AS3020: Aerospace Structures

Module 1: Design of Aircrafts

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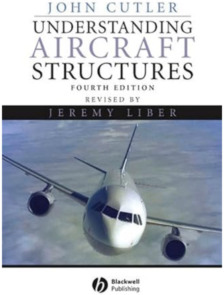
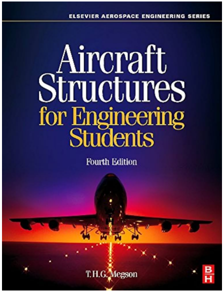


Chapters 1-5,7,9 in Cutler (2005)



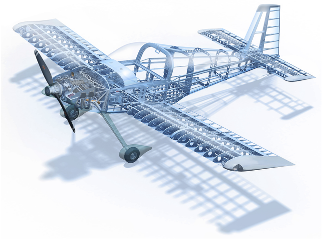
Chapters 12-15 in Megson (2013)

Introduction

In this module we seek to gain an *executive understanding* of,

- the evolution of the structural design of aircrafts;
- the balance of the different loads on an aircraft;
- joining processes used in aircrafts.

Why do aircrafts look the way they do?



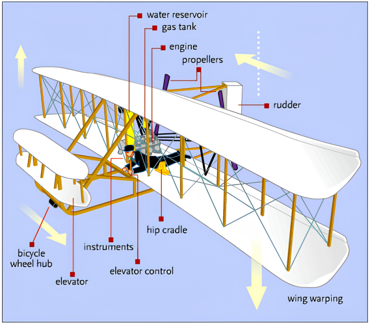
RV-14 Airframe *"Airframe" 2024*

Textbook References

- Chapters 1-5,7,9 in John Cutler. Understanding Aircraft Structures, Wiley, 2005. ISBN: 978-1-4051-2032-6
- Chapters 12-15 in T. H. G. Megson. Aircraft Structures for Engineering Students, Elsevier, 2013. ISBN: 978-0-08-096905-3.

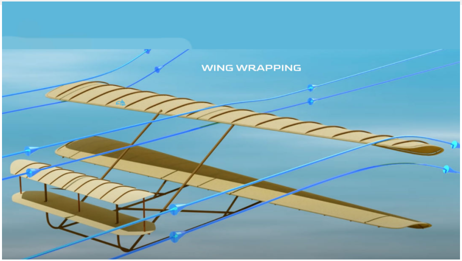
1.1. Wired Brace Construction: The Wright Flyer

Historical Overview

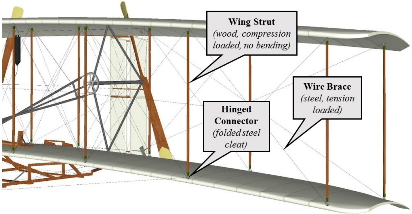


The Wright Flyer, 1903 *NOVA — Wright Brothers' Flying Machine — Pilot the 1903 Flyer (Non-Interactive) — PBS 2024*

- The bi-wing construction for structural integrity
- Light-weight wired-brace construction



The warping wing *History of First Flight 2024.*



Wired brace construction *Flyer Fatality – Solution 2024*

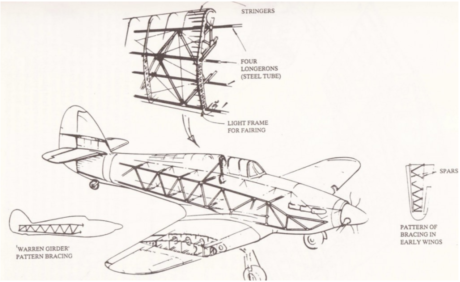
1.2. Braced Fuselage Design

Historical Overview

- The wired-braced, box-strut design approach persisted for a couple decades or so (∼1930s)
- Wooden struts/longerons replaced by steel-tubes in this time

Frame of the 1917 Sopwith Camel Team of Volunteers Finish Building WWI Plane after More than 20 Years 2022

- **Warren trusses** replaced wire braces ("Warren-girder" design)



Hawker Hurricane frame, 1935 Cutler 2005

Warren Truss *STRUCTURE Magazine — The Warren Truss* 2024

Patented truss (∼1840s) formed by equilateral triangles

1.2. Braced Fuselage Design

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Frame of the 1917 Sopwith Camel *Team of Volunteers Finish Building WWI Plane after More than 20 Years* 2022

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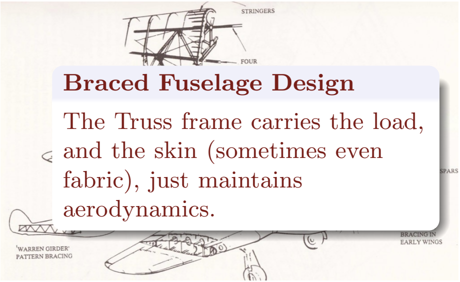


Braced Fuselage Design

The Truss frame carries the load, and the skin (sometimes even fabric), just maintains aerodynamics.

