Overview of Structural Analysis

Overall strategy: understand how to solve simple structural problems by hand and leverage this knowledge with computational tools to solve complicated problems. We will also use computational tools to validate simplifying assumptions. Tasks will include not only analysis, but optimization (design).

- **Chapter 1:** Structural analysis overview: components, load, flow, role of analysis, fail safe vs. safe life...
  - Airplane structures (many space structures are similar)
    - Major components: spar, rib, skin, stringers, longheron, bulkhead, former, frame, etc. (more detail later, including interaction of the basic components) [PICTURES](take directory!)
  - Load flow
  - **Comment:** Often the built-up structure behaves like a simple structural element (e.g. modeling of a wing as a beam). Often the behavior of the components of a complex structure is like simple structural elements. (e.g. uniaxial rods that form a truss)

- **Design and analysis** *(will show video later in semester... Applegate & Homeyer)*
  - Process
  - Uncertainties
    - Fail safe vs safe life *(balloon + tape demo)*
    - Factor of safety
    - Tools of the structural analyst
      - Books/proprietary design guides
      - Statics, strength of materials
      - Finite elements
      - Experience/judgment
      - Experimental results
    - Analysis versus experimentation... roles are changing!
      - Need simple example!
    - The [Comet disaster](lack of accurate analysis tools)
    - The Challenger disaster *(environmental effect)*
    - Columbia disaster *(damage + environmental effect)*
Aircraft Structural Considerations
03/03/2011

Presented by: Steve Applegate

Acknowledgements

This presentation was originally developed by Byron Rodgers for instruction at Texas A&M.

Frank Sauer expanded the content when he started giving the presentation after Byron passed away in 2007.

Additional content on Damage Tolerance was recently added to the presentation with inputs from Ed Nichols.

Aircraft Design Considerations

- Determining the Aircraft arrangement requires inputs from various groups
- It is the responsibility of the Stress group to ensure load paths for all items
- Structural Arrangement is not always optimum
- Compromises are necessary to meet all requirements

Aircraft Structure

How does aircraft structure differ from other structure?
- Weight Efficiency
  - Weight is $ and performance
  - To minimize weight the arrangement of structural members is optimized to ensure efficient loads paths.
  - Aircraft structure consists of thin gage members that operate near buckling or in the post-buckled regime.
    • Buckling due to shear and compression loading may be allowed at very low load levels
    • Post-Buckled behavior is the realm of aircraft stress analysis
**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!**
  - Inhibit or degrade mechanical operation or reduce clearances between moveable parts.
  - Affect aerodynamic characteristics or result in significant changes to the distribution of external or internal loads.
  - Result in detrimental deformation: delamination, yield, or result in subsequent maintenance actions.

- **Structure Will Meet Specified Durability/ Damage Tolerance/ Fail Safety Requirements.**
  - No Failures With Specified Damage Within Allowed Inspection Intervals

---

**What does a structural analyst do?**

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

---

**Analysis and Sizing Steps**

- Understand Criteria, Requirements & Function
- Load Conditions and Environment
- Obtain Geometry / Establish Configuration
- Identify/Determine Internal Loads for Each Part Balance Loads & Reactions (free body diagrams)
- Develop Shear, Moment, and Axial Loads (and diagrams)
- Conduct Analyses/Sizing using Appropriate Loads, Methods, and Allowables

Document Throughout Process:
- Assumptions
- Geometry Used
- Internal Loads, Balances
- Analysis
- References, Etc.

---

**Aircraft Loads, Conditions & Requirements**

**Requirements Have Evolved With Experience/Lessons Learned**

<table>
<thead>
<tr>
<th>Flight Loads:</th>
<th>Ground Loads:</th>
<th>Other Loads &amp; Conditions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maneuver</td>
<td>Vertical Load Factor</td>
<td>Fatigue</td>
</tr>
<tr>
<td>Gust</td>
<td>Braking</td>
<td>Fall Safety</td>
</tr>
<tr>
<td>Control Deflection</td>
<td>Turns</td>
<td>Damage Tolerance</td>
</tr>
<tr>
<td>Buffet</td>
<td>Catapult</td>
<td>Bird Strike</td>
</tr>
<tr>
<td>Inertia</td>
<td>Arrested Landing</td>
<td>Ditching</td>
</tr>
<tr>
<td>Vibration</td>
<td>Aborted Takeoff</td>
<td>Lightning Strike</td>
</tr>
<tr>
<td></td>
<td>Spin-Up</td>
<td>Windmilling</td>
</tr>
<tr>
<td></td>
<td>Spring Back</td>
<td>Thermal</td>
</tr>
<tr>
<td></td>
<td>One Wheel/Two Wheel</td>
<td>Jacking</td>
</tr>
<tr>
<td></td>
<td>Towing</td>
<td>Pressurization</td>
</tr>
<tr>
<td></td>
<td>Ground Winds</td>
<td>Power Plant</td>
</tr>
<tr>
<td></td>
<td>Break Away</td>
<td>Hall</td>
</tr>
</tbody>
</table>

