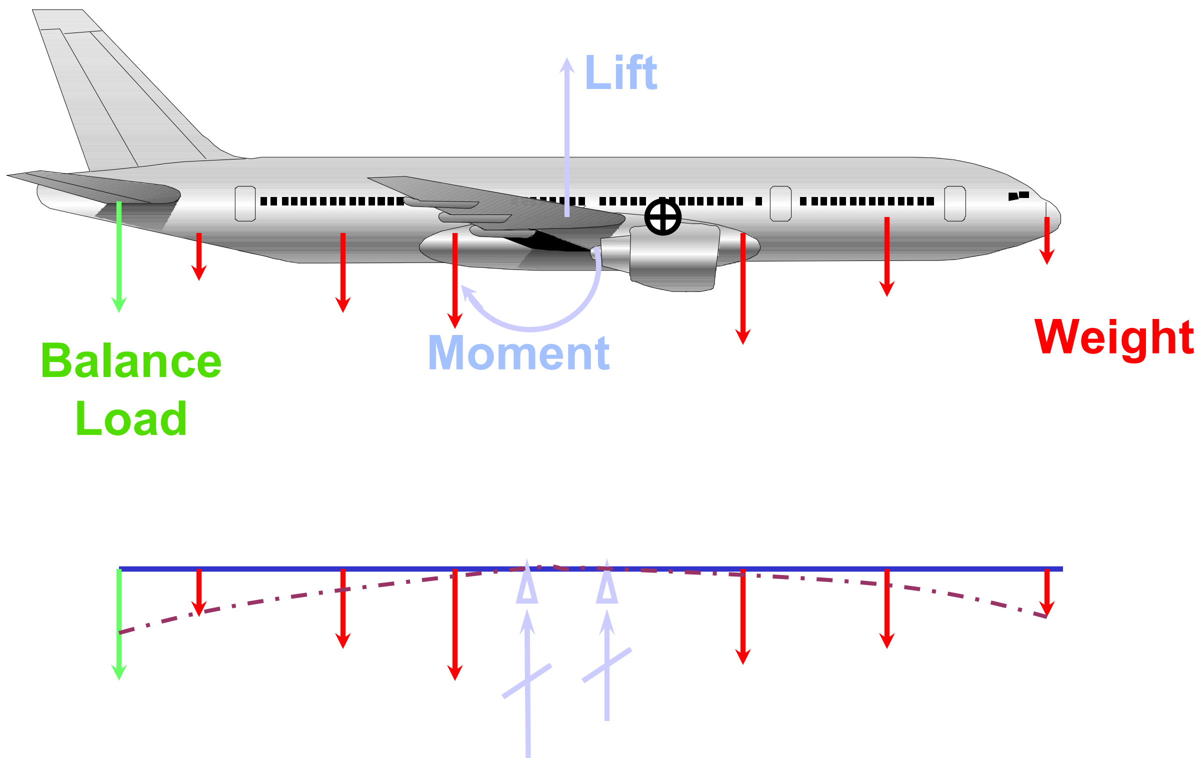
- **Consider all load conditions and requirements**
- **Develop a static load balance for each critical condition**
  - **Apply loads realistically**
  - **Determine where they are going to be balanced**
- **Cut sections to determine local internal loads**
- **Provide a path for the loads to follow (Load will follow stiffest path!)**

Do this for local loads as well as for general vehicle loads

Note: Most members serve more than one function

Let’s Treat the Aircraft as an Assembly of Beams

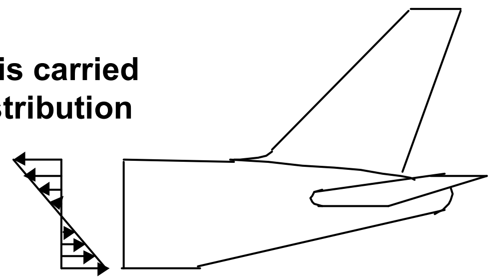
- We can idealize the fuselage as a beam, e.g.:



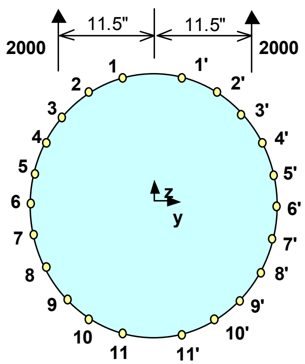
Internal Loads/Load Paths - Fuselage

Consider fuselage to act as a beam

Bending moment is carried based on Mc/I distribution

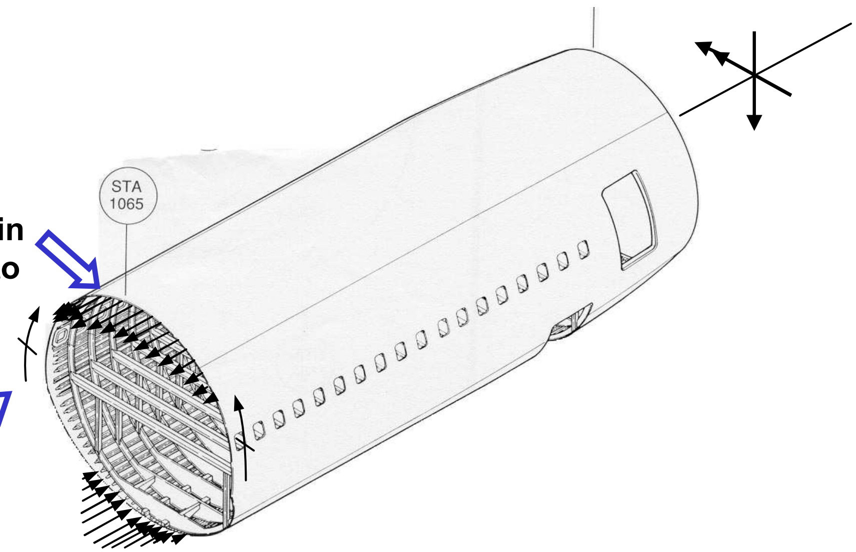


For a downward tail load, body will carry a shear and a bending moment

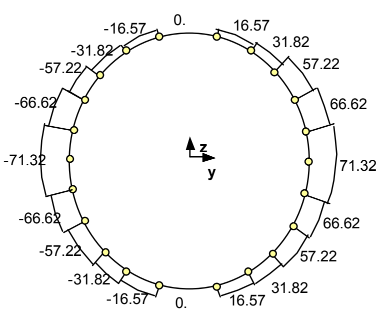


Crown longerons and skin carry tension loads due to bending moment

Skins carry shear load in-plane with VQ/I distribution

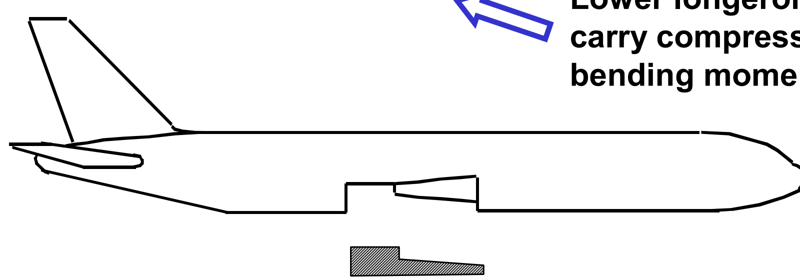


Bruhn Section 21.12 (Fig A21.62)



Bruhn Figure A21.62

Lower longerons (with effective skin) carry compression axial loads due to bending moment



Keel Beam added to restore load path on lower surface (wing carry through and wheel well areas)

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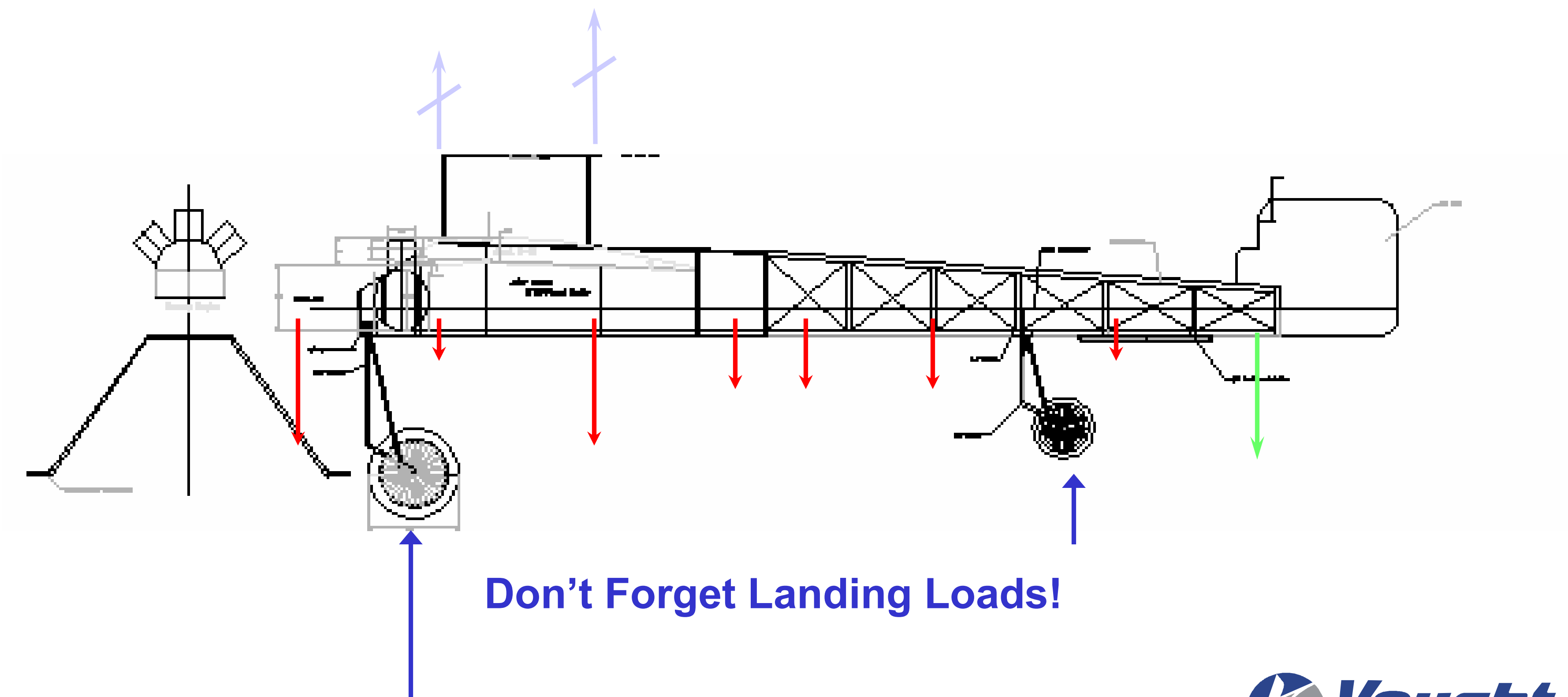
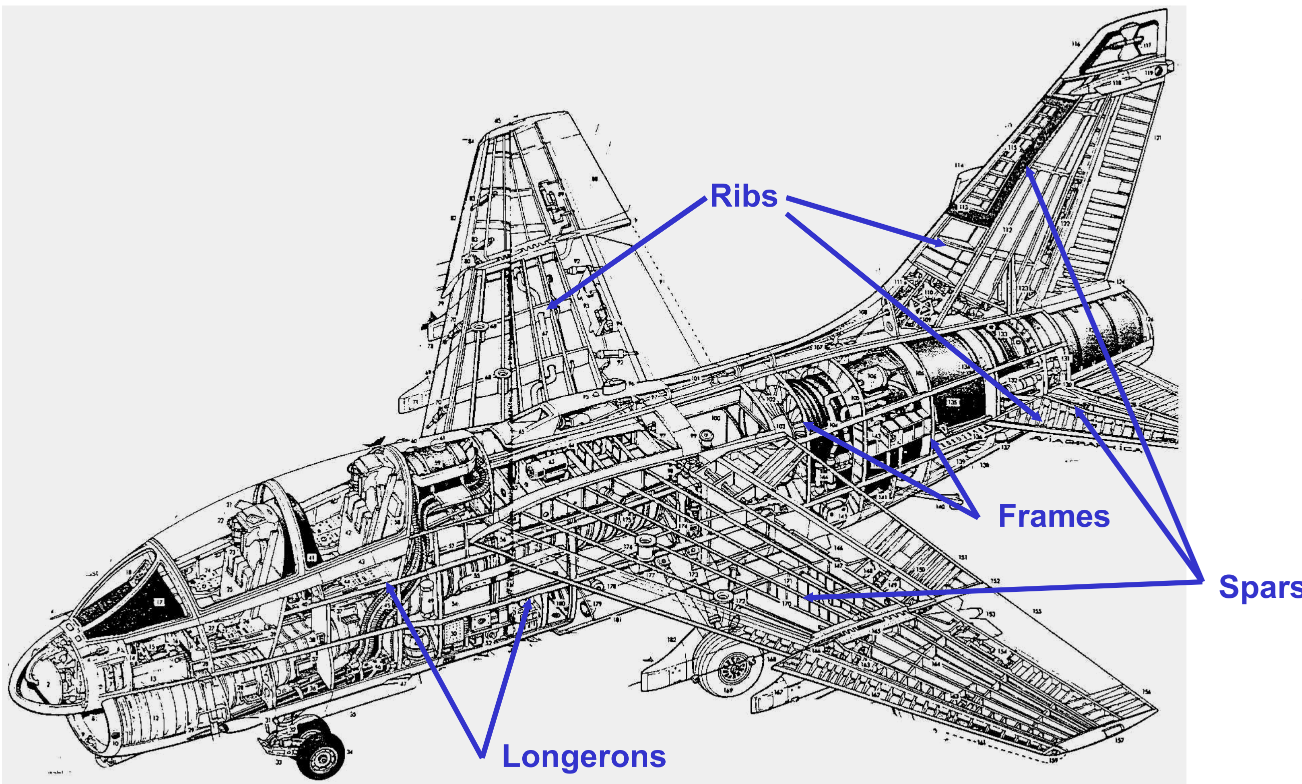
Trusses Work Well as Light Weight Beams

