Aircraft Design
Introduction to Aircraft Structures

Ludovic Noels

Computational & Multiscale Mechanics of Materials – CM3
http://www.ltas-cm3.ulg.ac.be/
Chemin des Chevreuils 1, B4000 Liège
L.Noels@ulg.ac.be
Loading

- **Primary purpose of the structure**
  - To transmit and resist the applied loads
  - To provide an aerodynamic shape
  - To protect passengers, payload, systems

- **The structure has to withstand**
  - Aerodynamic loadings
  - Thrust
  - Weight and inertial loadings
  - Pressurization cycle
  - Shocks at landing, …
Aerodynamic loading

- **Example: wing loading**
  - Pressure distribution on an airfoil
    - Results from angle of attack and/or camber
  - This distribution can be modeled by
    - A lift (per unit length)
    - A drag (per unit length)
    - Applied at the Center of Pressure (CP)
  - As the CP moves with the angle of attack, this is more conveniently modeled by
    - Lift and drag
    - A constant moment
    - Applied at the fixed Aerodynamic Center (AC)
      - Can actually move due to compression effects
  - As the structural axis is not always at the CP
    - There is a torsion of the wing (particularly when ailerons are actuated)
    - There is always flexion
Aerodynamic loading

- Example: wing loading (2)
  - The lift distribution depends on
    - Sweep angle
    - Taper ratio
    - ...
  - Load can be modeled by
    - Lift and moment
    - Applied on the aerodynamic center
Aerodynamic loading

• Example: wing loading (3)
  – The lift and moment distributions result into
    • A bending moment
      – Due to \( l(y) \)
    • A torsion
      – Due to \( m(y) \)
      – Due to the fact that \( l(y) \) is not applied on the structural axis
    • Which depend on
      – Velocity
      – Altitude
      – Maneuver
      – Surface control actuation
      – Configuration (flaps down or up)
      – Gust
      – Take off weight
Aerodynamic loading

- **Load intensity**
  - Global loading can be represented by the load factor $n$ (in g-unit)
    - $n$ corresponds to the ratio between
      - The resulting aerodynamic loads perpendicular to the aircraft $x$-axis
      - The weight
    - When flying: $n \sim \frac{L}{W}$
    - Steady flight: $n = 1$
    - Pullout: $n > 1$
  - Loading factor depends on
    - Velocity
    - Altitude
    - Maneuver
    - Surface control actuation
    - Configuration (flaps down or up)
    - Gust
    - Take off weight
Aerodynamic loading

- **Placard diagram (Altitude-Velocity dependency)**
  - **Design altitude**
    - High enough to reduce drag (as density decreases with the altitude)
    - Above turbulence zone
  - **Design cruise Mach** ($M_C$)
    - Usually maximum operating Mach:
      Mach obtained at maximum engine thrust $M_C = M_{mo} \sim 1.06 M_{cruise}$
    - Temperature evolves linearly with altitude until the stratosphere
Aerodynamic loading

- **Placard diagram (2)**
  - Above the design altitude
    - Although density is reduced, the compressibility effects do not allow flying at higher Mach
    - The plane will fly at the same $M_C$ number
  - Ceiling
    - At high altitude the density is too small
      - The wing cannot produce the required lift
      - The engines cannot produce the required thrust

---

**Table:**

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>$M_C$</th>
<th>True airspeed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Graph:**

- Lift and thrust limit
- Stratospheric limit
- Design altitude
- Turbulences zone

**Legend:**

- $M_C$:
  - $168M_C$
  - $295.2M_C$
  - $340M_C$

**Other:**

- **T** (K): 216.5, 288
- **$\rho$ (kg m$^{-3}$):** 0.36, 1.22
- **$p$ (kPa):** 22.6, 101.3
Aerodynamic loading

- Placard diagram (3)
  - 1957, Lockheed U2
    - Ceiling 21 km (70000 ft)
    - Only one engine
    - AR $\sim 10$
    - Stall speed close to maximum speed

\[ \begin{array}{c|c|c|c|c|c|c}
\text{True airspeed (m/s)} & \text{Altitude (km)} & \text{MC} & 168MC & 295.2MC & 340MC & \text{Stratospheric limit} \\
\hline
216.5 & 11 & 0.36 & 1.22 & 22.6 & 91 & \text{Lift and thrust limit} \\
288 & 10.8 & & & & & \text{Stratospheric limit} \\
\end{array} \]
Aerodynamic loading

• Placard diagram (4)
  – Below design altitude, when getting closer to the sea level
    • Density increases
      – Engines cannot deliver enough thrust to maintain $M_C$ (drag increases with $\rho$)
      – Drag has to be kept constant
        $\rho V_{\text{True}}^{2/2}$ constant ($V_{\text{True}}$ is the true airspeed)
        – From the dynamical pressure $\rho V_{\text{True}}^{2/2}$, the equivalent velocity at sea level can be deduced: $V_e = V_{\text{True}} (\rho / \rho_0)^{1/2}$ ($\rho_0 =$ density at sea level)
    • Equivalent velocity is constant $\longrightarrow$ true airspeed is decreasing
      – There can be an operational limit as take off speed

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Lift and thrust limit</th>
<th>Stratospheric limit</th>
<th>Design altitude</th>
<th>Turbulences zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Lift and thrust limit</th>
<th>Stratospheric limit</th>
<th>Design altitude</th>
<th>Turbulences zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Lift and thrust limit</th>
<th>Stratospheric limit</th>
<th>Design altitude</th>
<th>Turbulences zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Lift and thrust limit</th>
<th>Stratospheric limit</th>
<th>Design altitude</th>
<th>Turbulences zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Altitude (km)</th>
<th>Lift and thrust limit</th>
<th>Stratospheric limit</th>
<th>Design altitude</th>
<th>Turbulences zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Aerodynamic loading