Specific Conditions are defined per:
- CFR14 Parts 23 and 25... (FAR).........Commercial (Subpart C = Structures)
- Mil-A-8860-8870 and SD-24L............ Military
Different Objectives - Different Configurations - Similar Process
Structural Arrangement is influenced by the type and size of the airplane

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

- Military Fighter/Attack
- Carrier Suitable
- Mach 2
- $n_{g} = 7.5g$

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

**Internal Loads/Load Paths - Arrangement**

- Stringer System
  - $d > h$

- Two-Spars
  - Stiffened skins
  - many ribs

**Internal Loads/Load Paths - Wing/Stabilizer**

- Stiffened Skin (many ribs)
- Shear Tied Ribs @ Concentrated Load Locations

**Internal Loads/Load Paths - Arrangement**

- 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

Stringers would not be efficient
**Internal Loads**

**Six Load Components and Five Distinct Types of Internal Loads**

1. Axial Tension
2. Axial Compression
3. Bending Moments
4. Shear
5. Torsion

These may act individually as uniform or varying loads, or they may be present in various combinations.

**Examples of Internal Loads**

Each Member Must Be in Static Equilibrium!

**Members Under Axial Tension Load**
- Static Strength – Size Net Tensile Stress < \( F_{tu} \)
- If Member is not Straight – Will Generate Bending Moment

**Members Under Axial Compression Load**
- Referred to as “Columns”
- Subject to Buckling – Critical Load Depends on
  - Length
  - Cross-Sectional Shape
  - Modulus of Elasticity
  - End Restraint
- If Member is not Straight – Will Generate Bending Moment

**Members Under Bending Moments**
- Generally Referred to as “Beams”
**Internal Loads**

**Members Under Shear Load**
- Effects Most Pronounced in Thin Panels
  - Webs of Beams
  - Skins of Fuselage, Wings and Tails

**Members Under Torsion Load**
- Generally Closed Section Members (such as Tubes) are Used
  - Open Section Members often Subjected to Torsion

**Members Under Combined Loads**
- Failure Involves Interaction of the Effects of Loads
  - In General, Appropriate Interaction Formulas are Applied
  - Beam Columns

---

**Internal Loads/Load Paths**

Load Paths in Wing/Stabilizer and Fuselage components

<table>
<thead>
<tr>
<th>Wing</th>
<th>Fuselage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending</td>
<td>Skin and Stringers</td>
</tr>
<tr>
<td>Shear</td>
<td>Skin and Stringers</td>
</tr>
<tr>
<td>Torsion</td>
<td>Skin and Spar Web</td>
</tr>
<tr>
<td>Concentrated Load</td>
<td>Skin and Spar Web</td>
</tr>
<tr>
<td>Introduction</td>
<td>Bulkheads</td>
</tr>
<tr>
<td>Hold Contour &amp;</td>
<td>Frames</td>
</tr>
<tr>
<td>Support Stringers</td>
<td></td>
</tr>
</tbody>
</table>

---

**Internal Loads/Load Paths**

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

- Consider all load conditions and requirements
  - If the design envelope is not well understood there is a high probability that the structure's limitations are not well understood

- 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
**Aircraft Loads, Conditions & Requirements**

Typical Commercial Transport Critical Static Load Conditions

- Positive Dynamic Gust
- Positive Maneuver and Static Gust
- Aileron Roll
- Negative Maneuver
- Negative Gust
- Engine Blade Out
- Taxi
- Lateral Maneuver
- Buffet
- Positive Checked Maneuver
- Negative Checked Maneuver

Different Load Conditions are Critical for Different Areas

---

**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.

**Example:**

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

Determine:

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

**Internal Loads/Load Paths - Wing/Stabilizer**

Typical VMT for Horizontal Stabilizer

<table>
<thead>
<tr>
<th>Percent Span</th>
<th>Shear (V)</th>
<th>Moment (M)</th>
<th>Torsion (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td>10^5 lbs</td>
<td>10^5 in-lbs</td>
</tr>
<tr>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Elastic Axis

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.

**Example:**

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

Determine:

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

Internal Loads/Load Paths - Wing/Stabilizer

**Quarter Ellipse Properties:**

\[ A = \text{Area} = 0.7854 ab \]
\[ b = \frac{0.4244a}{2} \]

Total Wing Force (Ultimate):

\[ P = 40,000 \text{ lbs} (6g)(1.5) = 360,000 \text{ lbs} \]

Each Fuselage Attach Must Resist \( \frac{1}{3} \) of the Total Load:

\[ R = 360,000 \text{ lbs}/2 = 180,000 \text{ lbs} \]

Moment at BL 0.0 is:

\[ M_0 = \frac{P}{2} \cdot y = R \cdot 25" = 180,000 \text{ lbs} \cdot [0.4244(360’')] = 180,000 \text{ lbs} (25’") = 20.0E+06 \text{ in-lbs} \]
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 - Ribs

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
• May Act as Fuel Boundaries

Intermediate Rib

Internal Loads/Load Paths - Ribs

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 than 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.