Hawker Hurricane frame, 1935 Cutler 2005

Warren Truss *STRUCTURE Magazine — The Warren Truss* **2024**

Patented truss (∼1840s) formed by equilateral triangles

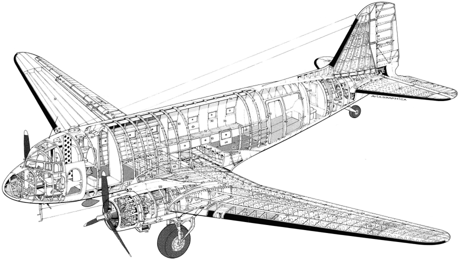
1.3. Semi-Monocoque Design

Historical Overview

- Ships have always had to maximize volume while maintaining a shape
- Bent wooden frames used to maintain the hull shape

A wooden ship hull Lyman-Morse Builds New in Wood and Glue - Professional BoatBuilder Magazine 2024

- The skin is now load-bearing: **stressed skin construction**, aka, **semi-monocoque construction**
- Since skins also carry load, the structure is at a generally lower stress level

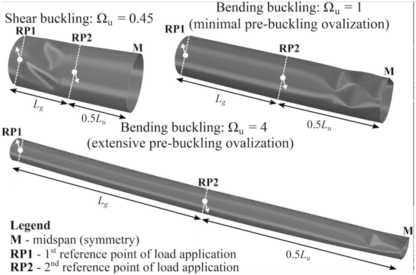


Douglas DC-3 (1933) Douglas DC-3 Cutaway Drawing in High Quality 2019

1.3. Semi-Monocoque Design

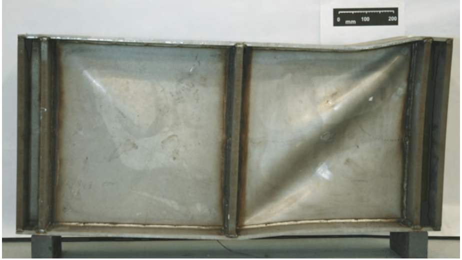
Historical Overview

- Thin-walled structures can carry tension much better than compression
- Buckling becomes a major issue under compression



Shear Buckling near an End of a Cylindrical Tube Where Shear Force (SFD) Dominates; "Local" Buckling in the Midlength Region on the Compressive Side Where the Bending Moment (BMD) Dominates; Extensive Tube Flattening Combined with Local Midlength Buckling of a Very Long Tube 2024

- The common-sensical thing to do is to **split up the skin into multiple smaller elements**
- We do this by means of **ribs/frames** holding the structure perpendicular to section and **stringers**, longitudinally.



Shear buckling *Saliba and Gardner 2013*

1.3. Semi-Monocoque Design

Historical Overview

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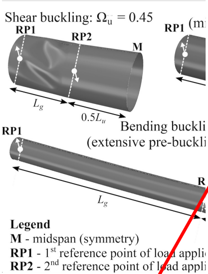
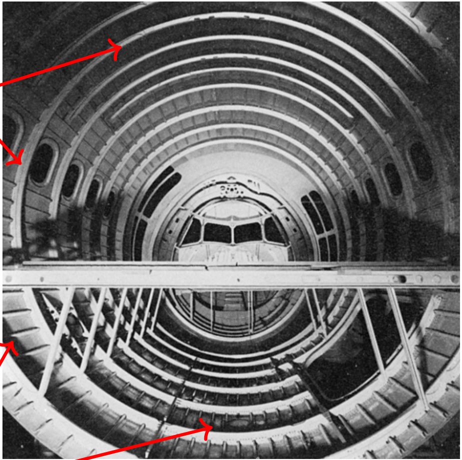


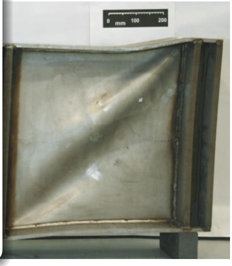
Shear … End of a Force … s; "Local" Region on the Compressive Side Where the Bending Moment (BMD) Dominates; Extensive Tube Flattening Combined with Local Midlength Buckling of a Very Long Tube 2024

Frames/Rings



Stringers

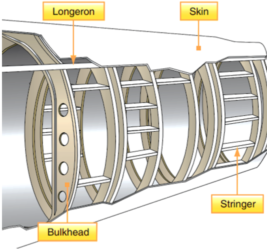
Insides of a fuselage *Megson 2013*



Shear buckling *Saliba and Gardner 2013*

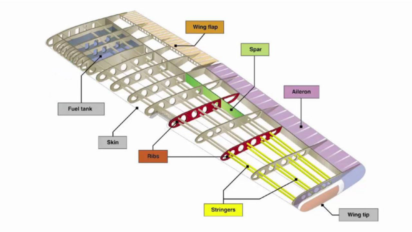
1.3. Semi-Monocoque Design

The Fuselage



Structural members in a fuselage 22.12.2. Monocoque Type 2024

The Wing



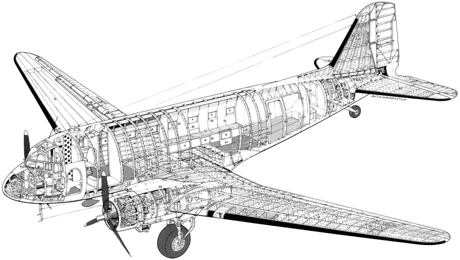
Structural members in a wing-box 22.16.2. Main Wing Box 2024

- The basic premises of the designs are identical, **but loads on the members vary**