- Wires, Fabric, Thin Sheet Metal or Composite Webs
- Wood, Metal, or Composite Axial Members



Internal Loads/Load Paths

- Primary Structural Components are fuselage, wing, and tail (horizontal and vertical stabilizers)
- Fuselage consists of skins, longerons, and frames
- Wing and Stabilizers consist of covers, spars, and ribs

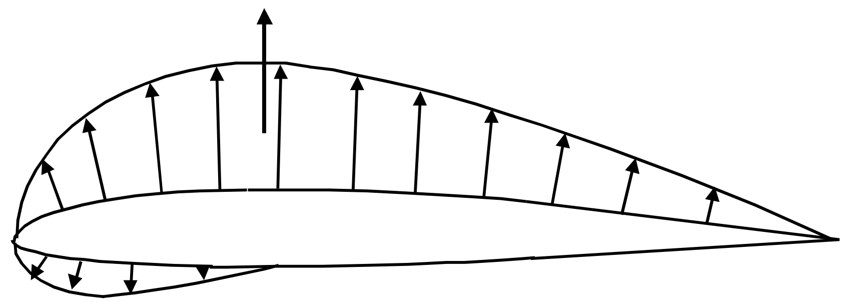


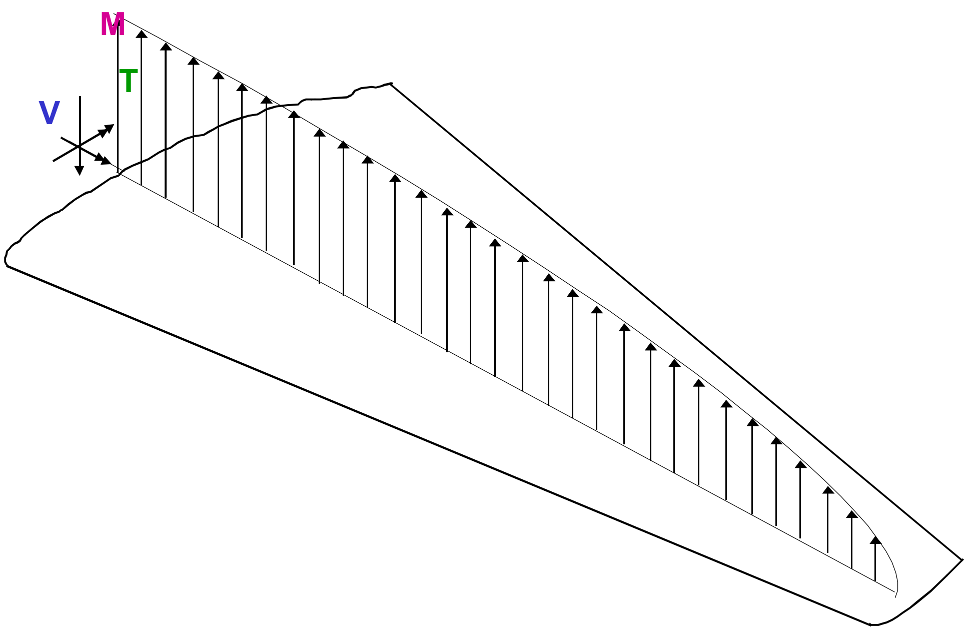
What do these members do?

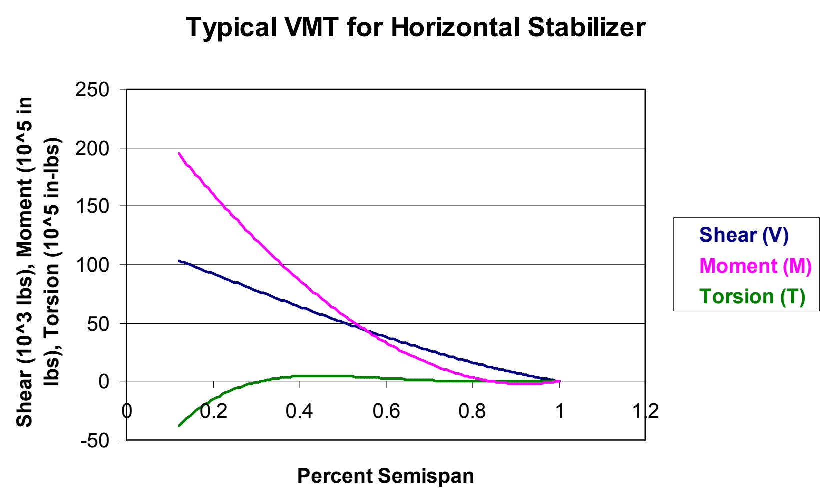
Internal Loads/Load Paths - Wing/Stabilizer

Idealize Wing as a Beam:

Loaded by distributed pressure. Shear (Lift, “V”), Moment (Lift * Arm, “M”), and Torsion (Pitching Moment, “T”) (all about elastic axis) are beamed to fuselage and balance tail load, inertia, and other side wing load.







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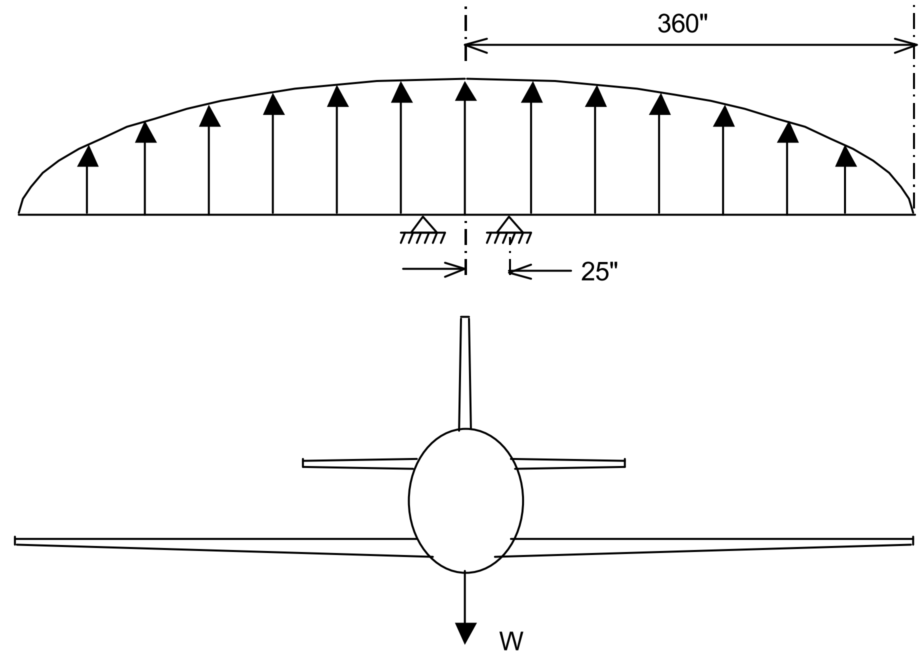
External Loads and Reactions

Example:

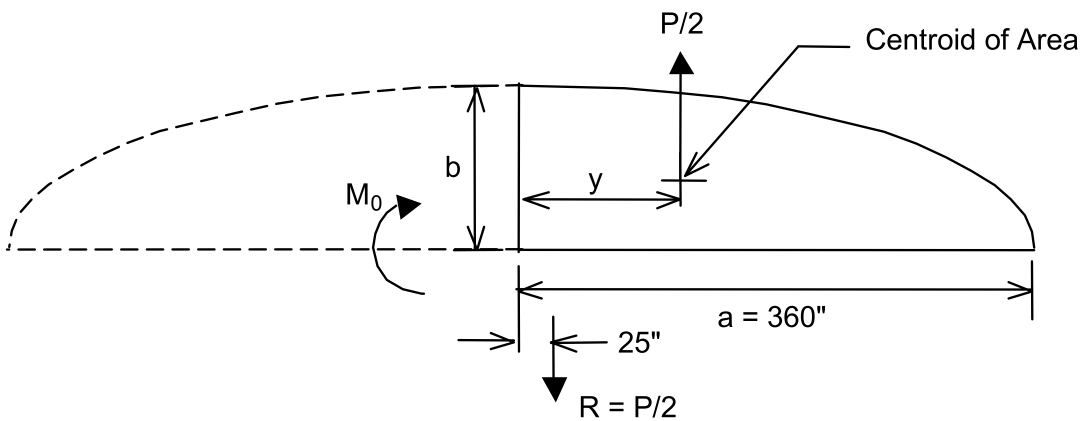
- **Continuous Wing**
- **Assume all Weight and Inertia Supported at Wing Elastic Axis (No Tail Loads)**
- **Elliptical Distribution**
- **W = 40,000 lbs**
- **Load Factor = 6g's**



Determine:

- **Maximum Ultimate Bending Moment**
- **Ultimate Support Loads at Fuselage attach Points**

External Loads and Reactions



Quarter Ellipse Properties:
A =Area = 0.7854 ab
y = 0.4244a

Total Wing Force (Ultimate):
P = 40,000 lbs (6g)(1.5) = 360,000 lbs

Each Fuselage Attach Must Resist ½ of the Total Load:
R = 360,000 lbs/2 = 180,000 lbs

Moment at BL 0.0 is
M_0 = P/2 * y – R * 25" = 180,000 lbs * [0.4244*(360")] – 180,000 lbs (25")
= 20.0E+06 in-lbs

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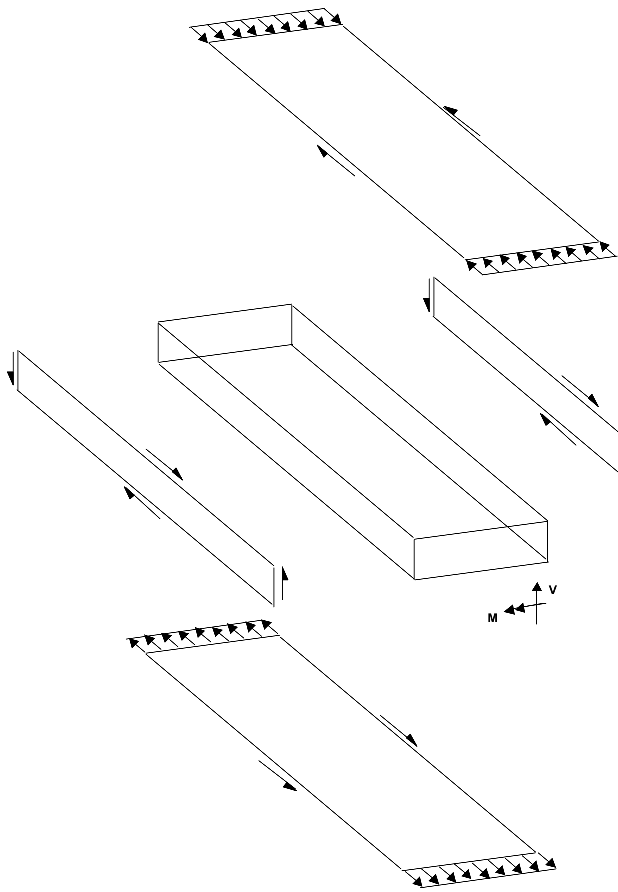
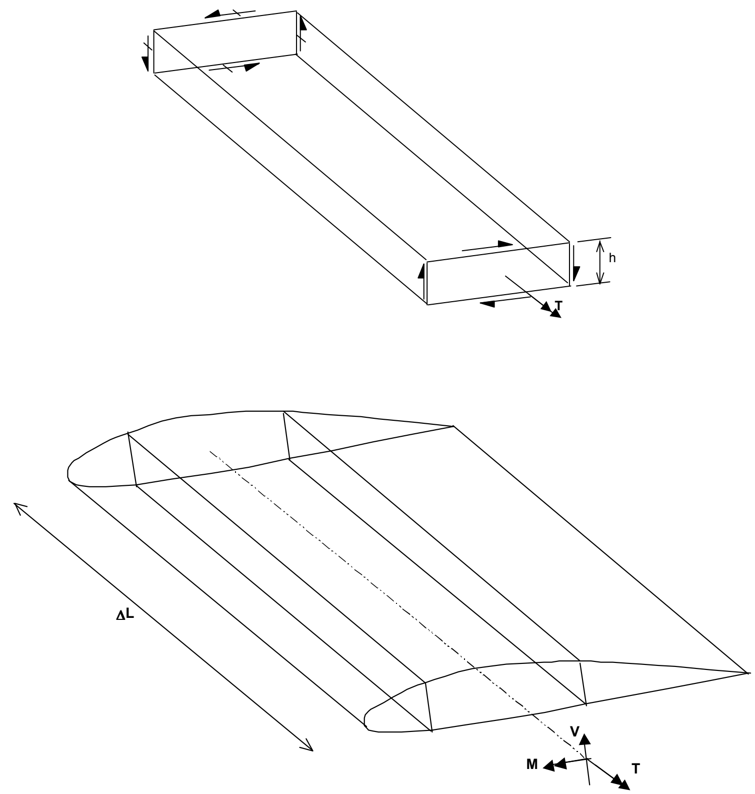
Internal Loads/Load Paths - Wing/Stabilizer