Fuel Loading - Roll Rate

\[
P = 0.34 \times K \times L \quad (6.5 \text{ pound/gallon fuel density})
\]

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.

Crushing Loads due to Wing Deflections (Brazier Loading)

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

Crushing Loads on a Rib
**Internal Loads/Load Paths - Ribs**

Built-In Curvature Loads
- Gathered by Ribs and Beamed to Spars

\[ P_{rib} = P_{seg} \times (\sin \alpha_2 - \sin \alpha_1) \]

\( \alpha_1, \alpha_2 \) are the “as built” angles

\( P_{seg} \) is load at rib \( i \)

---

**Internal Loads/Load Paths - Ribs**

Pressure + Inertia Loads

External + Internal Pressures + Inertia

**Internal Loads/Load Paths – Intermediate Ribs**

External Pressure and Curvature Loads are Beamed to Ribs

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

-218,800 in-lbs
-179,200 in-lbs
205,500 in-lbs
-218,800 in-lbs
406,000 in-lbs
7382 lbs

**Internal Loads/Load Paths – Shear Tied Ribs**

Ribs redistribute pressure and inertia loads into cellular box structure.
**Internal Loads/Load Paths - Ribs**

Ribs redistribute concentrated loads into cellular box structure.

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

![Diagram of Concentrated Loads](image)

**Internal Loads/Load Paths - Ribs**

**Trailing Edge and Control Surface Shear and Moment**

![Diagram of Trailing Edge and Control Surface Shear and Moment](image)

**Leading Edge and Trailing Edge Moments Balanced into Box by Ribs**

**Internal Loads/Load Paths - Spars**

Spars are primarily shear beams
- Carry wing shear loads
- With covers, carry torsion
- React local concentrated loads
- May also act as fuel boundaries

**3 Basic Types of Spars**
- Stiffened Web
- Truss beam
- Thin Section

![Diagram of Spars](image)

**Internal Loads/Load Paths - Spars**

**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**

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel loads</td>
<td>$q_1$</td>
<td>200 lbs/in</td>
</tr>
<tr>
<td>Bird strike load</td>
<td>$q_2$</td>
<td>200 lbs/in</td>
</tr>
<tr>
<td>Local concentrated</td>
<td>$q_3$</td>
<td>500 lbs/in</td>
</tr>
</tbody>
</table>

For a shear beam,

$q = q_1 + q_2 + q_3 = 9500 \text{ lbs}$

$P = \frac{1}{2}bh$ (web shear flow)

$P = \frac{M}{h}$ (chord load)

$h = \text{Distance between chord centroids}$
• Idealize the fuselage as a beam

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

Lower Stringer / 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).

Bending moment is carried based on M/I distribution.

Crown Stringers / Longerons and skin carry tension loads due to bending moment.

Internal Loads / Load Paths - Fuselage

Skins carry shear load in-plane with V/I distribution.

Skins carry torsion load in-plane with T/2A_{encl} distribution.

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

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

Frames provided to reduce Stringer / Longeron column length.
Body skins also carry external and compartment pressures as a membrane.

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

**Internal Loads/Load Paths - Fuselage**

**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&D, Thermal, Manufacturing/Processing Considerations)
- Does The Certification Basis Demonstrate Compliance With Criteria & Requirements
  - Detail Analysis Notes
  - Tests
  - Reports

**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
    - \( \frac{M_c}{(Ad^2)} \)
    - \( \frac{VQ}{(Ad^2)} \) or \( V(h) \)
    - \( \frac{T}{2A_{enc}} \)
  - 2 Wing Cuts
    - \( \frac{M}{h} \) Cover/Spar Cap Axial Loads
    - Split V between spars (balance about SC or centroid)
    - \( \frac{T}{2A_{enc}} \) 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
    - .004 in/in (compression)
    - .0045 in/in (tension)

**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
- Arrester Landing
- Aborted Takeoff
- Spin-Up
- Spring Back
- One Wheel/Two Wheel
- Towing
- Ground Winds
- Break Away

**Other Loads & Conditions:**

- Fatigue
- Fail Safety
- Damage Tolerance
- Bird Strike
- Ditching
- Lightning Strike
- Windmilling
- Thermal
- Jacking
- Pressurization
- Power Plant
- Hall
- 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
Engineering Requirements

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 Collect & Codify Its Experience

Evolution of Requirements

Evolution of Requirements

Safe Life vs Fail-Safe

CFR 25.571 Amendment 25-0 12/24/64

http://accidents-ll.faa.gov/ll_main.cfm?TabID=1&LLID=28&LLTypeID=2
Safe Life vs Fail-Safe

Fail-Safe vs Damage Tolerance

CFR 25.571 Amendment 25-45 12/1/78

Damage Tolerance - Multi Site Damage

CFR 25.571 Amendment 25-96 4/30/96

Damage Tolerance - Multi Site Damage

http://accidents-il.faa.gov/il_main.cfm?TabID=1&LLID=39&LLTypeID=2

http://accidents-il.faa.gov/il_main.cfm?TabID=3&LLID=20&LLTypeID=2

http://accidents-il.faa.gov/il_main.cfm?TabID=3&LLID=20&LLTypeID=2
**Bird Strike**

Pilot Window  
CFR 23.775(H) Amendment 23-49  3/11/96  2lb Bird  [Commuter Category]  
General  
CFR 25.571(E) Amendment 25-45  12/1/78  4lb Bird  
Empennage  
CFR 25.631 Amendment 25-23  5/8/70  8 lb Bird  
Pilot Window  
CFR 25.775(B)(C)  2/1/65  4lb Bird

How a goose at 185 knots can ruin your day. Pilot was injured but was able to land the aircraft (Beech Baron) safely.