1.3. Semi-Monocoque Design

Historical Overview

- Through experience, the industry has converged onto the following numbers:
  - Frame-spacing: ~ 500 mm
  - Frame-sections: $\sim 75 - 150$ mm
- A few more considerations:
  - The skins need to be **fastened onto the frames**
  - Moving to more and more lightweight structures, thin walls are very prone to **Sheet-buckling/wrinkling** (even "thermal" buckling)



Douglas DC-3 (1933) Douglas DC-3 Cutaway Drawing in High Quality 2019

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Sandwich Structures

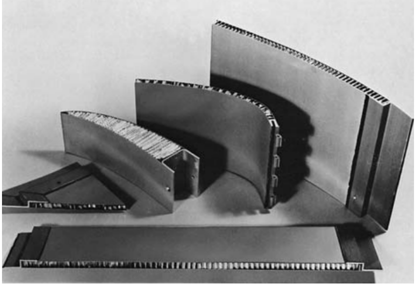

Figure from Cutler 2005

Increase bending stiffness by holding plates a large distance apart using very thin members/fillers.

1.3. Semi-Monocoque Design

Historical Overview

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Composite Materials

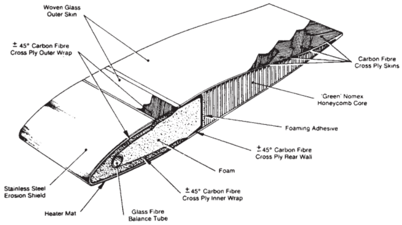

Figure from Megson 2013

By tailoring the properties of materials, we can achieve superior strength-weight and stiffness-weight ratios.

1. Historical Overview

Design Overview

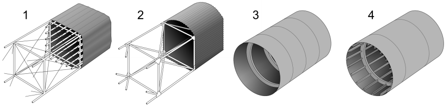

Figure from "Airframe" 2024

The "converged" aircraft

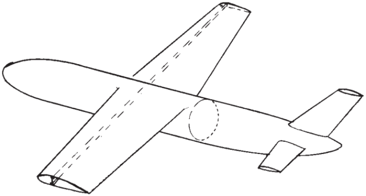

Figure from Cutler 2005

Parts of an aircraft

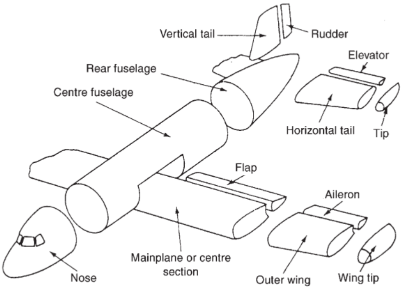

Figure from Megson 2013

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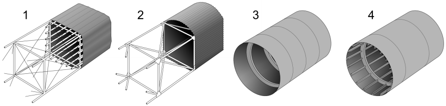
Design Overview



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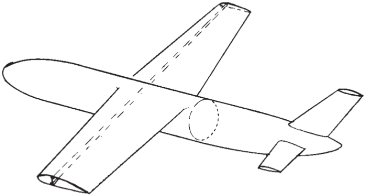

Figure from *Cutler 2005*

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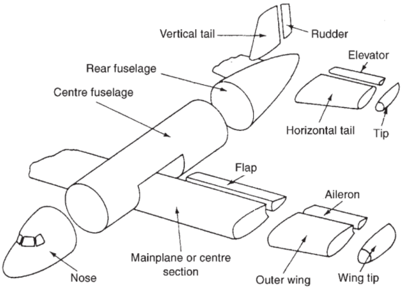


Figure from *Megson 2013*

- **"Wings"**: Mainplane, tail plane

1. Historical Overview

Design Overview

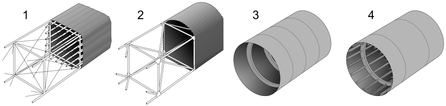


Figure from "Airframe" 2024

The "converged" aircraft

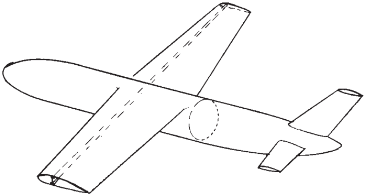


Figure from Cutler 2005

Parts of an aircraft

High Lift Devices

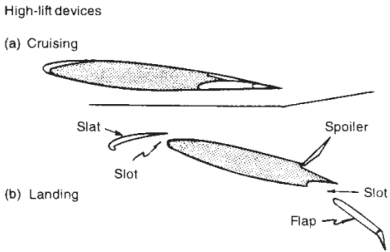
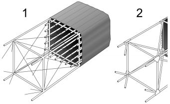


Figure from Cutler 2005

- **"Wings"**: Mainplane, tail plane
- **High lift devices**: flaps, elevators (ailerons)