- **Placard diagram (5)**
  - Maximum velocity?
  - During a dive the plane can go faster than the design mach cruise
    - Design dive Mach (FAR) is defined as the minimum between
      - $1.25 \, M_C$
      - Mach actually obtained after a 20-second dive at $7.5^\circ$ followed by a 1.5-g pullout $\Rightarrow M_D \sim 1.07 \, M_C$
    - Above design altitude the maximum velocity is limited by $M_D$ constant
    - Below design altitude the maximum dive velocity $V_D$ is the minimum of
      - $1.25 \, V_C$
      - The dive velocity (20-second dive at …) $\sim 1.15 \, V_C$
      - The velocity corresponding to $M_D$

![Diagram showing various flight conditions and limits](image-url)
Aerodynamic loading

- Maneuver envelope (Velocity-load factor dependency)
  - Extreme load factors
    - Light airplanes ($W < 50000$ lb)
      - From -1.8 to minimum of
        - $2.1 + 24000 \text{ lb/}[W \text{ [lb]} + 10000 \text{ lb}]$
        - $3.8$
    - Airliners ($W > 50000$ lb)
      - From -1 to 2.5
    - Acrobatic airplanes
      - From -3 to 6
  - Two design velocities
    - These are equivalent velocities
    - Design dive velocity $V_D$
      - The plane cannot fly faster
    - Design cruise velocity $V_C$
  - Are these load limits relevant if the plane fly slower than $V_C$?

![Diagram of equivalent airspeed and load factors](image_url)
Aerodynamic loading

- **Maneuver envelope (2)**
  - At velocity lower than design cruise $V_C$
    - A pullout is limited by the maximum lift the plane can withstand before stalling
      - In terms of equivalent velocity and maximum lift coefficient flaps up, the maximum load factor becomes:
        \[ n = \frac{L}{W} = \frac{\rho_0 V_c^2 S C_{L_{\text{max},1}}}{2W} \]
    - $V_A$: Intersection between stall line and $n_{\text{max}}$
      - This is the maximum velocity at which maximum deflection of controls is authorized
    - $V_{s1}$: Intersection between stall line and $n = 1$
      - This is the stall velocity in cruise (flaps up)
    - FAR requirement
      - $V_A > V_{s1} n^{1/2}$ but
      - $V_A$ can be limited to $V_C$
Aerodynamic loading

• Maneuver envelope (3)
  – Negative load factor
    • At low velocities
      – Same thing than for pullout: stall limits the load factor
    • At high velocities
      – When diving only a pullout is meaningful
      – Linear interpolation between
        » \( V_e = V_D \) & \( n=0 \)
        » \( V_e = V_C \) & \( n=-1 \)

![Graph showing equivalent airspeed vs. load factor]
**Aerodynamic loading**

- **Maneuver envelope (4)**
  - Configuration flaps down
    - The maximum lift coefficient changes, so the load factor
      - Landing configuration
        \[ n = \frac{L}{W} = \frac{\rho_0 V_e^2 S C_{L_{\text{max},0}}}{2W} \]
      - Takeoff configuration
        \[ n = \frac{L}{W} = \frac{\rho_0 V_e^2 S C_{L_{\text{max}}}}{2W} \]
    
  - Stall velocities
    - \( V_s \): take off
    - \( V_{s0} \): landing
    - \( V_{s1} \): flaps up
  
  - \( V_F \): velocity below which the flaps can be down (structural limit)
  
- **FAR requirements**
  - \( V_F > 1.6 \ V_{s1} \) in take off configuration (MTOW)
  - \( V_F > 1.8 \ V_{s1} \) in approach configuration (weight)
  - \( V_F > 1.8 \ V_{s0} \) at landing configuration (weight)
Aerodynamic loading

• Maneuver envelope (5)
  – Altitude dependency
    • Use of equivalent velocity reduces the effect of altitude
    • But the envelope still depends on the altitude
      – With the altitude the speed of sounds decreases and density is reduced
        » For a given equivalent velocity the compressibility effects are higher
          (higher Mach number) and the maximum lift coefficient decreases
      – The computed $V_D$ will be lower as limited by $M_D$ constant
    • One flight envelope is therefore valid for an altitude range
    • Another factor which is altitude-dependant, and that should also be considered, is the gust factor
Aerodynamic loading

- **Gust effect**
  - Airfoil in still air
    - Airplane velocity $V$
    - Attack angle $\alpha_0$
  - Sudden vertical gust $U$
    - The plane keeps temporarily the same
      - Velocity $V$
      - Attitude $\alpha_0$
    - Due to the vertical velocity the angle of attack becomes $\alpha = \alpha_0 + \Delta \alpha \simeq \alpha_0 + \frac{U}{V}$
    - Resulting increase of plane lift (neglecting change of plane velocity)
      \[
      \Delta L \simeq \frac{\rho V^2 S \partial_a C_{L_{\text{plane}}} \Delta \alpha}{2} \simeq \frac{\rho V S C_{L_{\alpha_{\text{plane}}}} U}{2}
      \]
  - Increase in load factor
    - As $\rho UV = \rho_0 U e V_e$ \[\Delta n \approx \frac{\rho_0 V e S C_{L_{\alpha_{\text{plane}}}} U e}{2W}\]
Aerodynamic loading

