Airframe Design and Construction
Part 1 – Wing Structural Design

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Site link: https://scholar.cu.edu.eg/?q=mohamedabdou/classes/airframe-design-and-construction-2-fuselage
Course details

Main text Book:
“Analysis and design of flight vehicle structures”, Bruhn

Grades:

- Attendance – 5 %
- Assignments – 10 %
- Midterm – 15 %
- Final exam – 70 %
Aircraft Structural Components

The main function of aircraft structures is to

- resist and transmit the applied loads (Ground, Aerodynamic, propulsion, payload)
- protect passengers
- provide aerodynamic shape

In most aircraft, the structure consists of thin shells as outer surface or skin that is supported by longitudinal stiffening members and/or frames to resist bending, compressive and torsional loads without buckling.
Aircraft Structural Components
Wing Structure

From aerodynamic point of view, the wing is defined as the main lifting surface in the aircraft and from structure point of view, it is the main structure element.

Wing structure elements

- Wing box – main structure element
- Spar (Flanges and shear web)
- Stringers
- Ribs
- Skin
Wing structure

• The *aerodynamic loads* over a wing produce combined loads in form of *tension*, *compression*, *bending*, and *torsion*.

• To provide *torsional resistance*, the wing is covered by *skins* and internal *shear webs* are added to form single or multiple closed cells.

• The *skin* surface also help in resisting *tension* and *shear stresses*, but inefficient in resisting compression.

• *Stringers* are used for *stiffening* the skin and *transferring* surface air pressure to cellular beam structure.

• *Ribs* are added to transfer large *concentrated loads* into the cellular beams.

• *Stringers* a long with spars resist *bending stresses, tension*, and *compression loads*. 
Course contents

➢ Introduction (Wing construction, loads, V-N diagram)
➢ Bending stresses - Beam theory
➢ Instability of columns and thin sheets (A18, C5)
➢ Effective width and Crippling strength of composite shapes (C7)
➢ Wing stress analysis (A19)
➢ Wing shear flow analysis
Failure of structure

• *Failure* of a structural unit can be due to *high loading condition* or over stress. This kind of failure can damage the whole aircraft.

• *Failure* in another manner can result from the *structure flexibility*. This flexibility can lead to failure due to *flutter* as an example.

• The objective of a structural designer is to ensure that a *structure can stand along with the surrounding loads without failure*. 
Structure design considerations

- An aircraft structure must be designed with light weight (Minimum cost).
- Wing-fuselage attached (Fitting) is important in mid-wing aircrafts.
- Wing cut-outs need special treatment.
- It is required that wings carry the applied limit loads without yielding and carry the design loads without failure (collapse).
- The wing can be assumed as a cantilevered beam in which loads decrease rapidly spanwise. So, an efficient structure should be designed with taper towards the wing tip.
Aircraft design considerations

• The aircraft general factor of safety in general is 1.5.
• The maximum loads mostly occur in landing, take off, and maneuvers.
• This is important because of many factors such as:
  
  ➢ The approximations involved in aerodynamic and structure analyses.
  ➢ Variation in the material physical properties
  ➢ Variations in fabrication.
  ➢ The aircraft should be safe under emergency conditions.
Aircraft loads

In general the aircraft loads can be specified to:

(1) Air Loads
   - Due to Airplane Maneuvers. (under the control of the pilot).
   - Due to Air Gusts. (not under control of pilot).

(2) Landing Loads
   - Landing on Land. (wheel or ski type).
   - Landing on Water.
   - Arresting. (Landing on Aircraft Carriers).

(3) Power Plant Loads
   - Thrust.
   - Torque.

(4) Take off Loads
   - Catapulting.
   - Assisted take off with auxiliary short period thrust units.

(5) Special Loads
   - Hoisting Airplane.
   - Towing Airplane.
   - Beaching of Hull type Airplane
   - Fuselage Pressurizing.

(6) Weight and Inertia Loads.
Aerodynamic loads

➢ The main load on the aircraft wing are the aerodynamic loads due to air pressure.

➢ The aerodynamic loads result on the fuselage are mainly due to drag. Since the fuselage does not designed to produce lift.
Aerodynamic loads

➢ It is more convenient when dealing with an airplane equilibrium to deal with the resultant of the total pressure load rather than dealing with the pressure distribution.