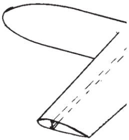
1. Historical Overview

Design Overvi



Figure

The "converge



Figu

Dimensions of an Aircraft

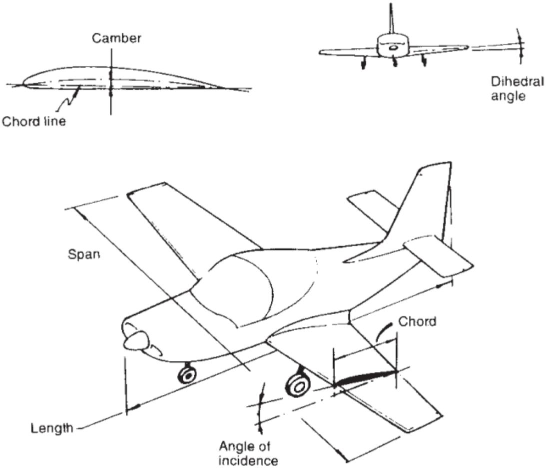
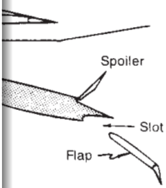


Figure from Cutler 2005



tler 2005

plane, tail

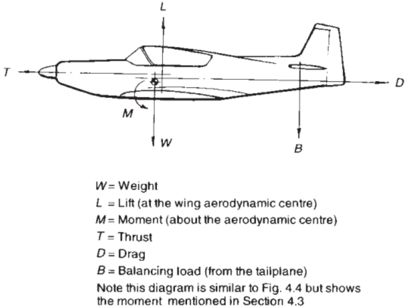
es: flaps,

s)

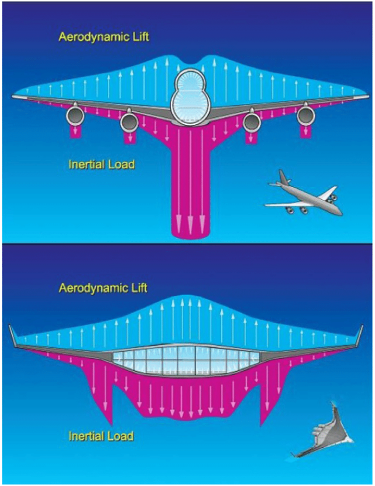
2. Aircraft Loads

2.1. Loads in Steady Level Flight

- The fuselage is being lifted up by the wing as the flight moves forward
- The load distributions are non-trivially related to flying conditions as well as design choices



Load at steady level flight *Cutler 2005*



Lift and inertial load distributions *Okonkwo and Smith 2016*

2.2. Loads During Maneuvers

2. Aircraft Loads

A maneuver is any disturbance to steady-level flight.
Note: Even increasing acceleration in level flight is a maneuver.

Steady Pull-out

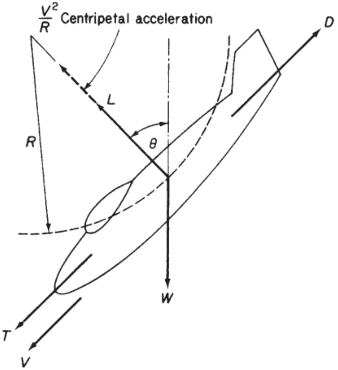


Figure from Megson 2013

Banking

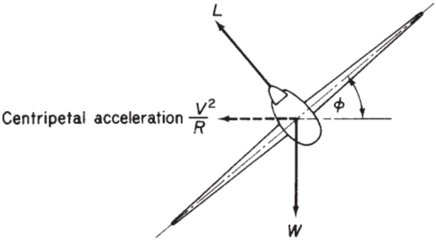
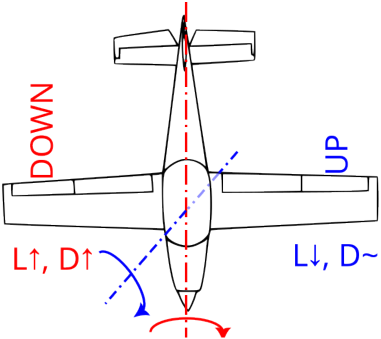


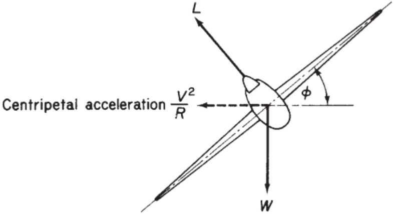
Figure from Megson 2013

2.2. Loads During Maneuvers: “Pure Roll” Banking

2. Aircraft Loads

Let us consider the pure roll condition for banking the aircraft.





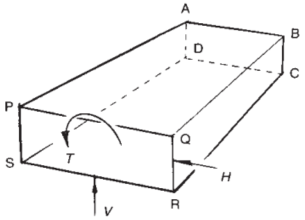
Figures from *The Aircraft Drag Polar 2017; Megson 2013*

2.3. Load-based Design

2. Aircraft Loads

Content from **sec. 5.6.4** in Cutler 2005.

Loads on a Box-Structure



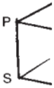
	Type of end load, i.e. tension (+) or compression (–) due to V	due to H	due to T	Type of load in total
Member PA	–	–	0	Large compressive load
QB	–	+	0	Smaller load
RC	+	+	0	Large tensile load
SD	+	–	0	Smaller load
		Type of shear load		
Skin PQBA	0	+	+	High-shear load
QRCB	+	0	+	High-shear load
SRCD	0	–	+	Lower-shear load
SPAD	–	0	+	Lower-shear load

2.3. Load-based Design

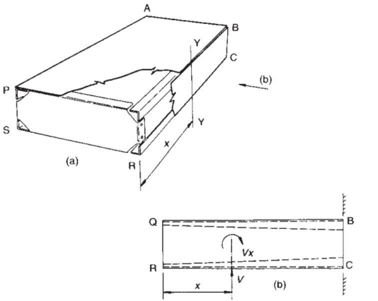
2. Aircraft Loads

Content from sec. 5.6.4 in

Loads



Design modifications due to shear-load V



- Flat member PQRS introduced to maintain **section-integrity**;
- Additional material added at the spar-webs (corners) to support **shearing**;
- "Corner material" increased at fixture to **support moments**.