---

**Bird Strike**

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

---

**Ditching**

CFR 25.801


---

**Lightning Strike**

CFR 25.581

Requirement is to assure no burn through or sparking in fuel tanks or areas where fuel vapors could be present due to leakage. This necessitates, among other things, a minimum skin thickness in fuel tank areas.
• FAA Windmilling design requirements:

Sec. 33.63 Vibration.

Each engine must be designed and constructed to function throughout its declared flight envelope and operating range of rotational speeds and power/thrust, without inducing excessive stress in any engine part because of vibration and without imparting excessive vibration forces to the aircraft structure.

3. A new section 33.74 is added to read as follows:

Sec. 33.74 Windmilling.

If the engine continues to windmill after it is shut down for any reason while in flight, continued Windmilling of that engine must not result in damage that could create a hazard to aircraft representing a typical installation during the maximum period of flight likely to occur with that engine inoperative.

• 747 China Airlines Flight 006

Lost power on outboard engine 19 February 1985

Windmilling of engine created dynamic wing oscillations

Resulted in loss of aircraft control and extensive structural damage

Evolution of FAA Requirements

• FAA Regulations have changed over time.
• The Website below provides a summary of when each Regulation was revised along with an explanation for why each change was made.


1) Click on Historical FAR by Part
2) Click on Part 23 or 25
3) Select the regulation of interest
4) Click on NPRM
5) Click on Final Rule

References

• Analysis & Design of Flight Vehicle Structures, Bruhn, E. F., Tri-State Offset Company.
• Aircraft Structures, Peery, D.J., McGraw-Hill Book Company, Inc.
• Formulas for Stress and Strain, Roark, R.J. and Young, W.C., McGraw-Hill, Inc.
• The Correct Use of Finite Element Models for Stress Analysis of Aircraft, Vaughan R.E. and Daniel M.F., 2004
Material Selection for Aerospace Applications

Ken Homeyer

Agenda

- Propaganda – Triumph Aerostructures - Vought Aircraft Division Overview
- Material Selection Criteria
- Material Types
- Material Forms
- Examples

Evolution Of The Company

Vought benefits from an industry legacy going back to the first producers of military aircraft in the United States. Our name extends to the company founded by aviation pioneer, Chance Milton Vought.
Triumph Group, Inc.
12,000+ employees 44 companies 64 locations

Who We Are - Design

Triumph’s engineers provide a full range of product development core competencies

- Design
  - Concept/ Preliminary / Detailed
  - Verification & Validation
  - Knowledge Based Engineering
  - Legacy Data Conversion

- Analysis
  - Retool Design
  - Static / Dynamic Analysis
  - Durability & Damage Tolerance

- Test
  - Material Properties and Structures Components
  - Full Scale Static, Fatigue & Drop Ground and Flight Test

Who We Are - Build

Triumph Aerostructures is a major subcontracting partner on many commercial and military aircraft programs. A Tier 1 Integrator, Vought Aircraft Division fills the gap between prime contractors and traditional subcontractors by providing large, complex aerostuctures on a turnkey basis.

- Fuselage Sections
  - Boeing 767/777 Fuselage Panels
  - Boeing 747 Fuselage Panels
  - Gulfstream G450/G550 Fuselage Sections

- Wings
  - Cessna Citation X Wing Panels
  - Gulfstream G450 Wings
  - Gulfstream G550/G650 Wings

- Engine
  - Honeywell Components
  - Gulfstream G450 Engine Details
  - C-17 Globemaster III Engine

Major Design Programs

- B-2 Intermediate Wing
- A330/340 Wing Control Surfaces
- V-22 Empennage
- Gulfstream GV Wing
- Boeing 747/777 AFA (Accurate Fuselage Assembly)
- Lockheed C-130, C-40, C-21, C-20, C-17 Fuselage Sections & Tail Sections
- Cessna Citation Columbus 850 Wing

Capabilities enhanced on these programs:
- 3-D Digital Product Definition
- FAA Certification Experience
- Virtual Co-Location
- Experience in Low-Cost Environment
Current Programs