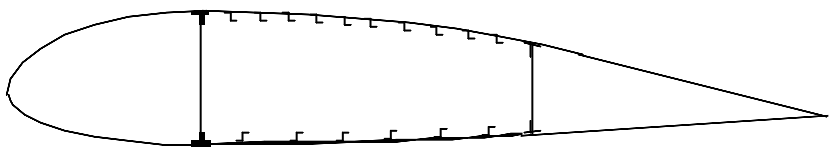
- Covers and Spar Webs form a Closed Box to Resist Torsion
- Shear Carried Primarily by Spar Webs
- Bending Carried Primarily by Covers or Cover Stringers with Effective Skin



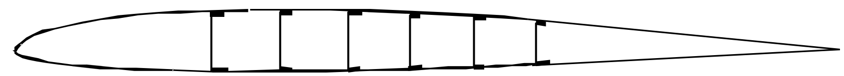


Internal Loads/Load Paths - Wing/Stabilizer

Main Types of Wing Primary Structure



Thin Skin (many stringers and ribs)



Thick Skin (many spars, few ribs)

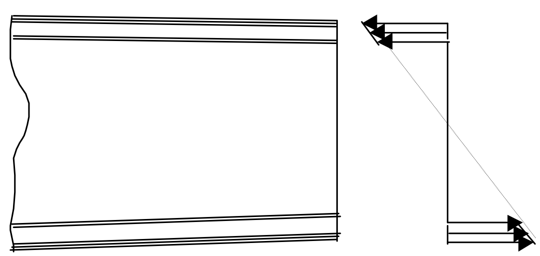
Transports & Bombers

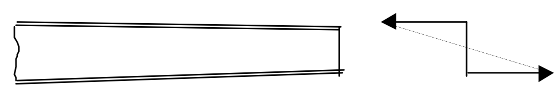
- **Deep Sections**
- **Skin Supported by Stringers Carries Bending Moments**

Fighters

- **Thin Sections**
- **Unstiffened Skins**
- **Skin and Spar Chords Carry Bending Moment**

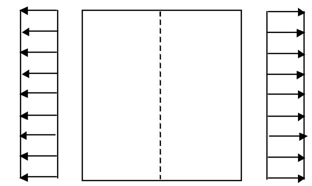
Section Bending Moments





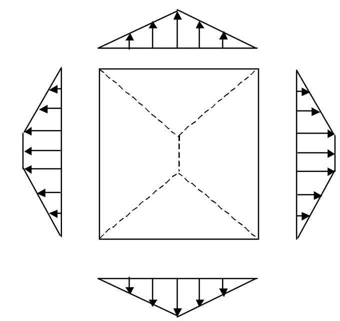
Stringers would not be efficient

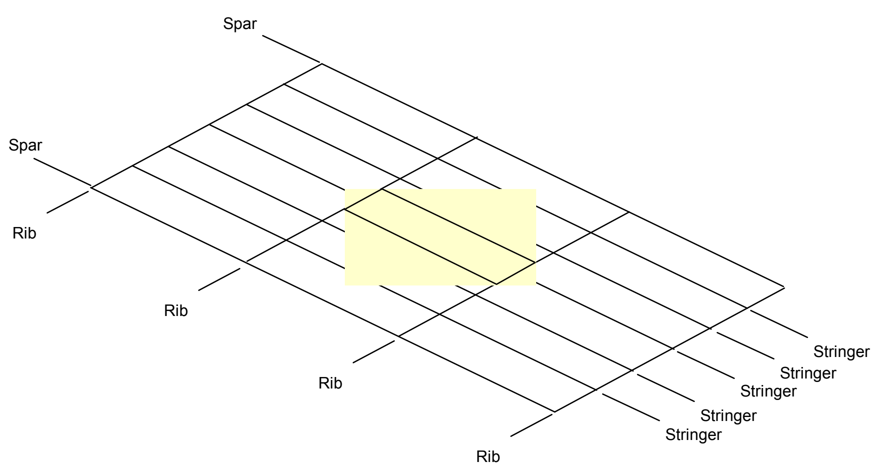
Internal Loads/Load Paths - Wing/Stabilizer

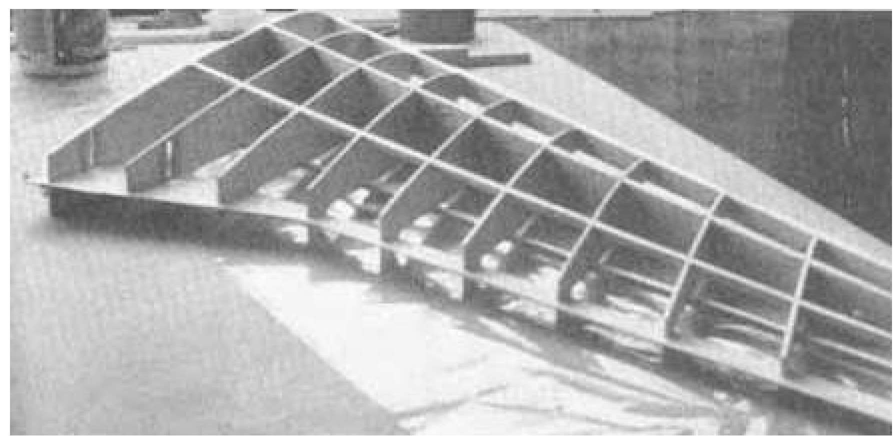


Pressures

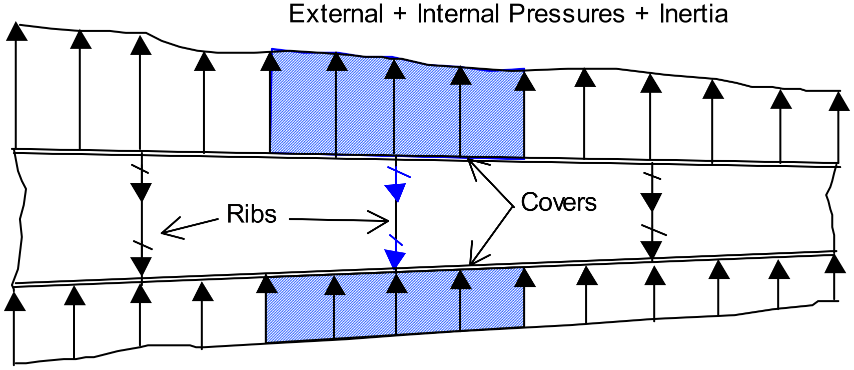
- **Plate Will Beam Pressure to Peripheral Supports**
- **Typically Assume All Load Beams to Sides or Assume Load Pillows to All Sides (Both Maintain Static Equilibrium)**



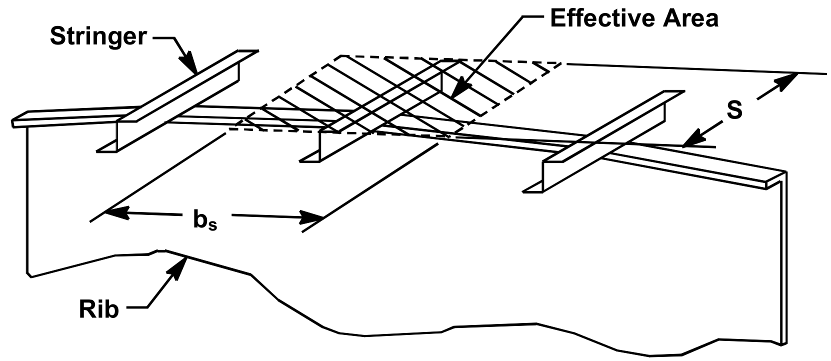




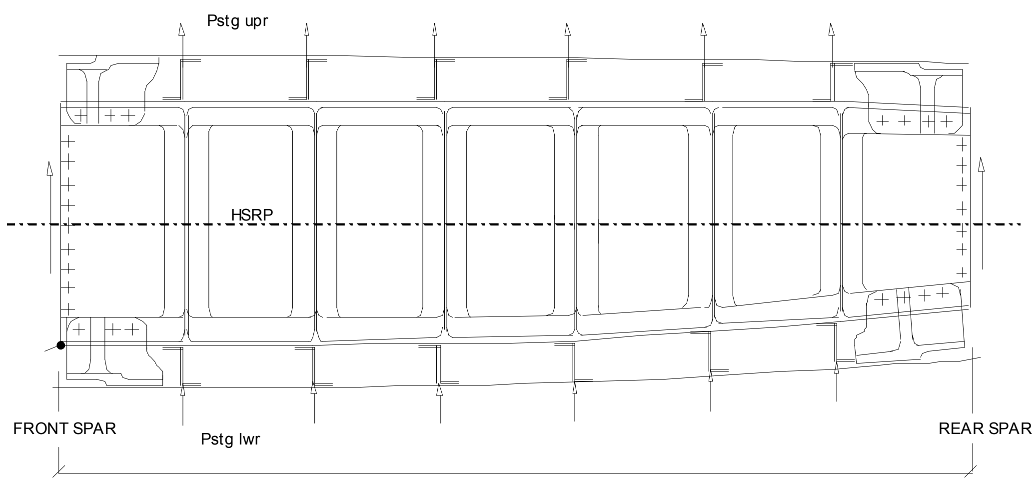
Internal Loads/Load Paths - Wing/Stabilizer



Pressure + Inertia Loads



Effective Area for Pressure Loads
s = rib spacing
b_s = stringer spacing



Ribs will Gather Loads and Beam to Spars

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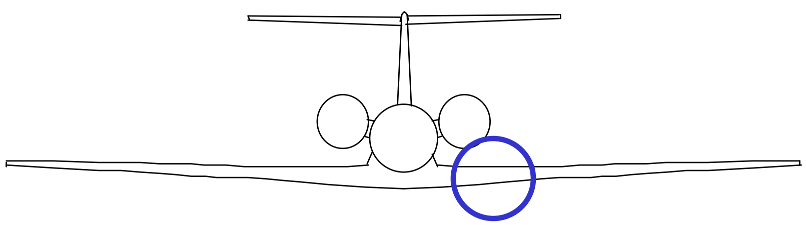
Internal Loads/Load Paths - Wing/Stabilizer

Built-In Curvature Loads

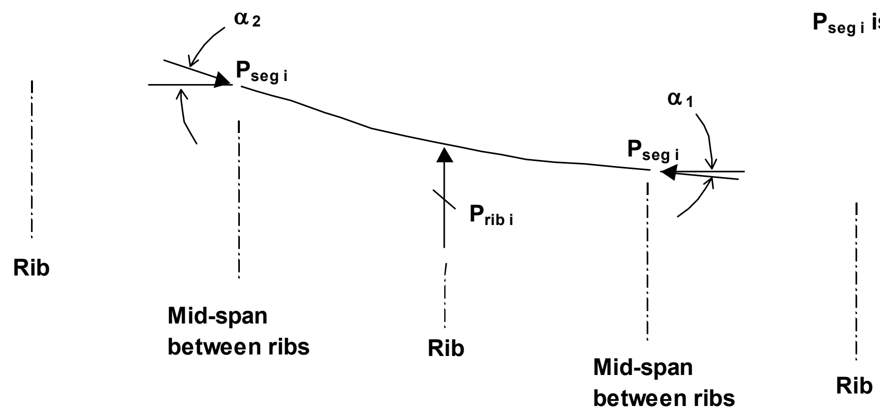
- Gathered by Ribs and Beamed to Spars

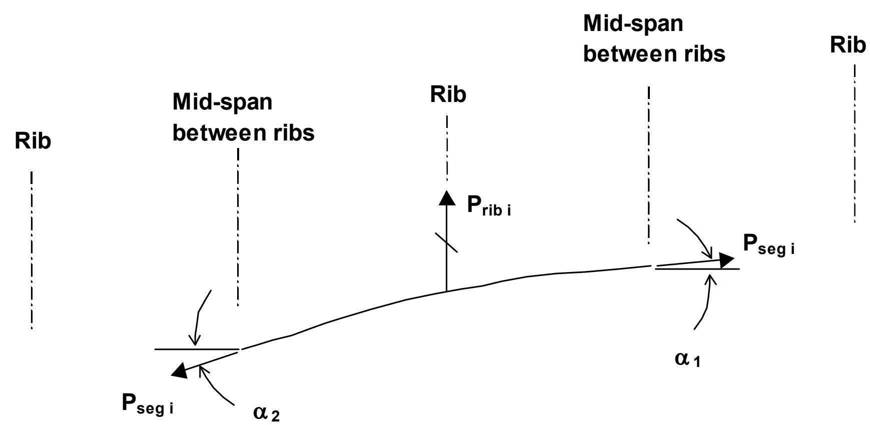


$P_{rib\ i} = P_{seg\ i} * (\sin\alpha_2 - \sin\alpha_1)_i$

α_1, α_2 are the "as built" angles

$P_{seg\ i}$ is load at rib_i





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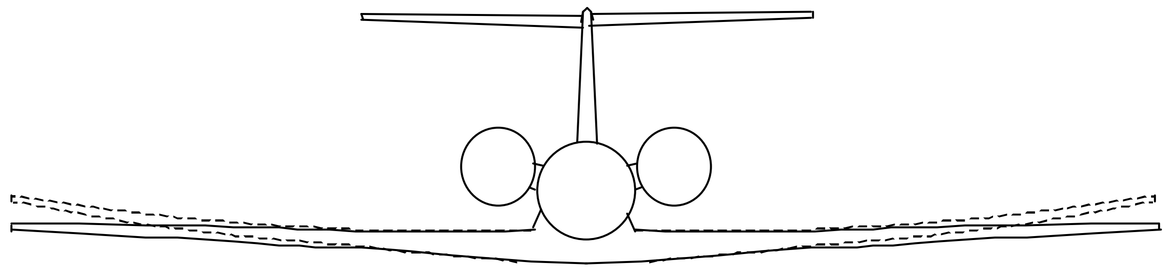
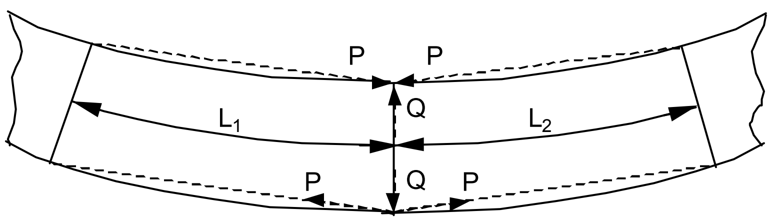
Internal Loads/Load Paths - Wing/Stabilizer