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load
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r load

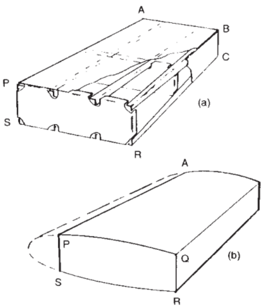
2.3. Load-based Design

2. Aircraft Loads

Content

Loads

Design modifications due to shear H and Torsion T



- Longitudinal members added to prevent **torsional collapse**;
- Horizontal members added to support shear load H, **increase buckling load-carrying capacity** (revisit plate buckling);
- In a real wing these will be,
  - Face PQRS: **Wing Ribs/Fuselage Frames**
  - Longitudinal members: **Stringers**
  - Face QBCR: **Wing Spars**

2.4. Flight Load Envelopes

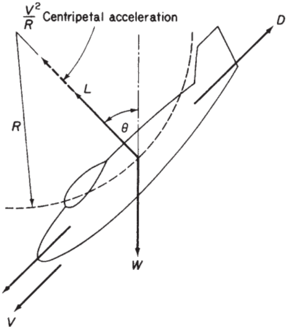
2. Aircraft Loads

- The aircraft experiences **heightened inertial loads** during maneuvers
- It has therefore become customary to specify max. permissible loads in “g’s”, i.e., in acceleration units

Example

In Cutler 2005, it is mentioned that EASA CS-25 specifies the following for large airplanes:

- $9g$ forwards;
- $1.5g$ upwards;
- $6g$ downwards;
- $3g$ rearwards.

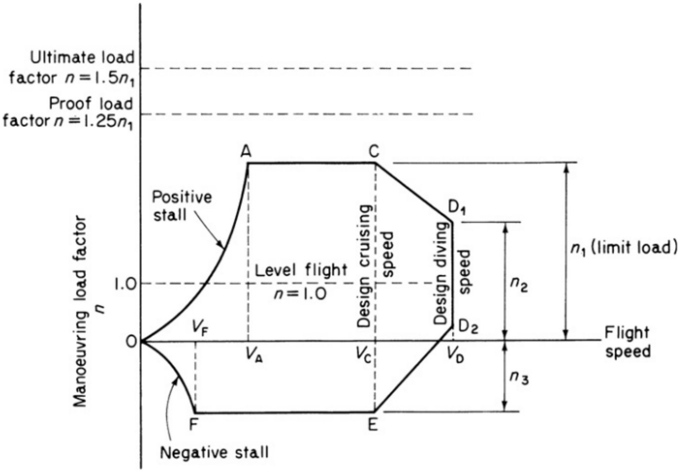


Loads During Steady Pull-Out Maneuver Megson 2013

2.4. Flight Load Envelopes: The V-n Diagram

2. Aircraft Loads

At any given flight speed, the envelope specifies the **load that the flight must be able to withstand**



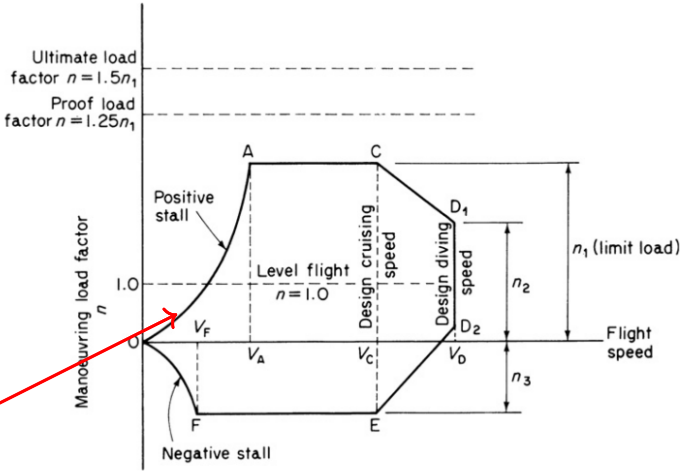
Flight Envelope from Megson 2013

2.4. Flight Load Envelopes: The V-n Diagram

2. Aircraft Loads

At any given flight speed, the envelope specifies the **load that the flight must be able to withstand**