- B747: Since 1966
- B767: Since 1980
- B777: Since 1993
- A340-300/600: Since 1988
- O450: Since 1983
- Citation X: Since 1992
- Citation: Since 1988
- Citation: Since 2008
- C-17: Since 1983
- V-22 Osprey: Since 1993
- Global Hawk: Since 1999
- A330: Since 1988
- A340-300/-500/-600: Since 1988
- G-450: Since 1983
- G-500/550: Since 1993
- Citation: Since 1992
- H-60 Black Hawk: Since 2004
- H-60 Black Hawk: Since 2004
- C-130J: Since 1963
- C-5: Since 2002
- KC-45A tanker: Since 1983
- C-17: Since 1983
- C-5: Since 2002
- Global Hawk: Since 1999
- V-22 Osprey: Since 1993

Who We Are - Test

Our testing capabilities include:
- Test plan development
- Test fixture and system design and fabrication
- Structural component – new and SLEP
- Full-scale structures – new and SLEP
- Land gear dynamic and carrier suitability
- Ground and flight test instrumentation
- FAA Type certification and military qualification
- Advanced development
- Prototyping

Since 1948, our test laboratories consistently offer customers cost-effective, state-of-the-art capabilities in a fully-equipped and certified facility centrally located in Dallas, Texas. Our U.S. Air Force, Federal Aviation Administration (FAA) certification and Department of Defense security clearances, our labs are the only testing facilities not operated by prime aerospace original equipment manufacturers (OEMs) with full-life cycle testing capabilities – including full-scale structures.

Our Customers

- Boeing
- Airbus
- Gulfstream
- Goodrich
- Sikorsky
- Northrop Grumman

Strong Relationships With OEM's And Other Tier 1s
Tomorrow…. Where We Are Focusing

Material Technology
- Higher performance materials, high temperature systems and complex product forms
- Out-of-autoclave, lower process temperature materials
- Specialty material solutions for embedded electronics, altered electrical properties

Manufacturing Technology
- Rapid prototyping "production processes"
- Affordable survivable structures fabrication methods and processes
- Processes that reduce non-recurring costs
- "How do we make complex stuff cheaper?"

Analytical Tools
- Advanced tools to support increasing part complexity & new materials and processes
- Elimination of conservatism in analytical methods – trust empirical data
- "No black aluminum, pick the right stuff!"

Factory Technology
- Adaptability and flexibility for short run, low rate production
- High rate production with increased accuracy
- "Faster, better and cheaper!"

Material Selection Criteria

Static Strength
- Material
  - Must Support Ultimate Loads Without Failure
  - Must Support Limit Loads Without Permanent Deformation
- Static Strength is the Initial Evaluation for Each Component
- Aluminum Is Usually the Initial Material Selection
  - If aluminum cannot support the applied load within the size limitation of the component, titanium or steel should be considered
  - If aluminum is too heavy to meet the performance requirements, composites or next generation materials should be considered

Stiffness
- Deformation of Material at Limit Loads Must Not Interfere With Safe Operation
  - There are cases where meeting the static strength requirement results in a component that has unacceptable deflections
  - The component is a ‘Stiffness’ driven design
Fatigue (Crack Initiation)

- Fatigue
  - Cracks start on the surface
  - Tension Driven Phenomenon
  - Spectrum Dependant
    - Number of Take-offs and Landing, Number of Gusts, etc.
    - Vibration (Hz)
  - Stress Concentrations Accelerate
    - Filled and Unfilled Holes
    - Sharp Corners
- Fatigue Resistant Design
  - Choose materials that resist cracking under cyclical loading
  - Limit component to a certain stress level based on the required life of the airframe
  - Further processing may improve fatigue properties such as shot peening or cold working

Damage Tolerance (Crack Growth)

- The Ability of a Material to Resist Crack Propagation Under Cyclical Loading
  - Slow Crack Growth Design
    - Design in Pad-up areas
    - Ensure proper fastener spacing and countersink depths
  - Use of Alloys With Increased Fracture Toughness

Weight

- Low Weight Is Critical to Meeting Aircraft Performance Goals
  - Materials are tailored for specific requirements to minimize weight
  - Materials with higher strength to weight ratios typically have higher acquisition costs but lower life cycle costs (i.e. Lower Fuel Consumption)

Corrosion

- Surface Corrosion
  - Galvanic Corrosion of Dissimilar Metals (see Chart)
  - Surface Treatments
    - Paint
    - Sealant
    - Proper Drainage
- Stress Corrosion Cracking
  - Corrosion due to specific internal stress being exceeded
  - Certain alloys are more susceptible to stress corrosion cracking (see Chart)
  - Especially severe in the short transverse grain direction (see Grain Direction)
**Corrosion - Dissimilar Metal Chart**

**Stress Corrosion Cracking (SCC) Chart**

**Producibility**
- Commercial Availability
- Lead Times
- Fabrication Alternatives (see Material Forms)
  - Built Up
  - Machined From Plate
  - Machined From Forging
  - Casting

**Cost**
- Raw Material Cost Comparisons
  - Aluminum Plate = $2 - $3 / lb.
  - Steel Plate = $5 - $10 / lb.
  - Titanium Plate = $15 - $50 / lb.
  - Fiberglass/Epoxy Prepreg = $15 - $25 / lb.
  - Graphite/Epoxy Prepreg = $50 - $100 / lb.
  - Graphite/Specialized Resin Prepreg = $250 - $500 / lb.
- Detail Fabrication Costs
- Assembly Costs
- Life Cycle Costs
  - Cost of Weight (Loss of Payload, Increased Fuel Consumption)
  - Cost of Maintenance
Specialized Requirements