➢ The wing pressure is replaced by a resultant $R$ acting on the center of pressure.
Aerodynamic loads

➢ Then, the resultant force $R$ is replaced by its components parallel and perpendicular to airstream.

➢ These components define the *lift* and *drag* forces acting on the *aerodynamic center* a.c.

➢ The center of pressure $CP$ is replaced by the aerodynamic center, because the CP changes with the A.O.A during flight, while the a.c location is approximately at 25% of wing chord from the L.E.

➢ The *aerodynamic center* is the point at which the moment due to lift and drag forces is constant.
Aerodynamic loads

Equations of Equilibrium For Steady Flight.

From Fig. A4.10 we can write:

\[ \Sigma F_x = 0, \quad D + W \sin \theta - T \cos \beta = 0 \]
\[ \Sigma F_z = 0, \quad L - W \cos \theta + T \sin \beta - E = 0 \]
\[ \Sigma M_y = 0, \quad -M_a - L - D - E + T_c \cos \beta + E_e = 0 \]

Equations of Equilibrium in Accelerated Flight.

\[ \Sigma F_x = 0, \quad D + W \sin \theta - T \cos \beta - I_D = 0 \]
\[ \Sigma F_z = 0, \quad L - W \cos \theta + T \sin \beta - I_L - E = 0 \]
\[ \Sigma M_y = 0, \quad -M_a - L - D - E + T_c \cos \beta + E_e + I_m = 0 \]

Signs used:

- Forces - Plus is up and toward tail
- Moment - Clockwise is positive.
- Distances from c.g. to force - Plus is up and toward tail.

T = engine thrust.
L = total wing lift plus fuselage lift.
D = total airplane drag.
M_a = moment of L and D with reference to wing a.c. (aerodynamic center)
W = weight of airplane.
I_L = inertia force normal to flight path.
I_D = inertia force parallel to flight path.
I_m = rotation inertia moment.
E = tail load normal to flight path.
Load factors

They are multipliers that help in simulate the dynamic forces effect on aircraft at steady flight.

An example is an airplane accelerated in z-direction.

Thus, \( n_z L - W - \frac{W}{g} a_g = 0 \)

Since \( L = W \)

Hence \( n_z = 1 + \frac{a_g}{g} \)
Load factors

The airplane can also be accelerated in x-direction

\[ n_x W = \frac{W}{g} a_x \]

\[ \Sigma F_x = 0, \text{ hence } T - D - n_x W = 0 \]

Hence \( n_x = \frac{T - D}{W} \)

Fig. A4.11

Fig. A4.13

T is greater than D
Airworthiness of aircrafts

• It is concerned with the *safety standards* for all aspects of aircraft construction.

• Standards such as *structural strength, factor of safety, design requirements, aerodynamics, performance, electrical and hydraulic systems*.

• The aircraft airworthiness are applied to any aircraft for human transportation.
Airworthiness of aircrafts

An example of airworthiness in aircraft design that

➢ “an airplane shall be designed for applied positive acceleration of +6 g and negative acceleration of -3.5g at all speeds corresponding to $C_{L\text{max}}$ up to 1.4 times the maximum level flight speed.

➢ The airplane should withstand further 30 ft/sec gust load.

➢ A design factor of safety 1.5 shall be used.
Flight envelop and factor of safety

➢ The regulations limits of an aircraft are included in what they called flight envelop or V-n diagram or velocity-acceleration diagram.

➢ The curves OA and OF define the stalled conditions of an aircraft and can be obtained from

\[ \text{Lift} = nW = \frac{1}{2} \rho V^2 SC_{L,\text{max}} \]
Flight envelop and factor of safety

➢ Limit load: is the maximum load for an aircraft during its normal operations.

➢ Proof load: is the product of the aircraft limit load and a proof load factor (1 – 1.25).

➢ Ultimate load: is the product of the aircraft limit load and an ultimate load factor (about 1.5).

An aircraft structure should be designed to withstand the proof load without instability or failure until a maximum load is achieved.
Flight envelop and factor of safety

➤ For speeds below the positive wind incidence ($V_A$) and the negative wind incident ($V_F$), the maximum loads that can be applied to an aircraft are governed by $C_{L,max}$ (stall conditions).