Crushing Loads due to Wing Deflections (Brazier Loading)

- **Reacted by Ribs**
- **Self Balancing (Do not Beam to Spars)**
- **Loads are Non-Linear**



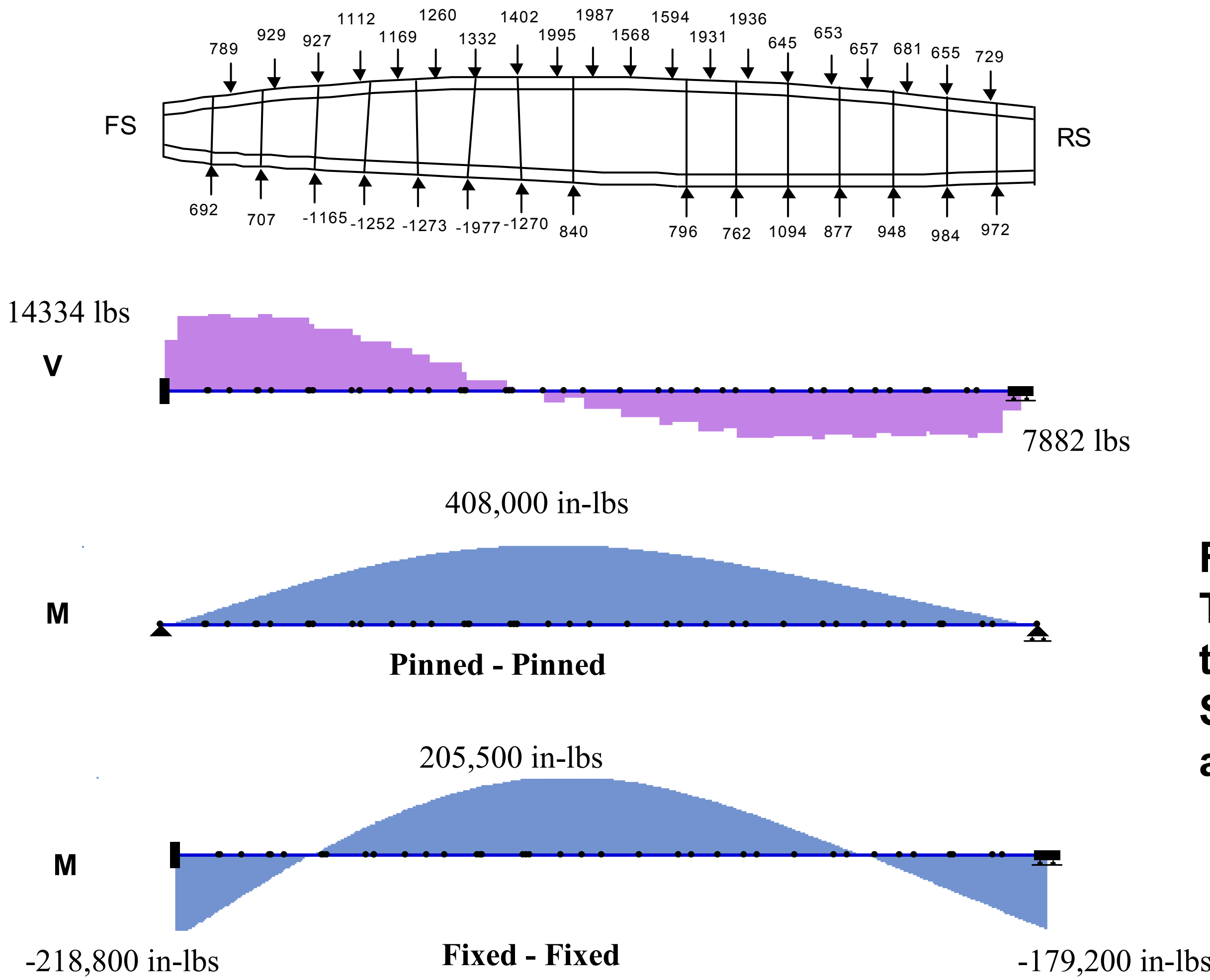


$$Q = \frac{PM}{EI}\,\frac{(L_1 + L_2)}{2}$$

Crushing Loads on a Rib

Internal Loads/Load Paths - Wing/Stabilizer

External Pressure and Curvature Loads are Beamed to Ribs



Fixity is Not Known. Typical Approach to Assume Both Simply Supported and Fully Fixed

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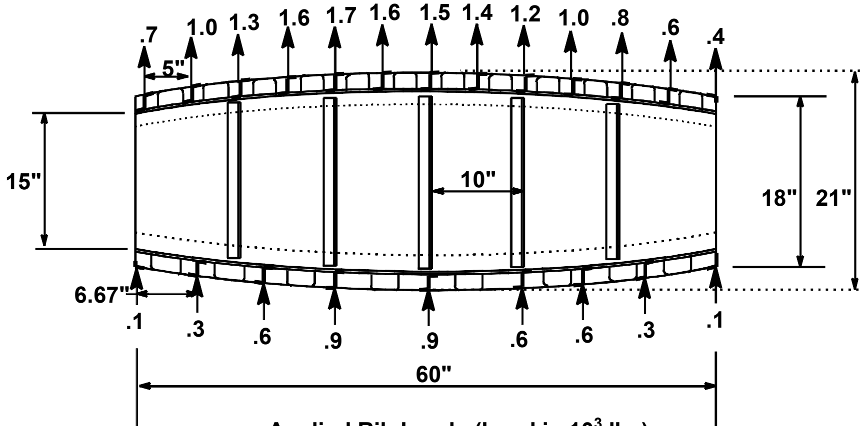
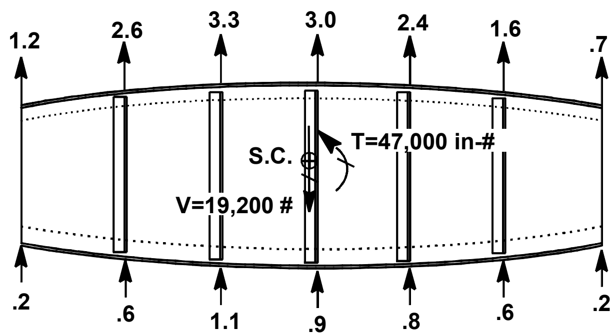
Internal Loads/Load Paths - Wing/Stabilizer

Internal + External Pressure, Inertia, Curvature, and Crushing Loads

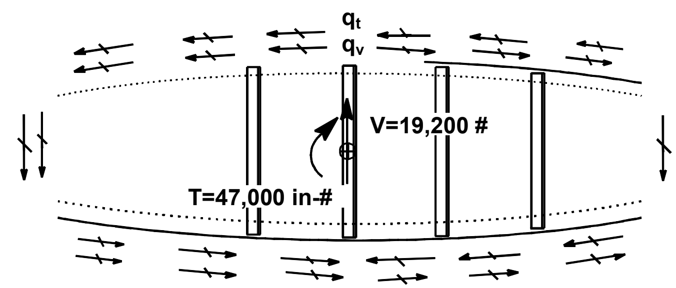


a. Applied Rib Loads (Load in 10^3 lbs)

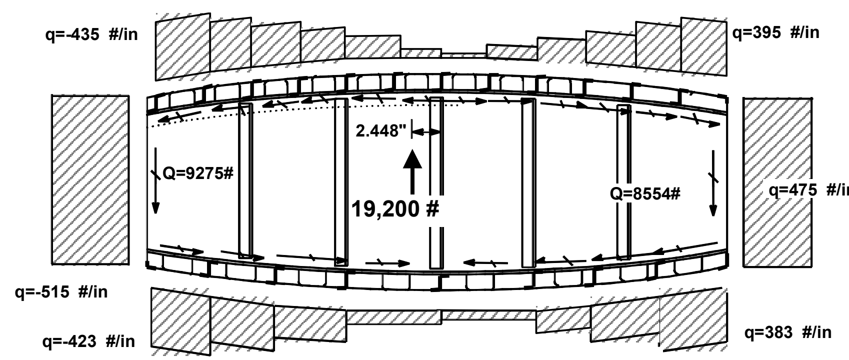


b. Loads Resolved to Stiffeners and Reacted at Shear Center

Ribs redistribute pressure and inertia loads into cellular box structure.



Loads at Shear Center Balanced by Shear Flows



Calculated Shear Flow Balance - Stiffened Skin

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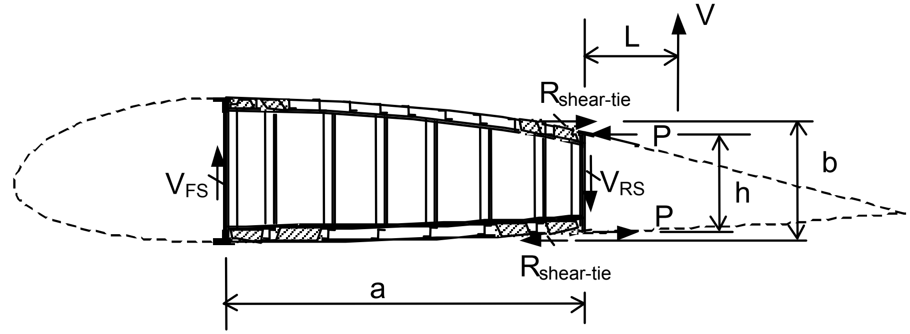
Internal Loads/Load Paths - Wing/Stabilizer

Trailing Edge and Control Surface Shear and Moment



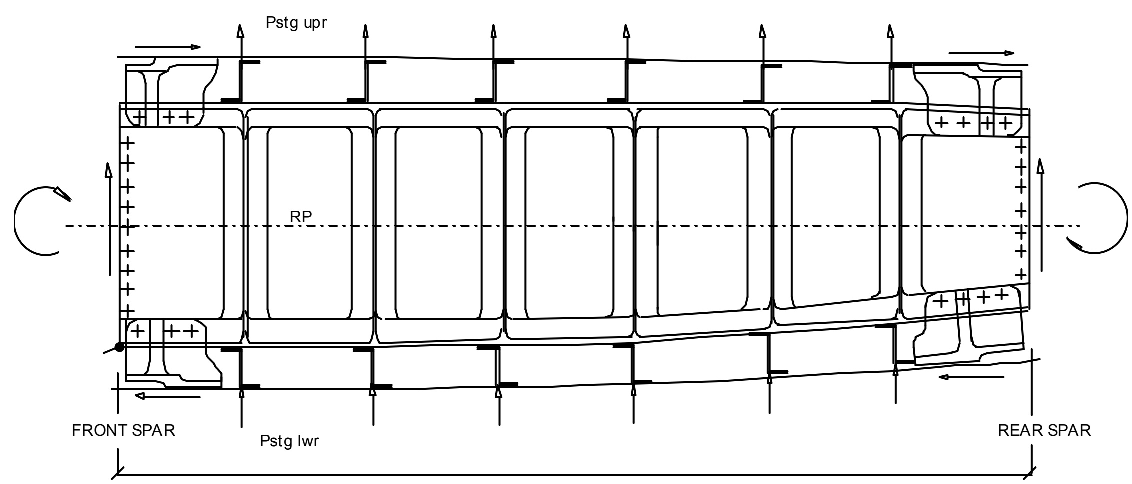
$P = VL/h$

$R_{shear\text{-}tie} = Ph/b$

$V_{FS} = -R_{shear\text{-}tie}\ b/a$

$V_{RS} = V + V_{FS}$

Leading Edge and Trailing Edge Moments Balanced into Box by Ribs



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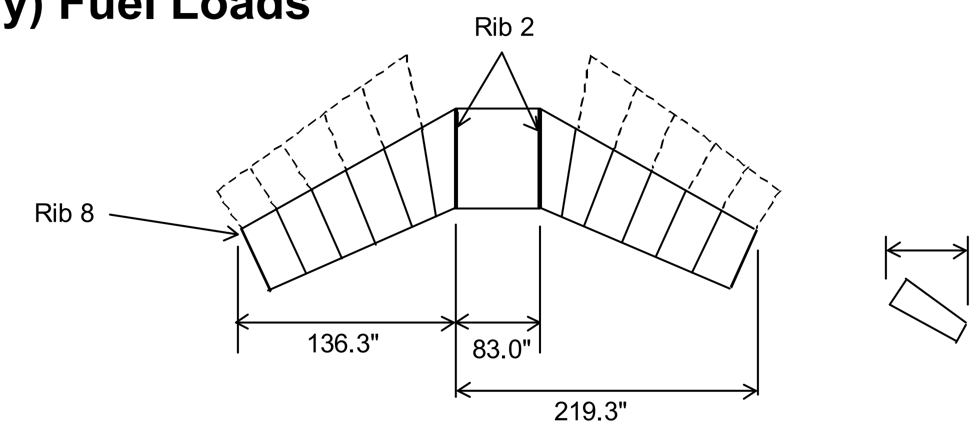
Internal Loads/Load Paths - Wing/Stabilizer

Emergency Landing (Crashworthy) Fuel Loads

If the time 'T' for fuel to flow from the upstream side of the barrier to fill a volume of air defined in the 1g flight condition is greater that 0.5 second, the internal baffle can be considered to be a solid pressure barrier.