• Gust effect (2)
  – Realistic vertical gust
    • The plane do not really see a sudden vertical gust
    • A real vertical gust can be modeled as graded
      – Ramp
      – Cosine
    • Modern methods consider power spectrum analysis
  – Gust alleviation factor: Before gust has reached its maximum value
    • The aircraft has developed a vertical velocity \( \Delta n \) reduces the severity
    • The aircraft might be pitching \( \Delta n \) effect on the loading (increase of decrease)
    • Elastic deformations of the structure \( \Delta n \) might increase the severity
  – So \( \Delta n \) becomes
    \[
    \Delta n \approx \frac{\rho_0 V_e S C_{L_{\alpha_{plane}}} U_e}{2W}
    \]
    • \( F \) is the gust alleviation factor (<1)
Aerodynamic loading

- **Gust alleviation factor**
  - Expression: \( \Delta n \approx \frac{\rho_0 V_e S F C_L \alpha_{plane} U_e}{2W} \)
  - FAR simple rule: \( n_g = 1 + \frac{F C_L \alpha_{plane} U_e V_e S}{498W} \)
    - \( W \) plane weight in lb
    - \( V_e \) equivalent plane velocity in knots (1 knot = 1.852 km/h)
    - Gust alleviation factor: \( F = \frac{0.88 \mu}{5.3 + \mu} \frac{\rho C_L \alpha_{plane} c g S}{2W} \)
    - Airplane weigh ratio: \( \mu = \frac{\rho C_L \alpha_{plane} c g S}{2W} \)
    - \( c \) mean aerodynamic chord
    - \( U_e \) equivalent gust velocity in ft/s
      - Is interpolated from statistical values at different altitudes and for different planes velocities
      - \( V_B \): Velocity when maximum load factor is governed by gust (see next slide)

<table>
<thead>
<tr>
<th>( U_e ) in ft/s</th>
<th>( V_e = V_B )</th>
<th>( V_e = V_C )</th>
<th>( V_e = V_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20000 ft and below</td>
<td>± 66</td>
<td>± 50</td>
<td>± 25</td>
</tr>
<tr>
<td>50000 ft and above</td>
<td>± 38</td>
<td>± 25</td>
<td>± 12.5</td>
</tr>
</tbody>
</table>
Aerodynamic loading

- **Gust envelope**
  - Gust load factor
    - \( n_g = 1 + \frac{F C_{L\alpha plane} U_e V_e S}{498W} \)
    - This gives two branches for \( n_g(V_e) \) for \( U_e > 0 \)
    - \( V_B \) is the intersection between
      - The stall curve
      - \( n_g(V_e) \)
    - This means that if
      - \( V_e < V_B \) the plane might stall in case of gust
      - So \( V_B \) is minimum speed to enter a gust region
  - **FAR requirements**
    - \( V_B \) can be < \( V_{s1} [n_g(V_C)]^{1/2} \)
    - \( V_B \) can be < \( V_C \)
    - \( V_B > V_A \)

<table>
<thead>
<tr>
<th>( U_e ) in ft/s</th>
<th>( V_e = V_B )</th>
<th>( V_e = V_C )</th>
<th>( V_e = V_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20000 ft and below</td>
<td>± 66</td>
<td>± 50</td>
<td>± 25</td>
</tr>
<tr>
<td>50000 ft and above</td>
<td>± 38</td>
<td>± 25</td>
<td>± 12.5</td>
</tr>
</tbody>
</table>
Aerodynamic loading

- **Gust envelope (2)**
  - Gust load factor
    \[ n_g = 1 + \frac{F C_L \alpha \text{plane} U_e V_e S}{498W} \]
  - This gives two branches for \( n_g(V_e) \) for \( U_e < 0 \)
  - Gust envelope is the linear interpolation between
    - Positive stall
    - \( n_g(V_B) \)
    - \( n_g(V_C) \)
    - \( n_g(V_D) \)

<table>
<thead>
<tr>
<th>( U_e ) in ft/s</th>
<th>( V_e = V_B )</th>
<th>( V_e = V_C )</th>
<th>( V_e = V_D )</th>
</tr>
</thead>
<tbody>
<tr>
<td>20000 ft and below</td>
<td>± 66</td>
<td>± 50</td>
<td>± 25</td>
</tr>
<tr>
<td>50000 ft and above</td>
<td>± 38</td>
<td>± 25</td>
<td>± 12.5</td>
</tr>
</tbody>
</table>
Aerodynamic loading

- **Design load factors**
  - **Limit load factor** $n_{\text{limit}}$
    - Maximum expected load during service (from gust envelope)
    - The plane cannot experience permanent deformations
  - **Ultimate load factor** $n_{\text{ultimate}}$
    - Limit load times a security factor (1.5)
    - The plane can experience permanent deformations
    - The structure must be able to withstand the ultimate load for 3 seconds without failure
**Structure**

- **First structure designs**
  - A wood internal structure smoothed by fabrics
  - A plywood structure was also used for the fuselage

![Figure 1-5 Wood-and-fabric-type wing structure](image-url)
Was wood a good choice?