The wings can't carry the aircraft to the left of here



Flight Envelope from Megson 2013

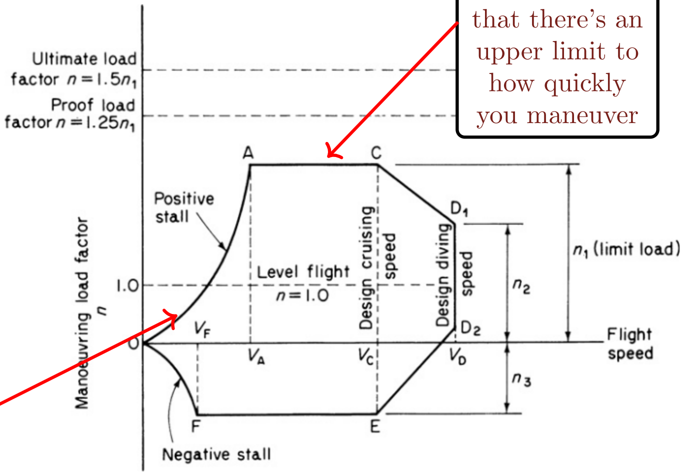
2.4. Flight Load Envelopes: The V-n Diagram

2. Aircraft Loads

At any given flight speed, the envelope specifies the **load that the flight must be able to withstand**

The logic for this cut-off is that there's an upper limit to how quickly you maneuver

The wings can't carry the aircraft to the left of here



Flight Envelope from Megson 2013

2.4. Flight Load Envelopes: The V-n Diagram

2. Aircraft Loads

At any given flight the e[...] speci[...] **load t[...] flight be a[...] with**

The logic for this cut-off is that there's an [...]it to [...]kly [...]uver

(limit load)

Flight speed

The[...] can't[...] the ai[...] the lef[...]

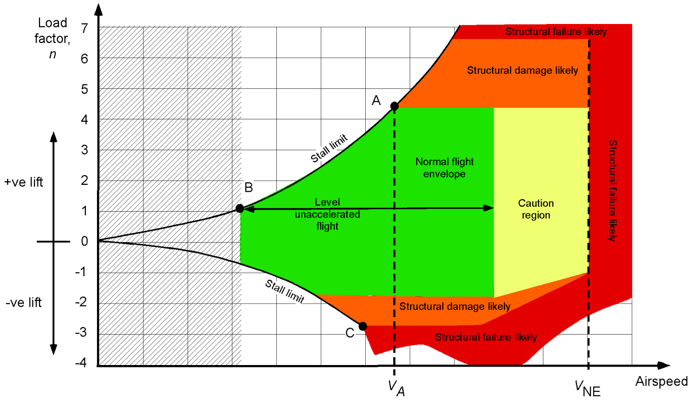
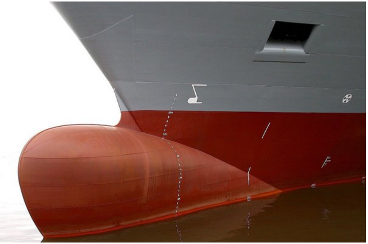


Figure from Leishman 2023

3. Joining Technology

3.1. Welding

- Welding is an “easy road out” for a designer but quite non-ideal in practice
  - Requires high skill;
  - Difficult to inspect for defects;
  - Poor fatigue strength.
- Extensively used in ship-hulls but not so much in aircraft skin
  - Think of the reasons!



The skins of most large ships are welded

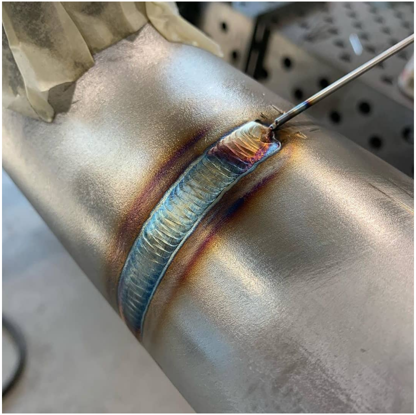
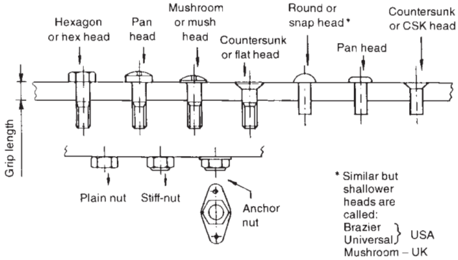


Figure from #WhyWeWeld 2020

3.2. Bolted and Riveted Joints

3. Joining Technology

- Bolts, screws, rivets
- Riveting process:
    - Pop riveting: https://www.youtube.com/watch?v=u9EnPAgo8p4
    - Hot riveting: https://www.youtube.com/watch?v=5aTL0Jvrf4I
- Attaching thin plates to the frames, riveting/bolting (fastening in general) is the most appropriate
- An important consideration for fastening in general is **maintenance**



Types of fasteners Cutler 2005

3.2. Bolted and Riveted Joints

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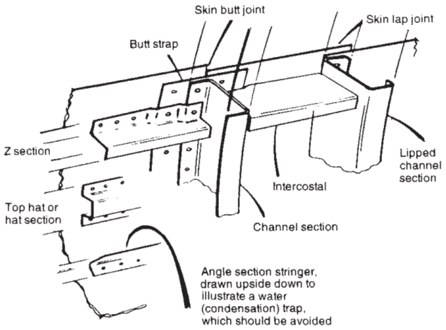