Conversely, an internal baffle may not be considered as a pressure boundary if the volume of air in the fuel cell downstream of the barrier is not adequate to meet the above criteria. In such cases, the pressures due to the hydrostatic fuel head must be calculated without consideration of this internal baffle.

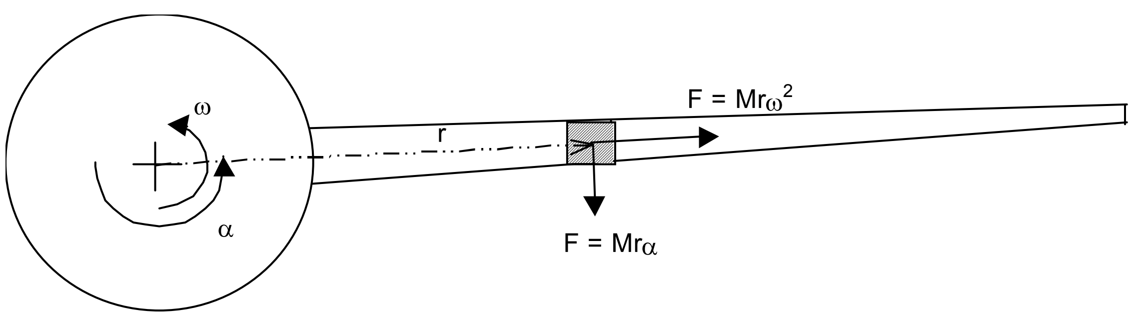


P = 0.34 * K * L (6.5 pound/gallon fuel density)

Where: P = design pressure at location 'a'; L = reference distance, feet, between the point of pressure and the farthest tank boundary in the direction of loading; K is defined in the table.

Loading Condition	K
Forward	9
Aft	1.5
Inboard	1.5
Outboard	1.5
Downward	6
Upward	3

Fuel Loading - Roll Rate



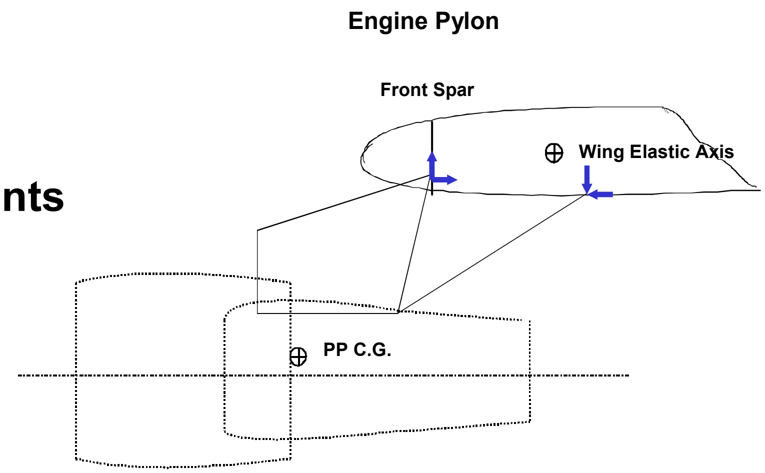
α = angular acceleration
ω = angular velocity

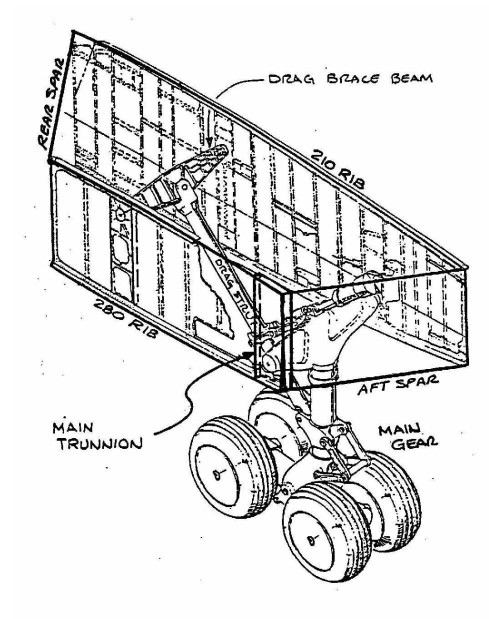
Internal Loads/Load Paths - Wing/Stabilizer

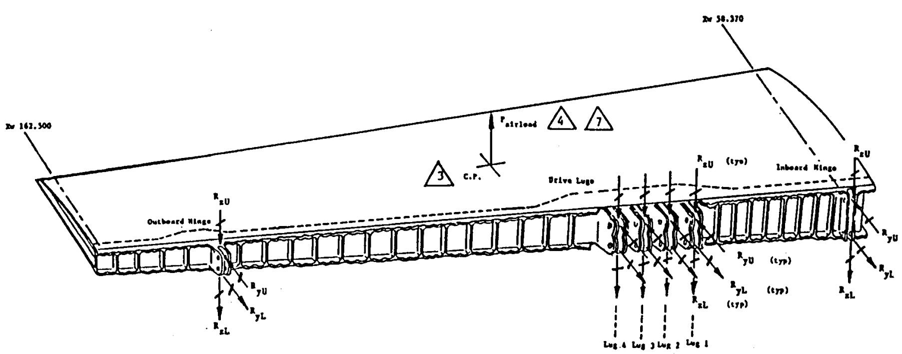
Ribs redistribute concentrated loads into cellular box structure.

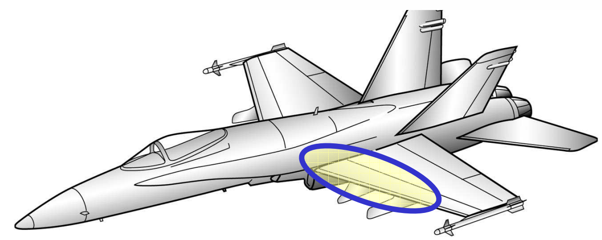
Concentrated Loads

- **Landing Gear**
- **Power Plant**
- **Fuselage Attachments**
- **Ailerons**
- **Flaps**
- **Ordnance**









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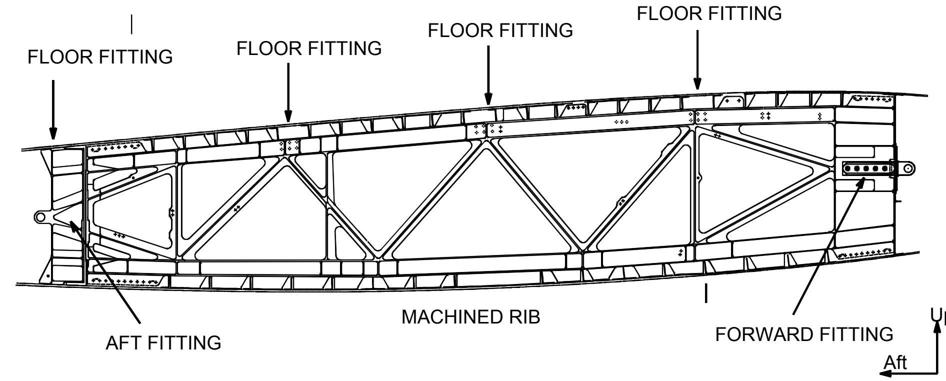
Internal Loads/Load Paths - Wing/Stabilizer

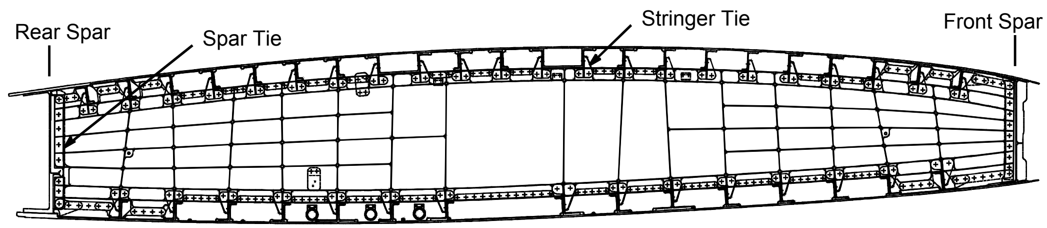
Ribs

- React and distribute air/fuel pressure loads
- React panel crushing loads
- React curvature loads
- Maintain wing/stabilizer chordwise contour
- Limit skin or skin/stringer column length
- React Local Concentrated Loads
  - Landing gear
  - Power plant
  - Fuselage attachments
  - Ailerons
  - Flaps
  - Ordnance
- May Act as Fuel Boundaries

Shear Tied Rib



Intermediate Rib



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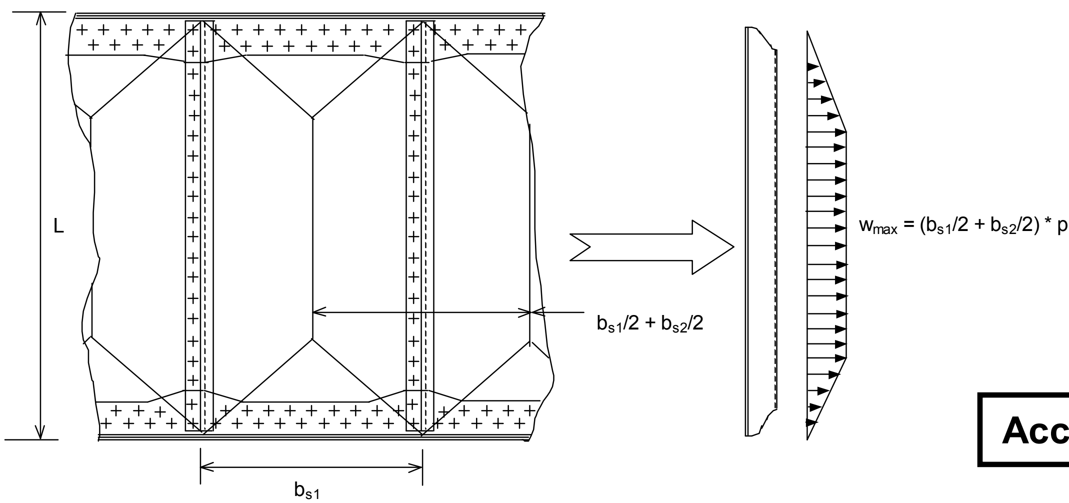
Internal Loads/Load Paths - Wing/Stabilizer

Spars are Primarily Shear Beams

- **Carry Wing Shear Loads**
- **With Covers, Carry Torsion**
- **React Local Concentrated Loads**
- **May Also Act as Fuel Boundaries**