- Specific mechanical properties of wood are favorable to aluminum alloy

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield or tensile strength* [MPa]</th>
<th>Young [MPa]</th>
<th>Density [kg · m⁻³]</th>
<th>Ratio Young-Density</th>
<th>Ratio Strength-Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>100*</td>
<td>14000</td>
<td>640</td>
<td>21.9</td>
<td>0.156</td>
</tr>
<tr>
<td>Structural steel</td>
<td>200</td>
<td>210000</td>
<td>7800</td>
<td>26.9</td>
<td>0.025</td>
</tr>
<tr>
<td>Aluminum</td>
<td>75</td>
<td>70000</td>
<td>2700</td>
<td>8.9</td>
<td>0.027</td>
</tr>
<tr>
<td>High strength steel alloy A514</td>
<td>690</td>
<td>210000</td>
<td>7800</td>
<td>26.9</td>
<td>0.088</td>
</tr>
<tr>
<td>Aluminum alloy 2014</td>
<td>400</td>
<td>73000</td>
<td>2700</td>
<td>9.3</td>
<td>0.148</td>
</tr>
<tr>
<td>Titanium alloy 6Al-4V</td>
<td>830</td>
<td>118000</td>
<td>4510</td>
<td>26.17</td>
<td>0.184</td>
</tr>
<tr>
<td>Carbon fiber reinforced plastic</td>
<td>1400* (theoretical)</td>
<td>130000</td>
<td>1800</td>
<td>72.2</td>
<td>0.777</td>
</tr>
</tbody>
</table>
Structure

• Was wood a good choice (2)?
  – Drawbacks of wood
    • Moisture absorption changed shape and dimensions
    • Glued structures affected by humidity
    • Strongly anisotropic
    • Oversee import
    • Not suited to stress concentration
  – Wood-fabric structures
    • Were not always waterproof
      – Picture Fokker Dr.I
    • Did not allow to build high-aspect ratio wing
      – Most of the planes were biplanes or triplanes with lower lift/drag ratio
Structure

• Was wood a good choice (3)?
  – Nowadays, only light aircrafts are built using this concept (ex: Mudry)
  – In 1915, Junkers constructed a steel plane
    • Cantilevered wing
    • Steel is too heavy (specific tensile strength too low)
• **Duralumin**
  – 1909, Alfred Wilm, Germany
    • An aluminum alloy containing
      – 3.5 per cent copper
      – 0.5 per cent magnesium
      – Silicon and iron as impurities
      spontaneously hardened after quenching from about 480°C.
  – This alloy had interesting specific mechanical properties
    • Yield 230 MPa but
    • Density only 2700 kg · m⁻³
  – The question was
    • How to efficiently use this duralumin?
Structure

• Monocoque
  – Instead of
    • Using a frame as main structure and
    • Covering it with thin metal sheets
  – The skin of the structure can be such that it resists the load by itself
    • Lighter than framed structures
    • Sport cars (carbon fiber)
    • Soda can (aluminum)
      – As long as it is filled, it is resistant
      – Empty, it is subjected to buckling
  – These structures are subject to buckling and cannot be used for an aircraft
Structure

- **Semi-monocoque**
  - Monocoques are subject to buckling
  - The skin of the shell is usually supported by
    - Longitudinal stiffening members
    - Transverse frames
to enable it to resist bending, compressive and torsional loads without buckling
  - These stiffeners are fixed to the skin instead of putting a skin on a structural frame
- **First semi-monocoque aircrafts were made of duralumin (example: spitfire)**
Semi-monocoque structure

- Global view
Semi-monocoque structure

- **Wing: Box-beam structure**
  - 2 or 3 spars
  - Ribs
  - Stringers fixed to the skin
  - Transport aircrafts
    - Skin >\(\sim 1.\text{ mm}\)
    - Ribs >\(\sim 0.5\text{ mm}\)
    - Spars >\(\sim 1.\text{ mm}\)
Semi-monocoque structure

- **Fuselage**
  - Circular if pressurized
  - Longerons
  - Stringers
  - Frames or formers
  - Bulkheads (see next slide)
Semi-monocoque structure

• **Fuselage (2)**
  - Circular if pressurized
  - Longerons
  - Stringers
  - Frames or formers
  - Bulkheads
    - **Reinforcement at**
      - Wing root
      - Empennage fixation
      - Engine fixation
      - ...
    - **Pressurization**
      - Between cabin and tailfin
      - B747, Japan Airline 123: bulkhead repaired with a single row of rivets instead of two
Design criteria

- **Structural integrity of the airframe**
  - Must be ensured in the event of
    - Failure of a single primary structural element
    - Partial damage occurrence in extensive structures (e.g. skin panels)
    - Crack propagation
      - Adequate residual strength and stiffness
      - Slow rate of crack propagation
  - Design for a specified life in terms of
    - Operational hours
    - Number of flight cycles (ground-air-ground)
Design criteria

- **Minimum structural weight**
  - **Wing**
    - Fixed items & fuel tank outboard of wing (reduce wing loading)
    - 1-m free of fuel at wing tip (avoid fire risk in case of electrostatic loads)
    - Heavy mass at the wing in front of the structural axis (reduce aeroelastic issues)
    - Use the same ribs to support landing gear, flaps, engine
    - If possible wing in one part (throughout the fuselage for mid-wing)
  - **Landing gear**
    - Commonly attached to the wing
    - Should not induce bending nor shearing larger than in flight
      - Close to the root
      - Just forward of flexural axis
Design criteria

• **Minimum structural weight (2)**
  - Fuselage
    • Heavy masses near the CG (reduce the inertia loads)
    • Limited number of bulkheads
  - Empennages
    • Far from the wing (to reduce the aerodynamic loading)
    • Supported by an existing bulkhead
  - Other
    • Simple structures (avoid rollers, …)
Design criteria

- Ease of maintenance and inspection
Materials

- **Aluminum alloys**
  - **Duralumin (2xxx)**
    - 4-7% Cu, 0.5-1.5% Mg, 0.2-2% Mn, 0.3% Si, 0.2-1% Fe
    - Picture: F15 horizontal stabilizer skin
  - **Magnesium-Silicon alloy (6xxx)**
    - 0.1-0.4% Cu, 0.5-1.5% Mg, 0.1-0.4% Mn, 0.3-2% Si, 0.1-0.7% Fe
  - **Aluminum-Zinc-Magnesium alloy (7xxx)**
    - 1-2.5% Cu, 1-7% Zn, 1-3% Mg, 0.3% Si
  - Used on fuselage and wing, also for rivets, ...