Detail on skin attachment to frame Cutler 2005

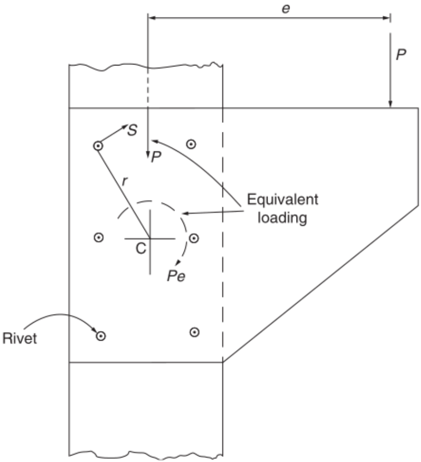
3.3. Strength of a bolted joint

3. Joining Technology

- Considering the strength of a loaded jointed system, we have to **compute the loads on each fastener individually and check for failure**

Bolt-Load Distribution

$$R = \frac{P}{n}, \quad S = \frac{Pe}{\sum r^2} r.$$



Eccentrically loaded joint Megson 2013

3.3. Strength of a bolted joint

3. Joining Technology

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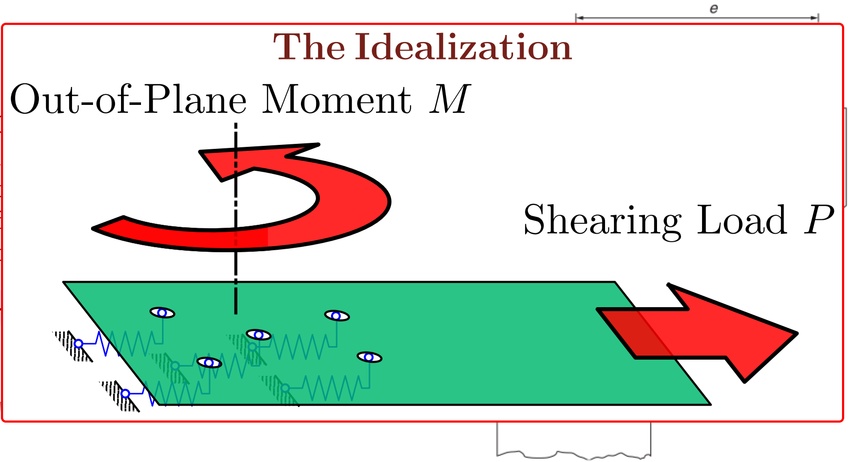

Eccentrically loaded joint Megson 2013

3.3. Strength of a bolted joint

Joining Technology

Some Heuristics for bolted connections

- If F_p is the proof load of a bolt (proportionality limit under tension), then the bolt is to be tightened to

$$\begin{aligned} &0.75F_p \text{ for non-permanent connections,} \\ &0.90F_p \text{ for permanent connections.} \end{aligned}$$

- If d is the *shank diameter* of a threaded fastener, $\mathbf{0.78\frac{\pi d^2}{4}}$ is a **conservative estimate of the effective area under tension/shear in the threaded portions**.
- The proof (proportionality limit) stress S_p is related to the yield limit S_y as $S_p \approx 0.85S_y$.
- From distortion energy theory, $\tau_{\max} = 0.577S_y$.

3.3. Strength of a bolted joint

Joining Technology

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Necessary Reading

In Budynas, Nisbett, and Shigley 2015:

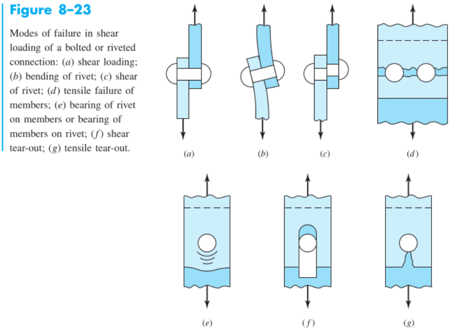
- Sec. 1-9, 1-11
- Sec. 5-3, 5-4, 5-5
- Sec. 8-12

4. Tutorial Session

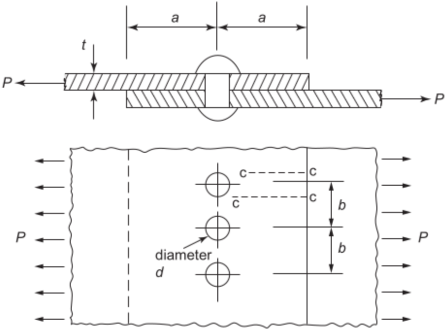
Joint Strength Computation

- Let us first consider the simple lap joint in the right

"Modes" of failure



Modes of joint failures Budynas, Nisbett, and Shigley 2015



Simple Lap Joint Megson 2019

4. Tutorial Session

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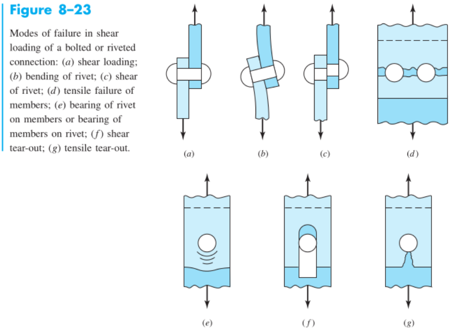
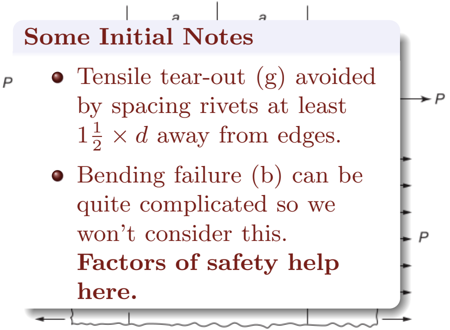