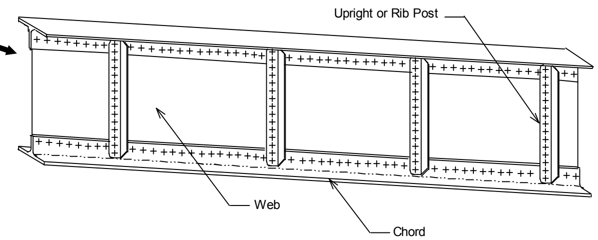
Exception to in-plane shear loading

Fuel Pressures



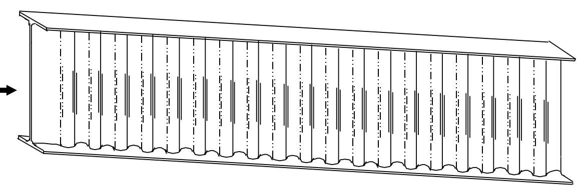
3 Basic Types of Spars

Fuel Loads
Bird Strike
Cost

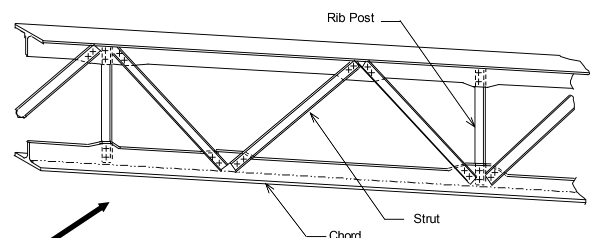


Stiffened Web

Thin Section
Fighter Wing



Sine wave



Access

Truss Beam

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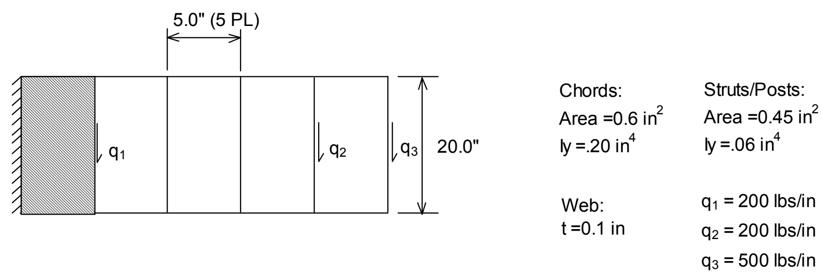
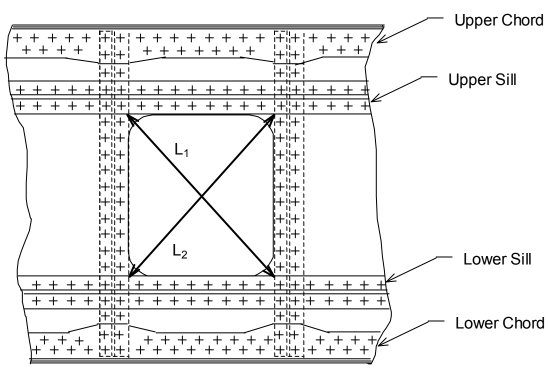
Internal Loads/Load Paths - Wing/Stabilizer

Web Type Spar

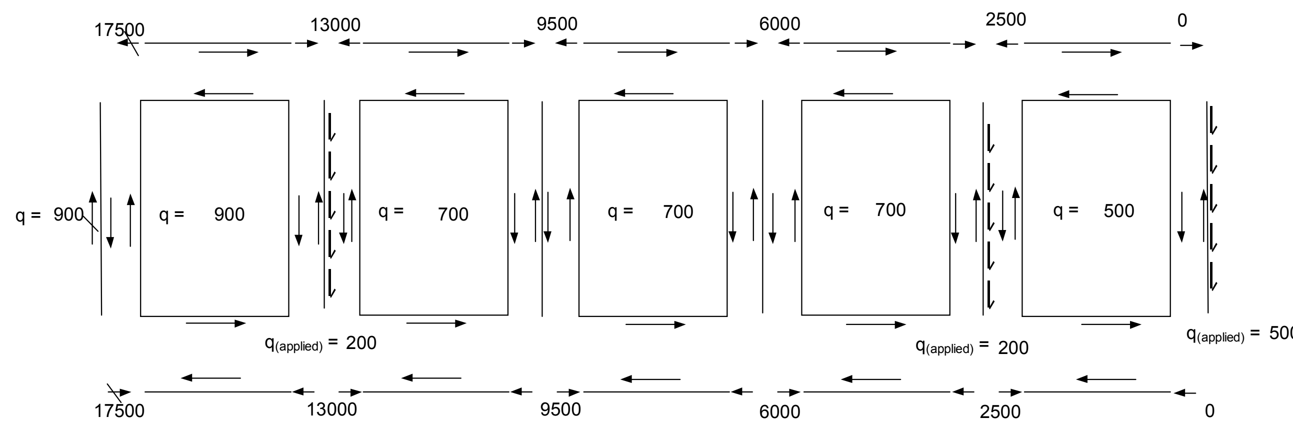
Most Common Type
(Usually Diagonal Tension)
Light Weight/Low Cost
Simple Internal Loads
Poor Access
Moderate to High Assembly Cost



Example Geometry and Applied Loads



Framed Out Access Hole



Web Type Spar

For a shear beam,
q = V/h (web shear flow)
P = M/h (chord load)
h = Distance between chord centroids

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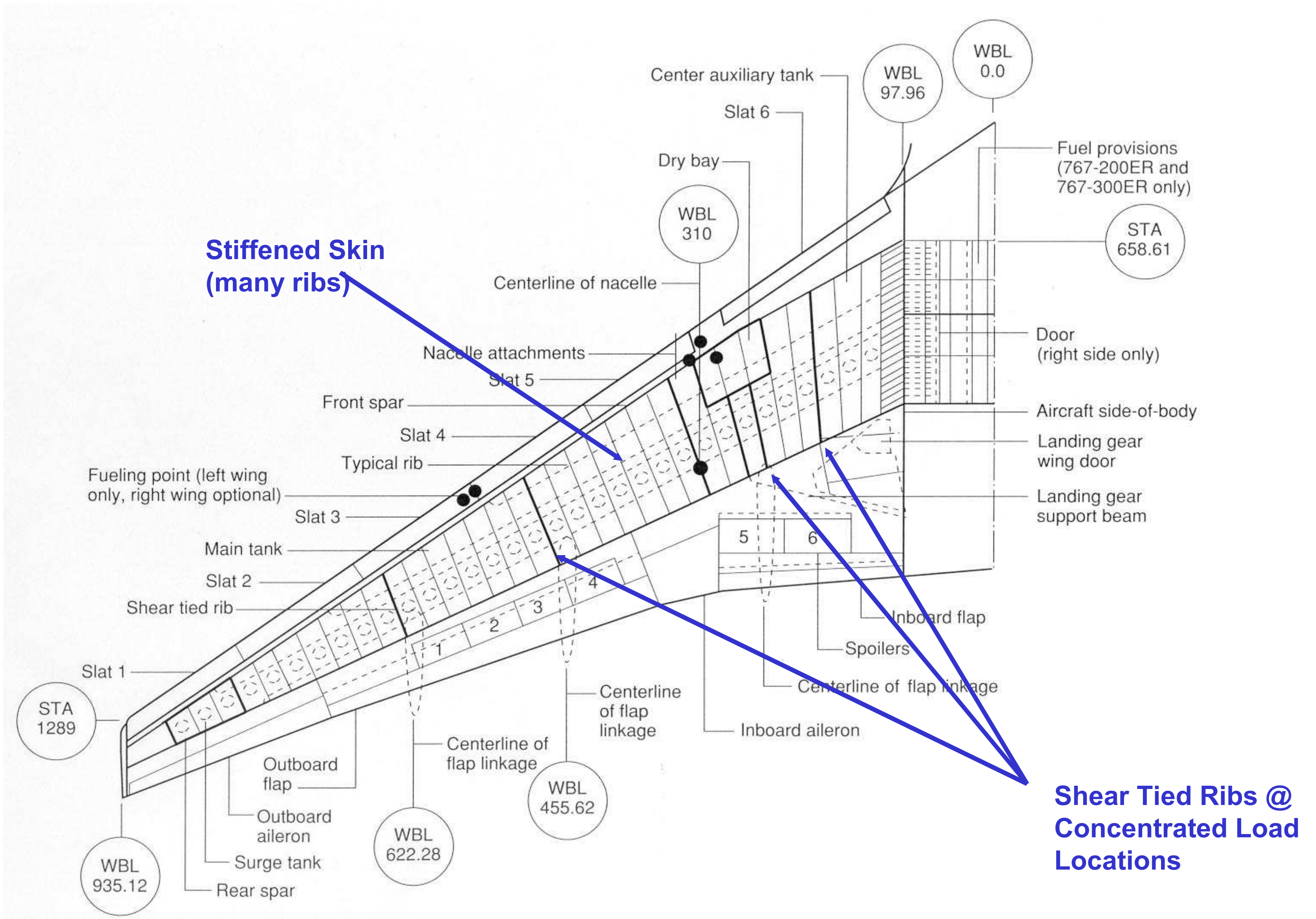
Internal Loads/Load Paths - Wing/Stabilizer



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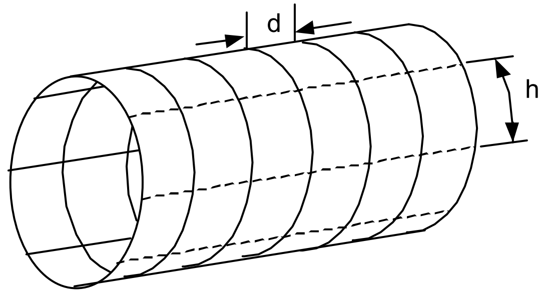
Internal Loads/Load Paths -Fuselage

Members and Load Paths in Fuselage have Wing/Stabilizer Counterparts

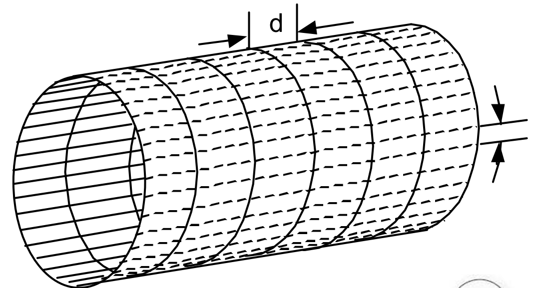
	Wing	Fuselage
Bending	Skins and Stringers	Skins and Stringers
Shear	Spar Webs	Skins
Torsion	Skins and Spar Webs	Skins
Concentrated Load Introduction	Ribs	Bulkheads
Hold Contour & Support Stringers	Ribs	Frames

Internal Loads/Load Paths - Fuselage

Crown Panel



Longeron System
d < h

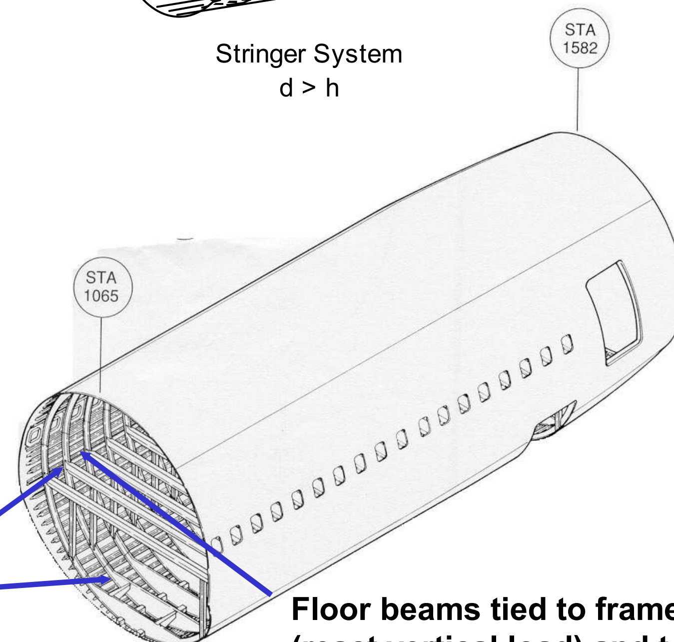


Stringer System
d > h

Longerons (stringers) carry axial loads

Skins carry shear, torsion and tension

Frames provided to reduce longeron column length



Frames also support cargo floor and passenger floor beams (react end loads into skins as shear)

Floor beams tied to frames (react vertical load) and to a longitudinal beam to react forward loads (landing and crash)

Seat rails run fore-aft and are supported by floor beams

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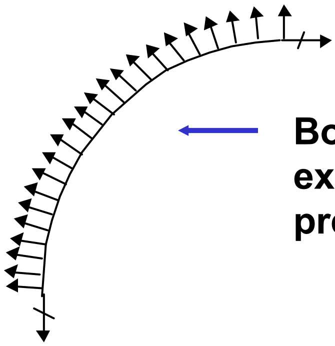
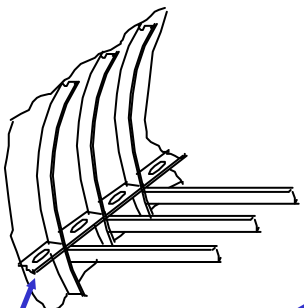
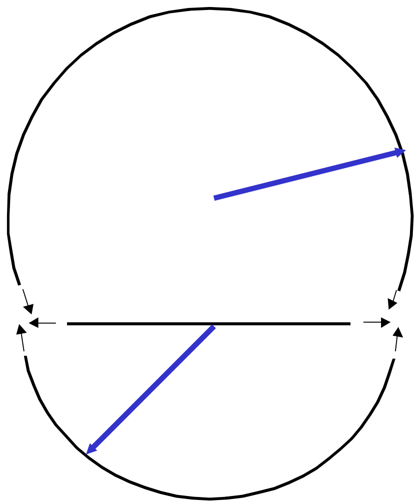
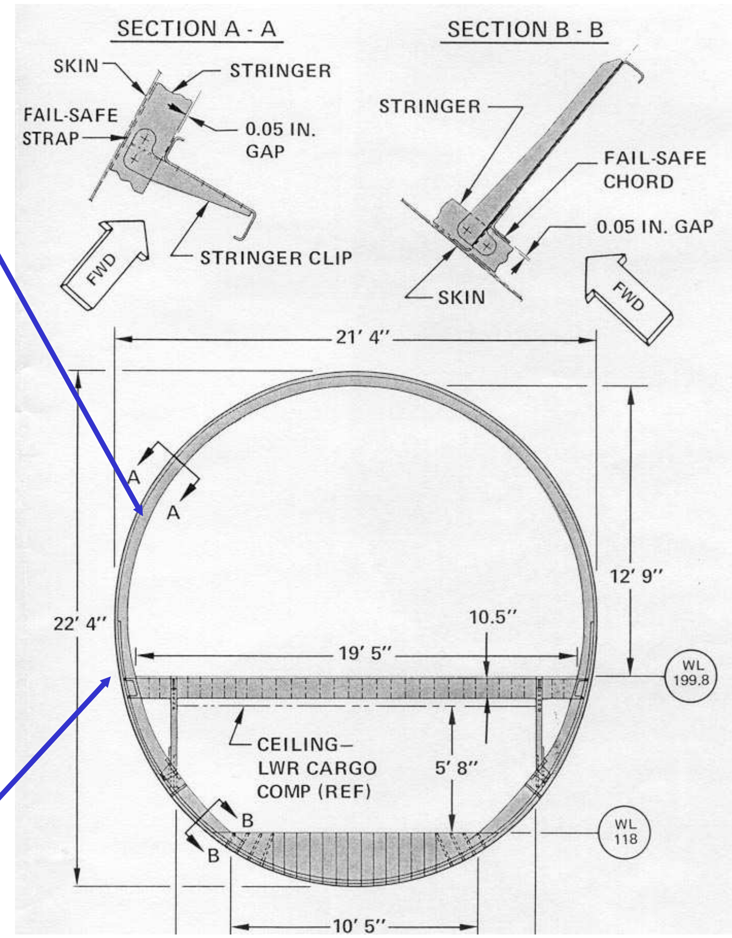
Internal Loads/Load Paths - Fuselage



Body skins also carry external and compartment pressures as a membrane.