<table>
<thead>
<tr>
<th></th>
<th>Yield [MPa]</th>
<th>Weldability</th>
<th>Machinability</th>
<th>Corrosion resistance</th>
<th>Fatigue properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T351</td>
<td>270</td>
<td>No</td>
<td>Average</td>
<td>Poor</td>
<td>Excellent</td>
</tr>
<tr>
<td>6061 T6</td>
<td>240</td>
<td>Excellent</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>7075 T651</td>
<td>400</td>
<td>No</td>
<td>Average</td>
<td>Average</td>
<td>Good</td>
</tr>
</tbody>
</table>
Materials

• Steel
  – Iron
    • Specific strength too low
  – Ultra-high-tensile strength carbon alloys
    • Brittleness
    • Not easily machinable, nor to weld
  – Maraging steel
    • Low carbon (<0.03%)
    • 17-19% Ni, 8-9% Co, 3-3.5 Mo, 0.15-0.25% Ti
    • High Yield strength (1400 MPa)
    • Compared to carbon-alloy
      – Higher toughness
      – Easier to machine and to weld
      – Better corrosion resistance
      – 3x more expensive
    • Aircraft arrester hook, undercarriage, …
    • Can be used at elevated temperature (400°C)
Materials

• **Titanium alloy**
  - High specific strength
    - Example Ti 6Al-4V
      - Yield 830 MPa, density 4510 kg · m⁻³
  - Properties
    - High toughness
    - Good fatigue resistance
    - Good corrosion resistance
      - Except at high T° and salt environment
    - Good Machinability and can be welded
    - Retains strength at high T° (500°C)
  - High primary and fabrication cost
    - 7X higher than aluminum alloys
  - Uses
    - Military aircrafts
      - Picture: F22 wing spars (Ti 6Al-4V)
    - Slat and flap tracks
      - Picture: B757 flap track (Ti 10V-2Fe-3Al)
    - Undercarriage
Materials

• Composite
  – Fibers in a matrix
    • Fibers: polymers, metals or ceramics
    • Matrix: polymers, metals or ceramics
    • Fibers orientation: unidirectional, woven, random
  – Carbon Fiber Reinforced Plastic
    • Carbon woven fibers in epoxy resin
      – Picture: carbon fibers
    • Tensile strength: 1400 MPa
    • Density: 1800 kg·m$^{-3}$
    • A laminate is a stack of CFRP plies
      – Picture: skin with stringers
Materials

- Composite (2)
  - Wing, fuselage, ...
  - Typhoon: CFRP
    - 70% of the skin
    - 40% of total weight
  - B787:
    - Fuselage all in CFRP
Materials

- **Composite (3)**
  - *Drawbacks*
    - “Brittle” rupture mode
    - Impact damage
    - Resin can absorb moisture

- **Glare**
  - Thin layers of aluminum interspersed with Glass Fiber Reinforced Plastic
  - Improves damage resistance
Materials

- **Materials summary**
  - Military aircrafts use more
    - Composite
    - Titanium alloy
  - Civil aircrafts
    - More and more composite
Assembly

- **Sub-assembly**
  - Each sub-assembly is constructed
    - In specialized designed jigs
    - In different factories, countries
• Component weight can be estimated
  – For conceptual design
  – Based on statistical results of traditional aluminum structures
  – Example: wing
Structural weight

- **Structural weight [lbs]**
  - Wing with ailerons
    \[ W_w = 4.22 S + 1.642 \times 10^{-6} \frac{n_{\text{ultim}} b^3 \sqrt{W_{\text{to}} ZFW}}{t_c \cos^2 \Lambda} \left( 1 + 2\lambda \right) \]
    
    - $S$: gross area of the wing [ft$^2$]
    - $W_{\text{to}}$: take off weight [lb]
    - $b$: span [ft]
    - $ZFW$: zero fuel weight [lb]
    - $\Lambda$: sweep angle of the structural axis
    - $t$: airfoil thickness [ft]
    - $\lambda$: taper ($c_{\text{tip}}/c_{\text{root}}$)
    - $c$: chord [ft]
  - Horizontal empennage & elevators
    \[ W_T = 5.25 S_{\text{exp}} + 0.8 \times 10^{-6} \frac{n_{\text{ultim}} b^3 W_{\text{to}} \bar{c} \sqrt{S_{\text{exp}}}}{t_T \cos^2 \Lambda_T l_T S_T^2} \]
    
    - $S_{\text{exp}}$: exposed empennage area [ft$^2$]
    - $l_T$: distance plane CG to empennage CP [ft]
    - $\bar{c}$: average aerodynamic chord of the wing [ft]
    - $S_T$: gross empennage area [ft$^2$]
    - $b_T$: empennage span [ft]
    - $t_T$: empennage airfoil thickness [ft]
    - $c_T$: empennage chord [ft]
    - $\Lambda_T$: sweep angle of empennage structural axis
Structural weight