- Temperature
- Lightning and Static Electricity Dissipation
- Erosion and Abrasion
- Marine Environment
- Impact Resistance
- Fire Zones
- Electrical Transparency

Performance vs. Cost Dilemma

- Highest Performance For The Lowest Cost Is the Goal of Every Airplane Material Selection.
  - Compromise Is Required
  - Define the Cost of Weight to the Aircraft

Material Types

Aluminum

- Accounts for ~80% of the structural material of most commercial and military transport aircraft
- Inexpensive and easy to form and machine
- Alloys are tailored to specific needs
Aluminum Alloys

- 2000 Series Alloys (Al-Cu-Mg)
  - Medium to High Strength
  - Good Fatigue Resistance
  - Low Stress Corrosion Cracking Resistance in ST Direction
  - 2024-T3 is the Yardstick for Fatigue Properties
  - Use in Tension Applications
    - Fuselage (Bending and Hoop loads)
    - Lower Wing Skin

- 5000 and 6000 Series Alloys
  - Low to Medium Strength
  - Easily Welded

Aluminum Alloys

- 7000 Series Alloys (Al-Zn-Mg-Cu)
  - High Strength
  - Comparable Fatigue Properties to 2000 Series
  - Improved Stress Corrosion Cracking Resistance
  - 7050 and 7075 Alloys Are Widely Used
  - 7475 Alloy Provides Higher Fatigue Resistance Similar to 2024-T3
  - Use in Compression Applications like Upper Wing Skin

Aluminum Tempers

Aluminum Tempers

Aluminum Tempers
Aluminum Tempers

<table>
<thead>
<tr>
<th>Material</th>
<th>Typical Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T3</td>
<td>High Strength Tension Applications.</td>
</tr>
<tr>
<td>2024-T351</td>
<td>Best Fracture Toughness / Slow Crack Growth Rate.</td>
</tr>
<tr>
<td>2024-T4</td>
<td>Good Fatigue Life.</td>
</tr>
<tr>
<td>2324-T3</td>
<td>8% Improvement in Strength over 2024-T3 with Increased Fatigue and Toughness Properties.</td>
</tr>
<tr>
<td>7075-T6</td>
<td>High Strength Compression Applications.</td>
</tr>
<tr>
<td>7075-T651</td>
<td>Higher Strength but Lower Fracture Toughness than 2024-T3.</td>
</tr>
<tr>
<td>7075-T7351</td>
<td>Excellent Stress Corrosion Cracking Resistance and Better Fracture Toughness, but Lower Strength and 7075-T6.</td>
</tr>
<tr>
<td>7050-T7451</td>
<td>Better Properties than 7075-T7351 in Thicker Sections.</td>
</tr>
</tbody>
</table>

Titanium
- Better strength to weight ratio than aluminum or steel
- Typically comprises ~5% by weight in commercial aircraft and up to ~25% by weight for high performance military aircraft
- Good corrosion resistance
- Good temperature resistance
- Good fatigue & damage tolerance properties in annealed form
- Typical alloy is Ti 6Al-4V either annealed or solution treated and aged
- High cost for metals

Steel
- Select when tensile strengths greater than titanium are necessary
- Usually limited to a few highly loaded components such as landing gear
- There are many steel alloys from which to choose. Select the one that is tailored for your application.
Steel (cont.)

MIL-HDBK-5 List of Aerospace Steel Alloys:

<table>
<thead>
<tr>
<th>Number</th>
<th>Steel Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2</td>
<td>Carbon steels</td>
</tr>
<tr>
<td>2.3</td>
<td>Low-alloy steels (AMS and proprietary grades)</td>
</tr>
<tr>
<td>2.3A</td>
<td>Special steels</td>
</tr>
<tr>
<td>2.4</td>
<td>Intermediate alloy steels</td>
</tr>
<tr>
<td>2.4A</td>
<td>5052-O-Mk</td>
</tr>
<tr>
<td>2.4B</td>
<td>5054-O-Mk</td>
</tr>
<tr>
<td>2.4C</td>
<td>4000 series aluminum alloys</td>
</tr>
<tr>
<td>2.4D</td>
<td>7000 series aluminum alloys</td>
</tr>
<tr>
<td>2.4E</td>
<td>11-7PH</td>
</tr>
<tr>
<td>2.5</td>
<td>Stainless steels</td>
</tr>
</tbody>
</table>
| 2.5A   | AISI Type 301

Composite Materials

Definition: Two or more distinct materials combined together to form a useful material with all the best qualities of the constituents and possessing some qualities not found in the constituents, but derived solely from their combination.