For duel-lobe configurations, longitudinal beam (crease beam) and floor beams react out-of-plane load component at lobe intersection

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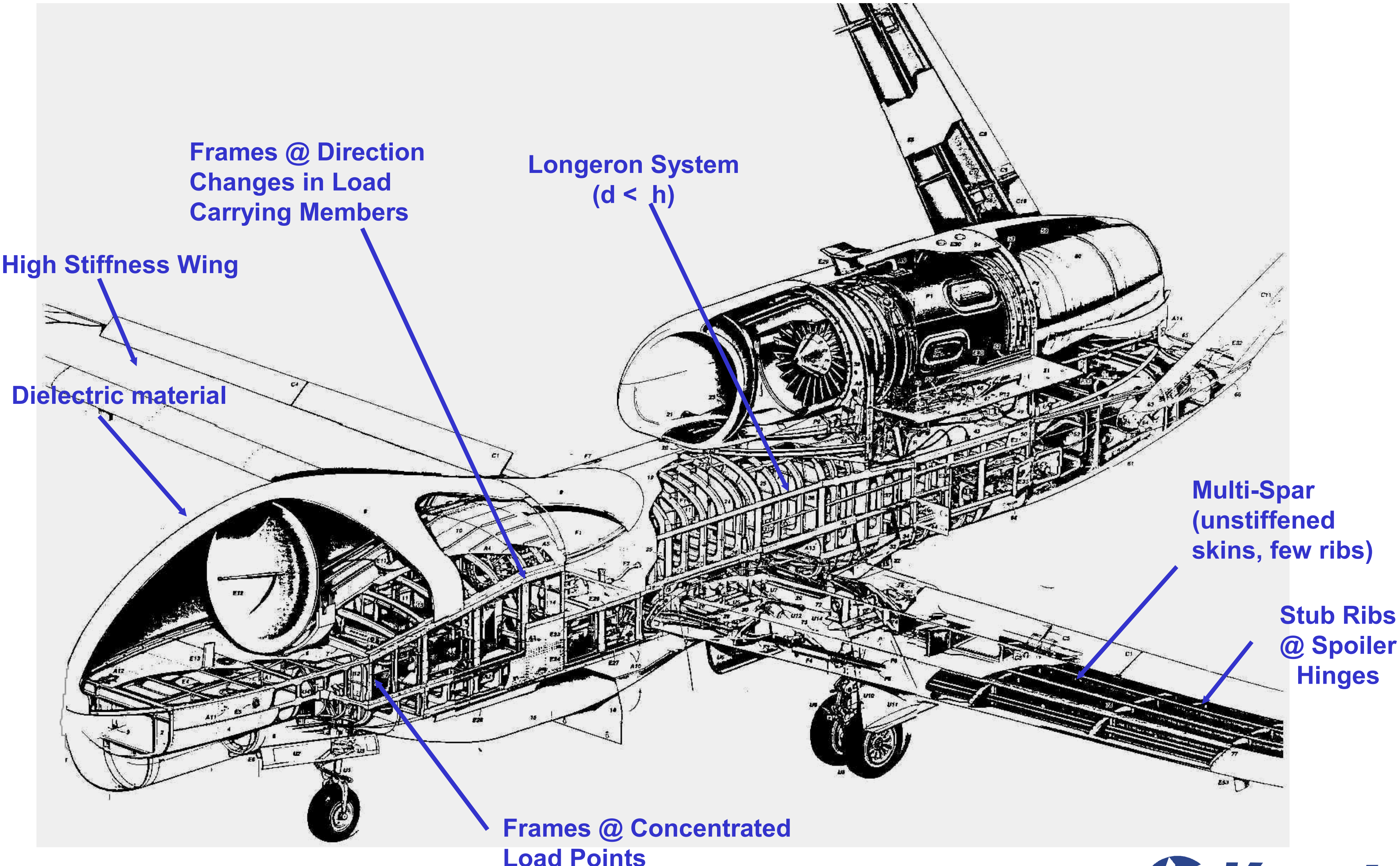
Internal Loads/Load Paths - Arrangement



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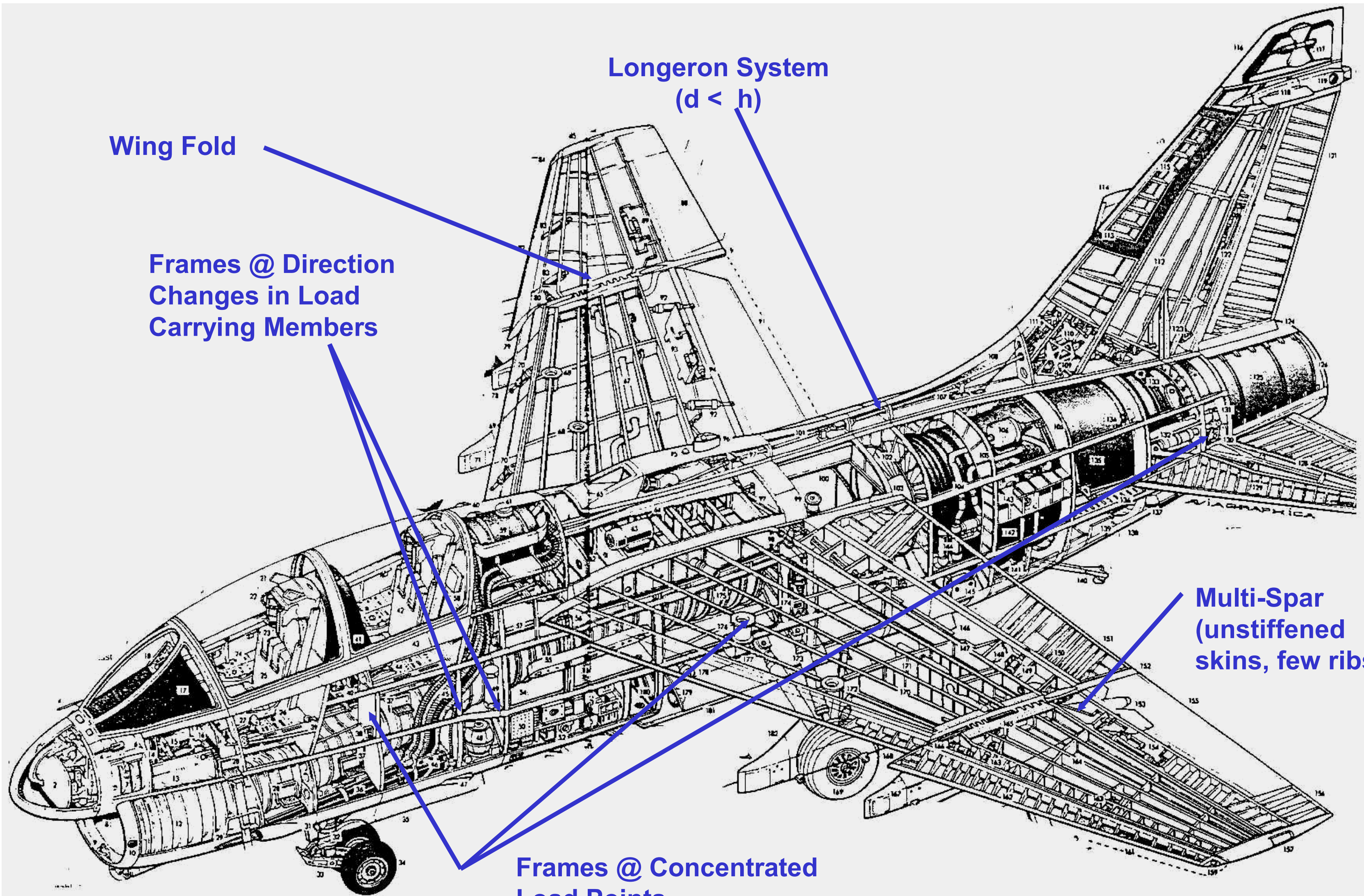
Internal Loads/Load Paths - Arrangement



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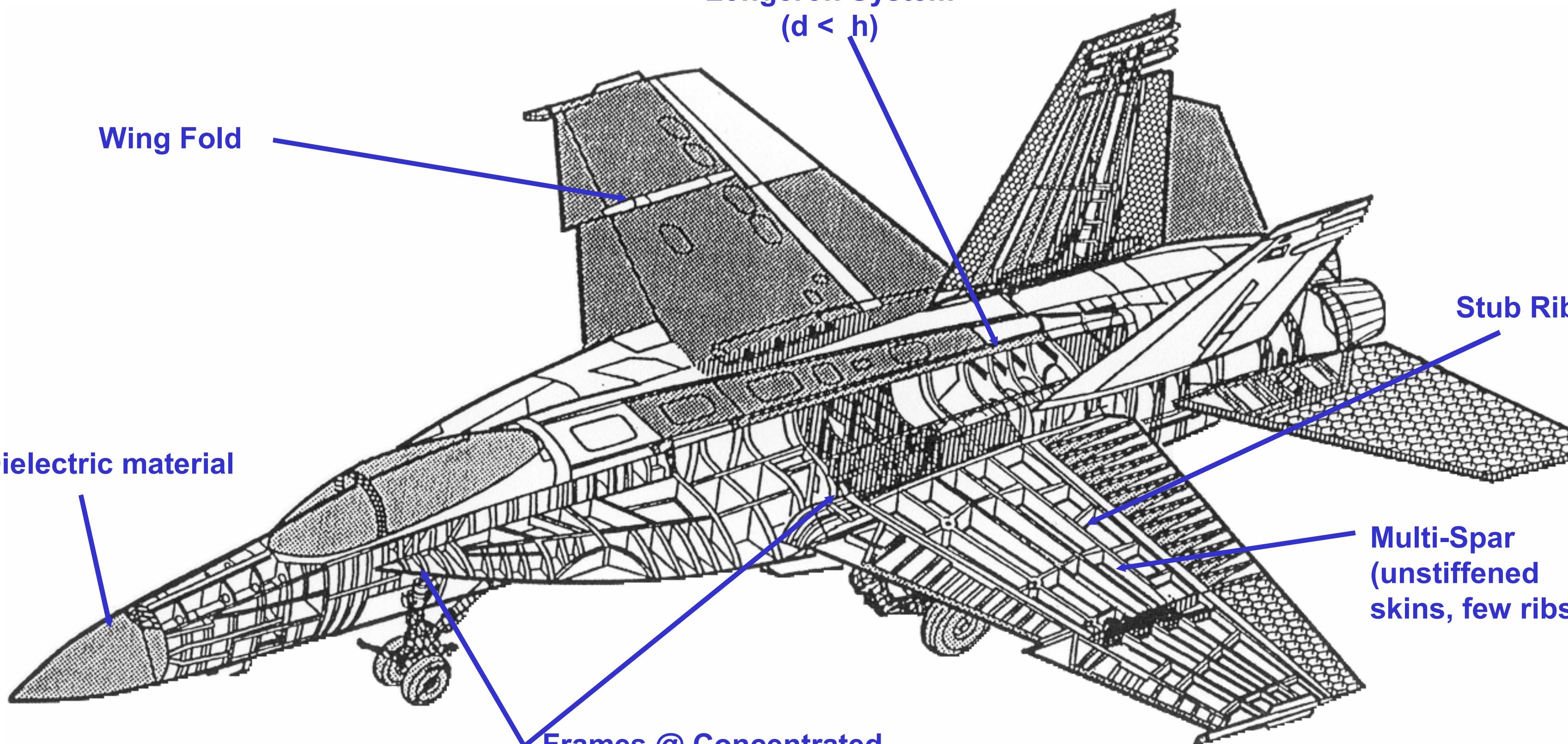
Internal Loads/Load Paths - Arrangement