- Structural weight [lbs] (2)
  - Fin without rudder
    \[ W_{F'} = 2.62 S_F + 1.5 \times 10^{-5} \frac{n_{ultim} b_F^3}{S_F} \left(8 + 0.44 \frac{W_{to}}{S_F} \right) \frac{t_F}{c_F} \cos^2 \Lambda_F \]

  \( S_F \): fin area [ft\(^2\)]
  \( t_F \): fin airfoil thickness [ft]
  \( \Lambda_F \): sweep angle of fin structural axis

  \( b_F \): fin height [ft]
  \( c_F \): fin chord [ft]
  \( S \): gross surface of wing [ft\(^2\)]

  - Rudder: \( W_r / S_r \sim 1.6 W_{F'} / S_F \)

  - Fuselage
    - Pressure index
      \[ I_p = 1.5 \times 10^{-3} \Delta p_{\text{max width fus}} \]
    - \( \Delta p \) [lb/ft\(^2\)] (cabin pressure ~2600m)
    - Bending index
      \[ I_b = 1.91 \times 10^{-4} n_{\text{limit at ZFW}} (ZFW - W_w - W_{\text{wing-mounted engines}}) \frac{\text{length fus}}{\text{height fus}^2} \]

    - Weight depends on wetted area \( S_{\text{wetted}} \) [ft\(^2\)] (area in direct contact with air)
      \[ W_{\text{fus}} = (1.051 + 0.102 I_{\text{fus}}) S_{\text{fus, wetted}} \]

      \[ I_{\text{fus}} = \begin{cases} 
      I_p & \text{if } I_p > I_b \\
      \frac{I_p^2 + I_b^2}{2I_b} & \text{if } I_p < I_b
      \end{cases} \]
Structural weight

- **Structural weight [lbs] (3)**
  - **Systems**
    - Landing gear
    - Hydromechanical system of control surfaces
      \[ W_{\text{gear}} = 0.04 \, W_{\text{to}} \]
      \[ W_{\text{SC}} = I_{\text{SC}} \left( S_{T_{\text{exp}}} + S_{F} \right) \]
      \[ I_{\text{sc}} \text{ [lb/ft}^2\text{]} : 3.5, 2.5 \text{ or } 1.7 \text{ (fully, partially or not powered)} \]
    - Propulsion
      \[ W_{\text{prop}} = 1.6 \, W_{\text{eng}} \sim 0.6486 \, T_{\text{to}}^{0.9255} \]
      \[ T_{\text{to}} \, : \, \text{Static thrust (M 0) at sea level [lbf], } *1\text{lbf} \sim 4.4 \text{ N} \]
    - Equipment
      - APU
      - Instruments (business, domestic, transatlantic)
      - Hydraulics
      - Electrical
      - Electronics (business, domestic, transatlantic)
      - Furnishing
        - if < 300 seats
        - if > 300 seats
        \[ W_{\text{furn}} \sim (43.7 - 0.037 \, N_{\text{seats}}) \, N_{\text{seats}} + 46 \, N_{\text{seats}} \]
      - AC & deicing
    - Payload (\( W_{\text{payload}} \))
      - Operating items (class dependant)
      - Flight crew
      - Flight attendant
      - Passengers (people and luggage)
  - **Definitions**
    - ZFW: Sum of these components
      \[ ZFW = \Sigma \, W_{i} \]
## Structural weight