Composite = Fiber/Filament Reinforcement + Matrix

- High Strength
- High Stiffness
- Low Density

Evolution of Design

- Material Substitution
  - Composite materials combined with metals design and manufacturing methods "Black Aluminum"
  - Least Efficient Method, <10% Weight Savings, High Costs
- Component Replacement
  - Redesign using composite materials and technology
  - Moderate weight savings 20-25%, Moderate costs
  - Most widely used method
- Vehicle Resizing
  - Extensive use of composites throughout airframe allows reduction of vehicle size, engine, thrust, etc.
  - Requires at least 20-30% composite utilization
  - Limited application to date

B-2 Intermediate Wing Composite Usage

Substitution of Composites Into Intermediate Wing Minimizes Weight Savings

Assume current composites usage in intermediate wing prior to sizing aircraft

Vehicle Sizing with Intermediate Wing Composites Maximizes Weight Savings

Assume current composites usage into Intermediate wing

6,400 Pounds Saved
- Average 16% saving per installation
- Observables saving
- Vehicle same size

16,000 Pounds Saved
- Receive substitution payoff plus:
  - Smaller vehicle
  - Lighter vehicle
  - Less fuel required
Composite Materials

• Fibers
  – Forms
    • Fabric
    • Tape
    • Tow and Slit Tape
  – Materials
    • Graphite (High Strength, Stiffness)
    • Fiberglass (Fair Strength, Low Cost, Secondary Structure)
    • Kevlar (Damage Tolerant)
    • Astroquartz (Transparency)

• Matrix
  – Epoxy (Primary Matrix Material) to 250° F Service Temp.
  – Bismaleimide (High Temp Applications) to 450° F Service Temp.
  – Polymide (High Temp Applications) to 650° F Service Temp.
General Sandwich Stiffened Construction

- Sandwich Construction. Panels composed of a lightweight core material to which two relatively thin, dense, high-strength or high-stiffness faces or skins are adhered.

- Core. The central member, usually foam or honeycomb, of a sandwich construction to which the faces of the sandwich are attached or bonded.

Durability of Composite Materials

- Corrosion Resistance
  - Organic Coatings in Composites Are Inherently Noncorrosive

- Weathering Resistance
  - Property Protected Fiberglass (Glass/Epoxy) Components Show No Apparent Degradation after 10 Years of Service and Operational and Climate Exposures per Air Force and Navy Standards

- Fatigue Resistance
  - Fatigue Life Much Greater than Metal Structures

- Impact Damage Resistance
  - Projects Designed for Composites Are Equal or Better than Metal Structures for Impact Damage. Minor Damage Well Not Propagate Under Load

Composite Issues

- Limitations
  - Size is limited by available facilities
  - Areas without splices are limited to raw material width
  - Shape is limited to material drapability
    - Drape – the ability of a fabric or prepreg to conform to a contoured surface.
    - Small radii and abrupt changes cause bridging
  - Joining
    - Dimensional inaccuracies in bolt patterns cause higher than anticipated bearing stresses on any one bolt
    - Metals deform to distribute load to other fasteners
    - Composites load a single fastener to failure and then distribute entire load to remaining fasteners
  - Lightning Strike
    - Need copper mesh or aluminum flame spray to protect

Material Comparison

- Selecting Materials for Design involves 2 questions
  - Is a composite or metal the best suited material?
  - If a composite, which one?

- Experience shows parts having the same configuration as conventional machined metal parts like lugs, bathtub fittings, etc., are generally considered not to be good application for composite materials.
Material Properties Comparison

<table>
<thead>
<tr>
<th>Material</th>
<th>Fty (ksi)</th>
<th>FY (ksi)</th>
<th>Fcy (ksi)</th>
<th>E (10^6 psi)</th>
<th>Density (lb/in³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T3 Aluminum</td>
<td>64</td>
<td>47</td>
<td>39</td>
<td>10.5</td>
<td>.101</td>
</tr>
<tr>
<td>7075-T6 Aluminum</td>
<td>78</td>
<td>71</td>
<td>70</td>
<td>10.3</td>
<td>.101</td>
</tr>
<tr>
<td>6Al-4V Titanium Annealed</td>
<td>134</td>
<td>126</td>
<td>132</td>
<td>16.0</td>
<td>.160</td>
</tr>
<tr>
<td>6Al-4V Titanium Solution Treated and Aged</td>
<td>150</td>
<td>140</td>
<td>145</td>
<td>16.0</td>
<td>.160</td>
</tr>
<tr>
<td>15-5PH Stainless Steel (H1025)</td>
<td>154</td>
<td>145</td>
<td>152</td>
<td>28.5</td>
<td>.283</td>
</tr>
<tr>
<td>Fiberglass Epoxy (Unidirectional)</td>
<td>80</td>
<td>60</td>
<td>5</td>
<td>.065</td>
<td></td>
</tr>
<tr>
<td>Graphite Epoxy (Unidirectional)</td>
<td>170</td>
<td>140</td>
<td>22</td>
<td>.066</td>
<td></td>
</tr>
</tbody>
</table>

Next Generation Materials

- Aluminum Lithium
- GLARE (Fiberglass Reinforced Aluminum)
- TiGr (Graphite Reinforced Titanium)
- Thermoplastics
- Resin Transfer Molding (RTM)
- Stitched Resin Fusion Injected (Stitched RFI)