➤ As the speed increases, the positive and negative limit loads can be applied ($n_1$, and $n_3$).

➤ Above the design cruising speed ($V_C$), the limit loads are decreased to be covered by lines $C \ D_1$, and $D_2 \ E$. 

![Flight envelop and factor of safety diagram](image-url)
The limit load factors \((n_1, n_2, \text{ and } n_3)\) are defined by airworthiness authorities for a particular aircraft.

Then, the flight envelop can be defined at a particular altitude, since the maximum lift, speed of sound, and the critical Mach number are decrease with increasing the altitude.

<table>
<thead>
<tr>
<th>Load factor (n)</th>
<th>Normal ((2.1 + 24000/(W + 10000)))</th>
<th>Semi-aerobic (0.75n_1 \text{ but } n_2 \leq 2.0)</th>
<th>Aerobatic (1.0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n_1)</td>
<td>4.5</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>(n_2)</td>
<td>3.1</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>(n_3)</td>
<td>1.8</td>
<td>3.0</td>
<td></td>
</tr>
</tbody>
</table>
Aircraft in landing – Example - 1

An aircraft having a total weight of 45 kN lands on the deck of an aircraft carrier and is brought to rest by means of a cable engaged by an arrester hook, as shown in the Figure. If the deceleration induced by the cable is 3 g determine the tension, $T$, in the cable, the load on an undercarriage strut and the shear and axial loads in the fuselage at the section AA; the weight of the aircraft aft of AA is 4.5 kN. Calculate also the length of deck covered by the aircraft before it is brought to rest if the touch-down speed is 25 m/s.
Aircraft in landing – Example - 1

*Given:*
- a/c weight of 45 kN
- brought to rest by means of a cable
- the deceleration by the cable 3 g
- weight aft of AA 4.5 kN.
- the touch-down speed is 25 m/s

*Required: determine*
- the tension, $T$, in the cable,
- the load on the undercarriage strut
- the shear and axial loads in the fuselage at the section AA
- the length of deck covered by the aircraft.
Aircraft in landing – Example - 1

Thrust and reaction calculations

Resolve the aircraft forces in the horizontal axis

\[ T \cos 10^\circ - ma = 0 \]

\[ T \cos 10^\circ - \frac{45}{g} 3g = 0 \]

\[ T = 137.1 \text{ kN} \]

Resolve the aircraft forces in the vertical axis

\[ R - W - T \sin 10^\circ = 0 \]

\[ R = 45 + 131.1 \sin 10^\circ = 68.8 \text{ kN} \]
Aircraft in landing – Example - 1

Shear and axial loads in section A-A

Let $N$ and $S$ be the axial and shear loads at the section AA, The inertia load acting at the CG of the fuselage aft of AA is $m_1 a$, where $m_1$ is the mass of the fuselage aft of AA. Then

$$m_1 a = \frac{4.5}{g} 3 g = 13.5 \text{ kN}$$

Resolving forces parallel to the axis of the fuselage

$$N - T + m_1 a \cos 10^\circ - 4.5 \sin 10^\circ = 0$$

$$N - 137.1 + 13.5 \cos 10^\circ - 4.5 \sin 10^\circ = 0$$

$$N = 124.6 \text{ kN}$$

Now resolving forces perpendicular to the axis of the fuselage

$$S - m_1 a \sin 10^\circ - 4.5 \cos 10^\circ = 0$$

$$S - 13.5 \sin 10^\circ - 4.5 \cos 10^\circ = 0$$

$$S = 6.8 \text{ kN}$$
Aircraft in landing - Example

Deck length

Finally, from elementary dynamics

\[ v^2 = v_0^2 + 2as \]

\[ v_0^2 = -2as \]

\[ 25^2 = -2(-3 \times 9.81)s \]

\[ s = 10.6 \text{ m} \]