- **Structural weight [lbs] (4)**

  - **Examples**

<table>
<thead>
<tr>
<th>Aircraft System</th>
<th>Citation-500</th>
<th>MDAT-30</th>
<th>MDAT-50</th>
<th>F-28</th>
<th>MDAT-70</th>
<th>DC-9-10</th>
<th>BAC-111</th>
<th>DC-9-30</th>
<th>737-200</th>
<th>727-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing System</td>
<td>1,020</td>
<td>3,143</td>
<td>4,360</td>
<td>7,526</td>
<td>5,910</td>
<td>9,366</td>
<td>9,817</td>
<td>11,391</td>
<td>11,164</td>
<td>17,682</td>
</tr>
<tr>
<td>Tail System</td>
<td>288</td>
<td>1,010</td>
<td>1,193</td>
<td>1,477</td>
<td>1,505</td>
<td>2,619</td>
<td>2,470</td>
<td>2,790</td>
<td>2,777</td>
<td>4,148</td>
</tr>
<tr>
<td>Body System</td>
<td>930</td>
<td>4,276</td>
<td>5,692</td>
<td>6,909</td>
<td>7,118</td>
<td>9,452</td>
<td>11,274</td>
<td>11,118</td>
<td>11,920</td>
<td>17,589</td>
</tr>
<tr>
<td>Alighting Gear System</td>
<td>425</td>
<td>1,379</td>
<td>1,874</td>
<td>2,564</td>
<td>2,440</td>
<td>3,640</td>
<td>3,465</td>
<td>4,182</td>
<td>4,038</td>
<td>7,244</td>
</tr>
<tr>
<td>Nacelle System</td>
<td>241</td>
<td>948</td>
<td>1,294</td>
<td>866</td>
<td>1,684</td>
<td>1,462</td>
<td>1,191</td>
<td>1,462</td>
<td>1,515</td>
<td>2,226</td>
</tr>
<tr>
<td>Propulsion System (less Dry Engine)</td>
<td>340</td>
<td>1,140</td>
<td>1,338</td>
<td>988</td>
<td>1,702</td>
<td>1,478</td>
<td>1,788</td>
<td>2,190</td>
<td>1,721</td>
<td>3,052</td>
</tr>
<tr>
<td>Flight Controls System (less Auto Pilot)</td>
<td>196</td>
<td>600</td>
<td>699</td>
<td>1,404</td>
<td>805</td>
<td>1,102</td>
<td>1,655</td>
<td>1,434</td>
<td>2,325</td>
<td>2,836</td>
</tr>
<tr>
<td>Auxiliary Power System</td>
<td>0</td>
<td>343</td>
<td>400</td>
<td>320</td>
<td>460</td>
<td>805</td>
<td>719</td>
<td>817</td>
<td>855</td>
<td>0</td>
</tr>
<tr>
<td>Instrument System</td>
<td>76</td>
<td>300</td>
<td>300</td>
<td>267</td>
<td>300</td>
<td>490</td>
<td>504</td>
<td>575</td>
<td>518</td>
<td>723</td>
</tr>
<tr>
<td>Hydraulic and Pneumatic System</td>
<td>94</td>
<td>257</td>
<td>300</td>
<td>406</td>
<td>345</td>
<td>681</td>
<td>1,391</td>
<td>753</td>
<td>835</td>
<td>1,054</td>
</tr>
<tr>
<td>Electrical System</td>
<td>361</td>
<td>617</td>
<td>825</td>
<td>953</td>
<td>1,040</td>
<td>1,631</td>
<td>1,610</td>
<td>1,715</td>
<td>2,156</td>
<td>2,988</td>
</tr>
<tr>
<td>Avionics System (incl. Auto Pilot)</td>
<td>321</td>
<td>586</td>
<td>586</td>
<td>923</td>
<td>586</td>
<td>1,039</td>
<td>1,368</td>
<td>1,108</td>
<td>1,100</td>
<td>1,844</td>
</tr>
<tr>
<td>Furnishings and Equipment System</td>
<td>794</td>
<td>2,657</td>
<td>3,548</td>
<td>3,335</td>
<td>4,772</td>
<td>6,690</td>
<td>7,771</td>
<td>8,594</td>
<td>9,119</td>
<td>11,962</td>
</tr>
<tr>
<td>Air Conditioning System</td>
<td>188</td>
<td>325</td>
<td>435</td>
<td>520</td>
<td>550</td>
<td>1,016</td>
<td>1,062</td>
<td>1,110</td>
<td>1,084</td>
<td>1,526</td>
</tr>
<tr>
<td>Anti-Icing System</td>
<td>101</td>
<td>384</td>
<td>448</td>
<td>520</td>
<td>511</td>
<td>472</td>
<td>234</td>
<td>474</td>
<td>113</td>
<td>639</td>
</tr>
<tr>
<td>Load and Handling System</td>
<td>2</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>19</td>
<td>9</td>
<td>57</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

| Empty Weight (less Dry Engine)       | 5,377        | 17,985  | 23,312  | 29,178| 29,748  | 41,962  | 46,328  | 49,770  | 51,240  | 75,528  |
| Dry Engine Weight                    | 1,002        | 2,480   | 3,373   | 4,327| 4,392   | 6,113   | 5,434   | 6,160   | 6,212   | 9,322   |
| Empty Weight (M.E.W.)                | 6,379        | 20,465  | 26,685  | 33,505| 34,140  | 48,075  | 51,762  | 55,930  | 57,452  | 84,850  |
| Takeoff Gross Weight                 | 11,650       | 34,480  | 46,850  | 62,000| 61,000  | 86,300  | 99,650  | 108,000 | 104,000 | 161,000 |