Basis of Properties

- Material property selection is dependent on the criticality of the structural component
  - Critical Single Load Path Structure
    - A Basis (99% Probability of Exceeding)
    - S Basis (Agency Assured Minimum Value)
  - Other Primary Structure With Redundant Load Paths
    - B Basis (90% Probability of Exceeding)
    - Without a Test, A or S Basis May Be Required
  - Secondary Structure
    - B Basis (90% Probability of Exceeding)
Material Properties Example

<table>
<thead>
<tr>
<th>Material Form</th>
<th>Thickness, in.</th>
<th>Sheet</th>
<th>Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuselage Skin</td>
<td>.25 or less</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuselage Frames</td>
<td>.25 or less</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rib and Spar Webs</td>
<td>.25 or less</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control Surfaces</td>
<td>.25 or less</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure Domes</td>
<td>.25 or less</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wing and Tail Skins</td>
<td>Greater than .25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monolithic Spars and Ribs</td>
<td>Greater than .25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fittings</td>
<td>Greater than .25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unitized Structure; Fewer Fasteners</td>
<td>Greater than .25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grain Orientation Can Be a Problem</td>
<td>Greater than .25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Speed Machining Has Lowered Fab Costs</td>
<td>Greater than .25</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sheet

- Rolled Flat Metal Thickness Less Than .25”
  - Fuselage Skin
  - Fuselage Frames
  - Rib and Spar Webs
  - Control Surfaces
  - Pressure Domes
- Good Grain Orientation
- Many Parts and Fasteners
- Fit Problems
  - Straighten Operations
  - Shims
  - Warpage

Plate

- Rolled Flat Metal Thickness Greater Than .25”
  - Wing and Tail Skins
  - Monolithic Spars and Ribs
  - Fittings
  - Unitized Structure; Fewer Fasteners
  - Grain Orientation Can Be a Problem
  - High Speed Machining Has Lowered Fab Costs
Extrusion

- Produced by forcing metal through a forming die at elevated temperature to achieve the desired shape
- Stringers
- Rib and spar caps
- Stiffeners
- Grain is aligned in the lengthwise direction
- Additional forming and machining required
- Used in conjunction with sheet metal webs

Forging

- Produced by impacting or pressing the material into the desired shape
  - Large fittings
  - Large frames/ribs
  - Odd shapes
- Control grain orientation
- Residual stresses can cause warpage during machining
- Tooling can be difficult

Casting

- Produced by pouring molten metal into a die to achieve the desired shape
  - Nacelle/engine components
  - Complex geometry
- Dramatically lowers part and fastener counts
- Poor fatigue and damage tolerance properties
- High tooling costs

Composite

- Produced by laying fabric, laying tape, winding, tow placement and 3D weaving or stitching
  - Skins
  - Trailing edge surfaces
  - Interiors and floors
- Properties can be oriented to load direction
- Excellent strength to weight ratio
- High cost of material and processes
- Poor bearing strength
Examples

Upper Wing Cover

- Compression Dominated
- Skin - 7075-T651 Aluminum Plate
- After Machining; Age Creep Formed To -T7351/-T73511
  - Reduces Compressive Yield Strength
  - Greatly Increases Stress Corrosion Resistance
- Stringers - 7075-T6511 Aluminum Extrusion

Lower Wing Cover

- Tension Dominated
- Skin - 2024-T351 Aluminum Plate
  - Good Ultimate Tensile Strength
  - Very Good Fatigue and Damage Tolerance Properties
- Stringers - 7075-T73511 Aluminum Extrusion
  - High Ultimate Tensile Strength
  - Good Damage Tolerance Properties

Spars

- 7050-T7451 Aluminum Plate
- High Tensile and Compressive Strength in Thick Sections
- Good Stress Corrosion Resistance
**Fixed Trailing Edge Surface**

- Graphite/Epoxy Fabric
- Aramid/Phenolic Honeycomb
- Fiberglass/Epoxy Fabric Corrosion Barrier
- Secondary Structure
- Stiffness Design

**Leading Edge**

- 2024-0 Clad Aluminum
- Heat Treated to -T62 After Stretch Forming to Shape
- Clad For Corrosion Resistance
- Polished For Appearance
- De-icing by Hot Air/Bird Strike Resistance

**Landing Gear Support Beam**

- Titanium 6Al-4V Annealed Forging
- Annealed Form Is Good For Fatigue And Damage Tolerance
- High Strength and Stiffness
- Critical Lug Design
- Height is Limited By Wing Contours

**Wing to Body Attachments**

- PH13-8Mo Cres Steel Bar
- Critical Lug Design
- High Strength Requirement
- Good Corrosion Resistance
Flap Tracks

- PH13-8Mo Cres Steel Bar
- Geometry Is Very Limited By Requirement To Be Internal To The Wing
- Results In Very High Stress Levels
- High Stiffness Is Required To Meet Flutter and Flap Geometry Criteria
- Good Corrosion Resistance