From the basics of dynamics

\[ \frac{dv}{dx} = a = \text{constant} \]

\[ v \, dv = a \, dx \]

\[ \int_{v_0}^{v} v \, dv = a \int_{x_0}^{x} dx \]

\[ \frac{1}{2}(v^2 - v_0^2) = a(x - x_0) \]

\[ v^2 = v_0^2 + 2a(x - x_0) \]
Example 2

Assume that the transport airplane as illustrated in Fig. A4.17 has just touched down in landing and that a braking force of 35000 lb. on the rear wheels is being applied to bring the airplane to rest. The landing horizontal velocity is 85 M.P.H. (125 ft/sec). Neglecting air forces on the airplane and assuming the propeller forces are zero, what are the ground reactions $R_1$ and $R_2$. What is the landing run distance with the constant braking force?
Example 2

Given:
- Breaking force 35000 Ib
- Horizontal velocity 125 ft/s

Required:
- The ground reactions $R_1$ and $R_2$
- Landing run distance
Example 2

Solve for the deceleration using the equilibrium equation

\[ \Sigma F_x = 35000 - M_{a_x} = 0 \]

hence,

\[ M_{a_x} = 35000 \]

or

\[ \left( \frac{W}{g} \right) a_x = 35000 \]

whence

\[ a_x = \left( \frac{35000}{100000} \right) 32.2 = 11.27 \text{ ft/sec}^2 \]
Example 2

Landing run distance

To find landing run \((s)\),

\[ v^2 - v_0^2 = 2 a_x s \]

\[ 0 - 125^2 = 2 (-11.27) s \]

hence,

\[ s = 695 \text{ ft.} \]

To find \(R_a\) take moments about point (A)

\[ \Sigma M_A = 100,000 \times 21 - 35000 \times 9 + 38 R_a = 0 \]

\[ R_a = 47000 \text{ lb. (2 wheels)} \]

\[ \Sigma F_g = 47000 - 100,000 + R_1 = 0 \]

\[ R_1 = 53000 \text{ lb.} \]

From the basics of dynamics

\[ \frac{dv}{dx} = a = \text{constant} \]

\[ v \frac{dv}{dx} = a \] dx

\[ \int_v^{v_0} v \, dv = a \int_{x_0}^x \, dx \]

\[ \frac{1}{2} (v^2 - v_0^2) = a(x - x_0) \]

\[ v^2 = v_0^2 + 2a(x - x_0) \]
Dynamic effect

• In all our calculations in the present course, we assume the airplane as a rigid body.

• This assumption is appreciated in preliminary design but not accurate enough, because in real flights the dynamic forces are significant.

• A good design procedure is

  ➢ to start with the rigid body assumption and perform an analytical design for the airplane structure.
  ➢ then solve the full airplane structure numerically for detailed analysis
  ➢ finally test the aircraft structure performance experimentally.
## SI units

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Unit</th>
<th>Symbol</th>
<th>Formula</th>
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<tbody>
<tr>
<td>Acceleration</td>
<td>Meter per second squared</td>
<td>...</td>
<td>m/s²</td>
</tr>
<tr>
<td>Angle</td>
<td>Radian</td>
<td>rad</td>
<td>†</td>
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<tr>
<td>Angular acceleration</td>
<td>Radian per second squared</td>
<td>...</td>
<td>rad/s²</td>
</tr>
<tr>
<td>Angular velocity</td>
<td>Radian per second</td>
<td>...</td>
<td>rad/s</td>
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<tr>
<td>Area</td>
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<tr>
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<td>kg/m³</td>
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<td>Energy</td>
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<tr>
<td>Force</td>
<td>Newton</td>
<td>N</td>
<td>kg·m/s²</td>
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<tr>
<td>Frequency</td>
<td>Hertz</td>
<td>Hz</td>
<td>s⁻¹</td>
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<tr>
<td>Impulse</td>
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<td>Length</td>
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<tr>
<td>Mass</td>
<td>Kilogram</td>
<td>kg</td>
<td>‡</td>
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<tr>
<td>Moment of a force</td>
<td>Newton-meter</td>
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<tr>
<td></td>
<td>Work</td>
<td>Joule</td>
<td>J</td>
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</table>

\[1\text{ Supplementary unit (1 revolution} = 2\pi \text{ rad} = 360°\).]
\[2\text{ Base unit.}\]
## U.S units

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<th>SI Equivalent</th>
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