**Manufacturer empty weight**
### Structural weight [lbs] (5)

#### Examples

<table>
<thead>
<tr>
<th>Aircraft System</th>
<th>727-200</th>
<th>707-320</th>
<th>DC-8-55</th>
<th>DC-8-62</th>
<th>DC-10-10</th>
<th>L-1011</th>
<th>DC-10-40</th>
<th>747</th>
<th>SCAT-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wing System</td>
<td>18,529</td>
<td>28,647</td>
<td>34,909</td>
<td>36,247</td>
<td>48,990</td>
<td>47,401</td>
<td>57,748</td>
<td>88,741</td>
<td>83,940</td>
</tr>
<tr>
<td>Tail System</td>
<td>4,142</td>
<td>6,004</td>
<td>4,952</td>
<td>4,930</td>
<td>13,657</td>
<td>8,570</td>
<td>14,454</td>
<td>11,958</td>
<td>8,590</td>
</tr>
<tr>
<td>Body System</td>
<td>22,415</td>
<td>22,299</td>
<td>22,246</td>
<td>23,704</td>
<td>44,790</td>
<td>49,432</td>
<td>46,522</td>
<td>68,452</td>
<td>54,322</td>
</tr>
<tr>
<td>Lighting Gear System</td>
<td>7,948</td>
<td>11,216</td>
<td>11,682</td>
<td>11,449</td>
<td>18,581</td>
<td>19,923</td>
<td>25,085</td>
<td>32,220</td>
<td>28,720</td>
</tr>
<tr>
<td>Nacelle System</td>
<td>2,225</td>
<td>3,176</td>
<td>4,644</td>
<td>6,648</td>
<td>8,493</td>
<td>8,916</td>
<td>9,328</td>
<td>10,830</td>
<td>15,650</td>
</tr>
<tr>
<td>Propulsion System (less Dry Engine)</td>
<td>3,022</td>
<td>5,306</td>
<td>9,410</td>
<td>7,840</td>
<td>7,673</td>
<td>8,279</td>
<td>13,503</td>
<td>9,605</td>
<td>6,310</td>
</tr>
<tr>
<td>Flight Controls System (less Auto Pilot)</td>
<td>2,984</td>
<td>2,139</td>
<td>2,035</td>
<td>2,098</td>
<td>5,120</td>
<td>5,068</td>
<td>5,188</td>
<td>6,886</td>
<td>10,777</td>
</tr>
<tr>
<td>Auxiliary Power Plant System</td>
<td>849</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1,589</td>
<td>1,202</td>
<td>1,592</td>
<td>1,797</td>
<td>--</td>
</tr>
<tr>
<td>Instrument System</td>
<td>827</td>
<td>550</td>
<td>1,002</td>
<td>916</td>
<td>1,349</td>
<td>1,016</td>
<td>1,645</td>
<td>1,486</td>
<td>3,400</td>
</tr>
<tr>
<td>Hydraulic and Pneumatic Group</td>
<td>1,147</td>
<td>1,557</td>
<td>2,250</td>
<td>1,744</td>
<td>4,150</td>
<td>4,401</td>
<td>4,346</td>
<td>5,067</td>
<td>10,670</td>
</tr>
<tr>
<td>Electrical System</td>
<td>2,844</td>
<td>3,944</td>
<td>2,414</td>
<td>2,752</td>
<td>5,366</td>
<td>5,490</td>
<td>5,293</td>
<td>5,305</td>
<td>6,002</td>
</tr>
<tr>
<td>Avionics System (incl. Auto Pilot)</td>
<td>1,896</td>
<td>1,815</td>
<td>1,870</td>
<td>2,058</td>
<td>2,827</td>
<td>2,801</td>
<td>3,186</td>
<td>4,134</td>
<td>4,178</td>
</tr>
<tr>
<td>Furnishings and Equipment System</td>
<td>14,702</td>
<td>16,875</td>
<td>15,884</td>
<td>15,340</td>
<td>38,072</td>
<td>32,829</td>
<td>33,114</td>
<td>48,007</td>
<td>20,615</td>
</tr>
<tr>
<td>Air Conditioning System</td>
<td>1,802</td>
<td>1,602</td>
<td>2,388</td>
<td>2,296</td>
<td>2,368</td>
<td>3,344</td>
<td>2,527</td>
<td>3,634</td>
<td>2,820</td>
</tr>
<tr>
<td>Anti-icing System</td>
<td>666</td>
<td>626</td>
<td>794</td>
<td>673</td>
<td>616</td>
<td>296</td>
<td>555</td>
<td>413</td>
<td>210</td>
</tr>
<tr>
<td>Load and Handling System</td>
<td>19</td>
<td>--</td>
<td>55</td>
<td>54</td>
<td>46</td>
<td>--</td>
<td>62</td>
<td>228**</td>
<td>--</td>
</tr>
</tbody>
</table>

| Empty Weight (less Dry Engine)         | 86,017  | 105,756 | 116,535 | 118,749 | 203,521  | 198,968| 224,148  | 297,867| 256,204 |
| Dry Engine Weight                      | 9,678   | 19,420  | 16,936  | 17,316  | 23,229   | 30,046 | 25,587   | 35,700 | 45,020  |

| Empty Weight (M.E.W.)                  | 95,695  | 125,176 | 133,471 | 136,065 | 226,750  | 229,014| 249,735  | 333,567| 301,224 |
| Takeoff Gross Weight                   | 175,000 | 312,000 | 325,000 | 335,000 | 430,000  | 430,000| 565,000  | 775,000| 631,000 |
Structural weight

• **CG locations**
  - Wing: 30% chord at wing MAC
  - Horizontal tail: 30% chord at 35% semi-span
  - Fin: 30% chord at 35% of vertical height
  - Surface controls: 40% chord on wing MAC
  - Fuselage: 45% of fuselage length
  - Main Gear: located sufficiently aft of aft c.g. to permit 5% - 8% of load on nose gear
  - Hydraulics: 75% at wing c.g., 25% at tail c.g.
  - AC / deicing: End of fuse nose section
  - Propulsion: 50% of nacelle length for each engine
  - Electrical: 75% at fuselage center, 25% at propulsion c.g.
  - Electronics and Instruments: 40% of nose section
  - APU: Varies
  - Furnishings, passengers, baggage, cargo, operating items, flight attendants: From layout. Near 51% of fuselage length
  - Crew: 45% of nose length
  - Fuel: Compute from tank layout
Fuel weight

For a given mission

- Taxi & takeoff
  \[ W_{\text{taxi}} = 0.0035 \ W_{\text{to}} \]
- Landing & taxi
  \[ W_{\text{land}} = 0.0035 \ W_{\text{to}} \]
- Reserve
  - Should allow
    - Deviations from the flight plan
    - Diversion to an alternate airport
  - Airliners
    - \( W_{\text{res}} \approx 0.08 \ ZFW \)
  - Business jet
    - \( W_{\text{res}} \) fuel consumption for ¾-h cruise
    - Climbing (angle of \( \approx 10^\circ \))
      \[
      \frac{W_{\text{climb}}}{W_{\text{TO}}} \approx \frac{1}{100} \left[ \frac{\text{cruise altitude [ft]}}{31600 \ [ft]} + \frac{1}{2} M_{\text{cruise}}^2 \right]
      \]
    - Descend: \( \approx \) same fuel consumption than cruise
    - Take Off Weight (TOW):
      \[ W_{\text{to}} = ZFW + W_{\text{res}} + W_f \]
    - Landing weight:
      \[ ZFW + W_{\text{res}} + 0.0035 \ W_{\text{to}} \]
References

• Lecture notes

• Other reference
  – Book