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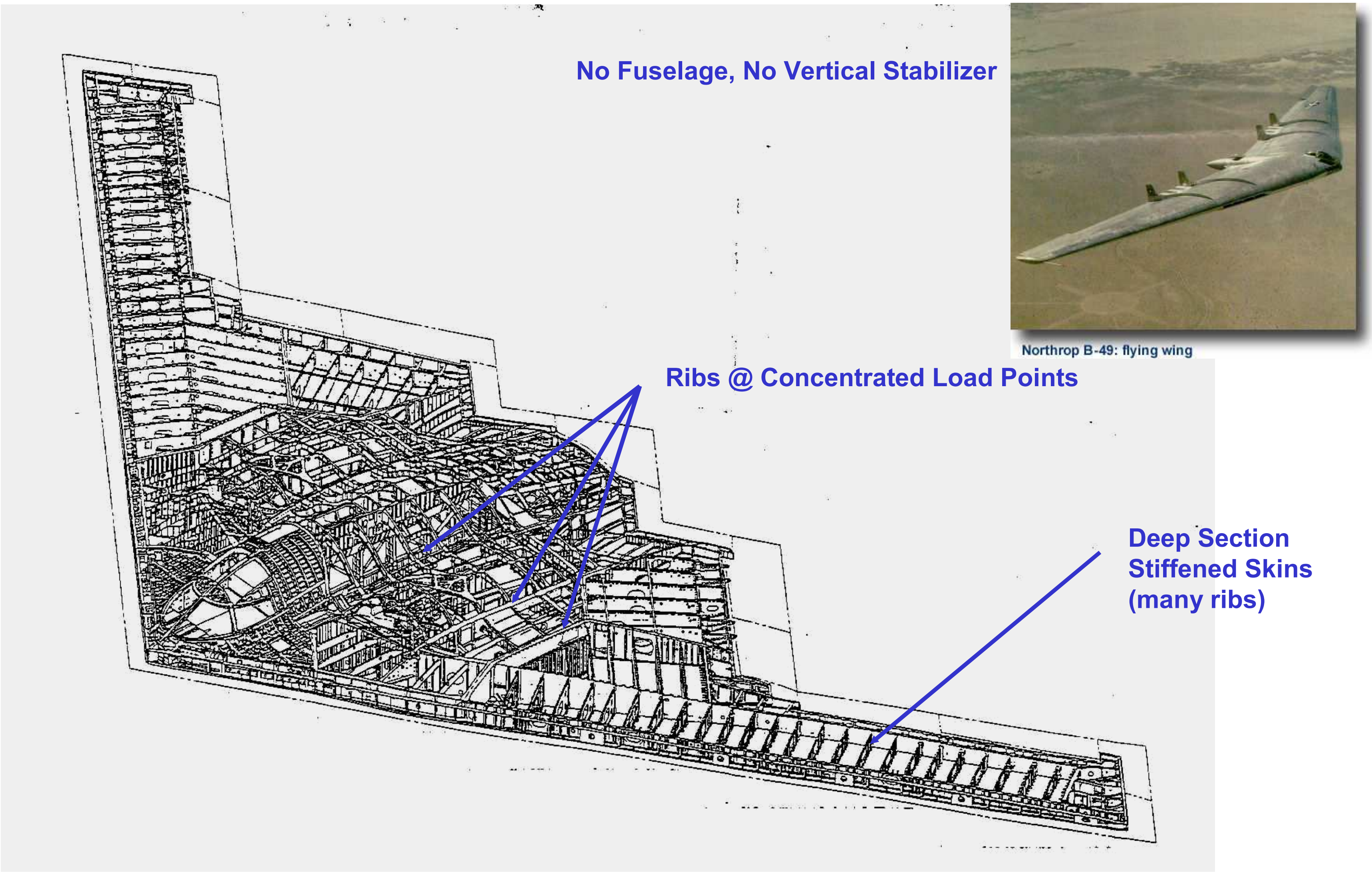
Internal Loads/Load Paths - Arrangement



Northrop B-49: flying wing

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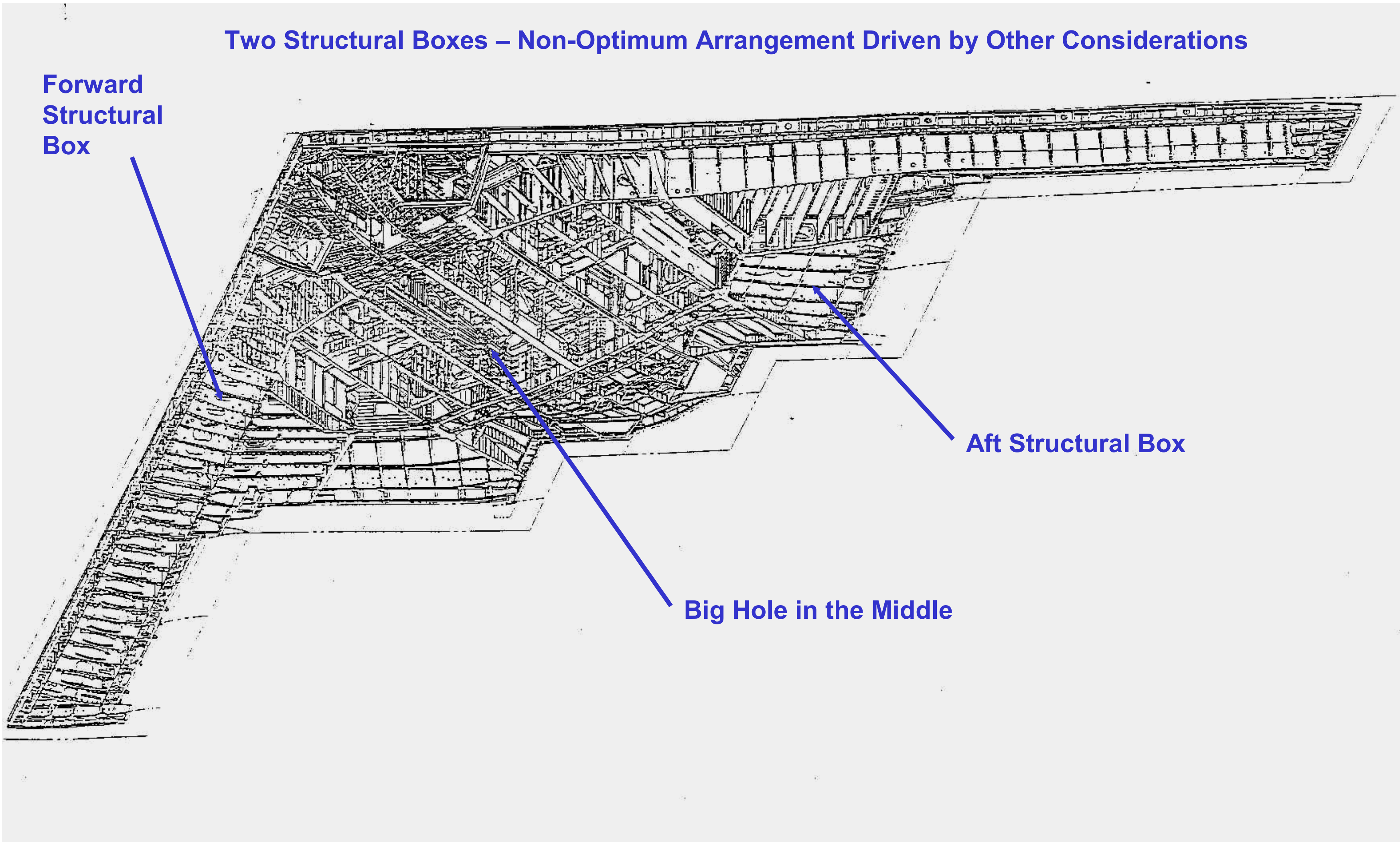
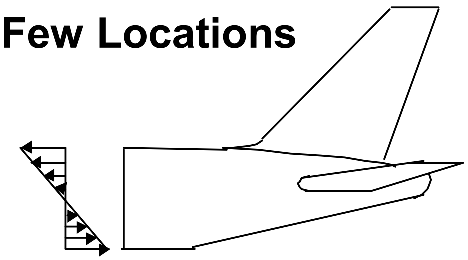
Internal Loads/Load Paths - Arrangement

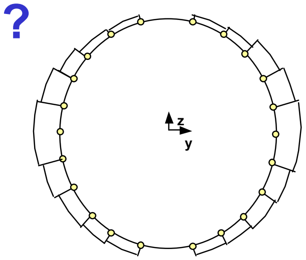


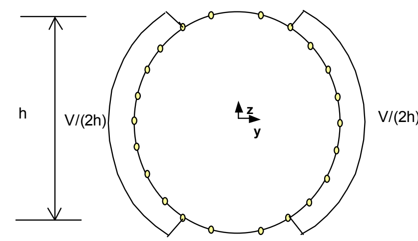
Preliminary Sizing

Considering How Little Time You Have, What Can You Do?

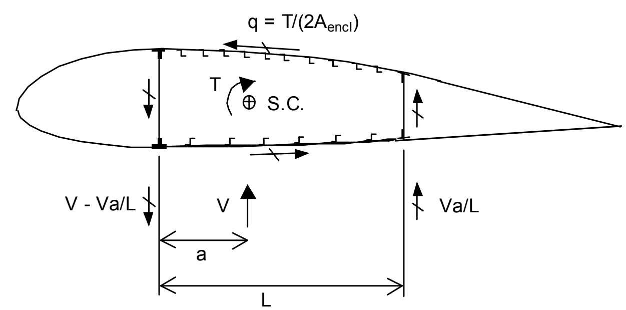
- **Develop External Loads – Corners of V-N Diagram**
- **Provide Good Internal Load Paths**
- **Develop the Internal Loads at a Few Locations**
  - **2 Body Cuts**
    - **$Mc/(Ad^2)$**
    - **$Vq/(Ad^2)$ or $V/(h)$**
    - **$T/(2A_{encl})$**
  - **2 Wing Cuts**
    - **M/h Cover/Spar Cap Axial Loads**
    - **Split V between spars (balance about SC or centroid)**
    - **$T/2A_{encl}$ Assume covers and outer spars carry all torsion**
- **Other, Special Locations – e.g., Engine, LG, Payloads**
- **Size to Cut-Off Ultimate Stress or Strain**
  - **Aluminum** **40 ksi (compression)**
40 ksi (tension)
25 ksi (shear)
  - **Advanced Composites** **.004 in/in (compression)**
.0045 in/in (tension)

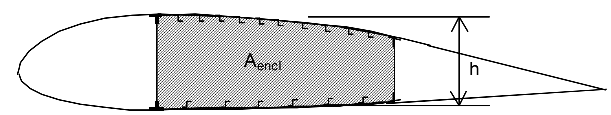






A_{encl} is enclosed area





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Some References

- <u>Airframe Structural Design</u>, Niu, Michael C.Y., Conmilit Press LTD., 1988.
- <u>Airplane Design</u>, Roskam, Dr. Jan, Roskam Aviation and Engineering Corporation, Ottawa, Kansas, 1985.
  - Part I: Preliminary Sizing of Airplanes
  - Part III: Layout Design of Cockpit, Fuselage, Wing and Empennage: Cutaways and Inboard Profiles
- http://www.aoe.vt.edu/~mason/Mason_f/SD1L32pp.pdf
- http://www.theflightcollection.com/index.jsp
- FAA Regulations Online, Plug "CFR 14" Into Search Engine – Look For "Part 23"
- <u>Analysis & Design of Flight Vehicle Structures</u>, Bruhn, E.F., Tri-State Offset Company, Cincinnati, Ohio, 1965.

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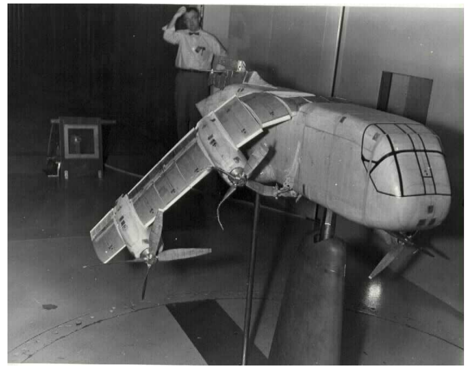
Some Other Considerations?

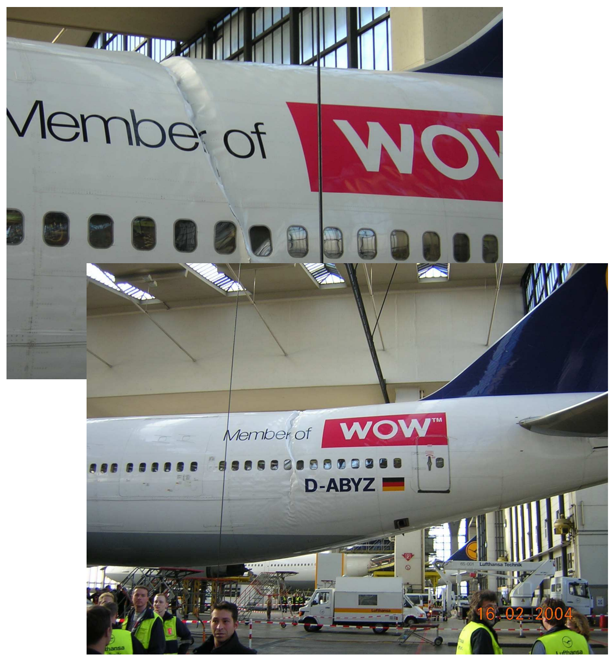
Emergency Exits



Aero-Elastic

In-Flight Deliveries

Short Runways



Jacking

Oversized Cargo

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