Modes of joint failures Budynas, Nisbett, and Shigley 2015



Some Initial Notes

- Tensile tear-out (g) avoided by spacing rivets at least $1\frac{1}{2} \times d$ away from edges.
- Bending failure (b) can be quite complicated so we won't consider this. **Factors of safety help here.**

Simple Lap Joint Megson 2019

4. Tutorial Session

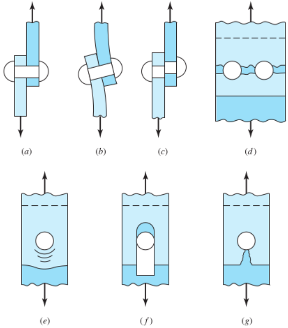
Joint Strength Computation

- Let us first consider the simple lap joint in the right

"Modes" of failure

Figure 8–23

Modes of failure in shear loading of a bolted or riveted connection: (*a*) shear loading; (*b*) bending of rivet; (*c*) shear of rivet; (*d*) tensile failure of members; (*e*) bearing of rivet on members or bearing of members on rivet; (*f*) shear tear-out; (*g*) tensile tear-out.



Modes of joint failures *Budynas, Nisbett, and Shigley 2015*

(c) Rivet Shear

$$\frac{Pb}{(\pi d^2)/4} = \tau_1$$

(d) Member-tensile failure

$$\frac{Pb}{t(b-d)} = \sigma_{ult}$$

(e) Bearing-pressure failure

$$\frac{Pb}{td} = p_b$$

(f) Member-shear failure

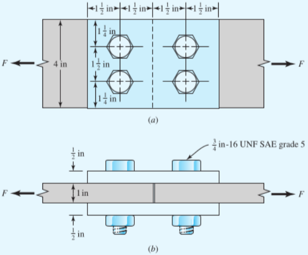
$$\frac{Pb}{2at} = \tau_2$$

4. Tutorial Session

Joint Strength Computation

Example 1 (8-6 in Budynas, Nisbett, and Shigley 2015)

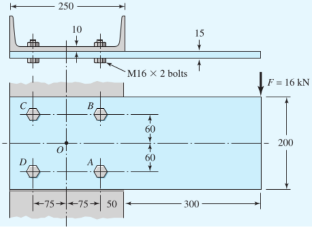
Two 1- by 4-in 1018 cold-rolled steel bars are butt-spliced with two $\frac{1}{2}$- by 4-in 1018 cold-rolled splice plates using four $\frac{3}{4}$ in-16 UNF grade 5 bolts as depicted in Fig. 8–24. For a design factor of $n_d = 1.5$ estimate the static load F that can be carried if the bolts lose preload.



Example 2 (8-5 in Budynas, Nisbett, and Shigley 2015)

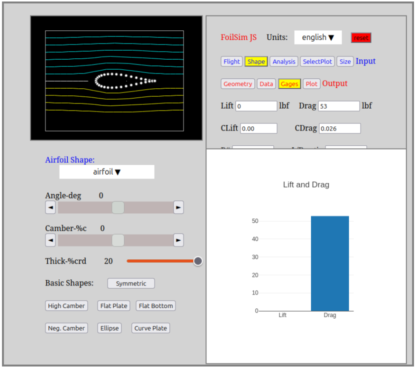
Shown in Fig. 8–28 is a 15- by 200-mm rectangular steel bar cantilevered to a 250-mm steel channel using four tightly fitted bolts located at A, B, C, and D. Assume the bolt threads do not extend into the joint.

For the $F = 16$ kN load shown find
(a) The resultant load on each bolt
(b) The maximum shear stress in each bolt
(c) The maximum bearing stress
(d) The critical bending stress in the bar

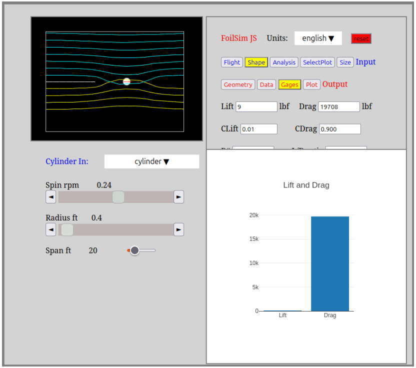


Aside: Airfoils!

- You can do some pretty interesting investigations using the interactive airfoil simulator tool here.



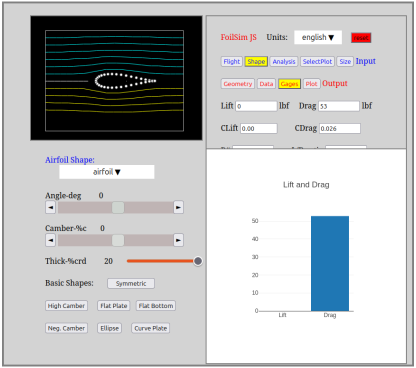
Case 1 Airfoil: 20 ft span, 4 ft chord, 0.8 ft thickness. Drag=53 lbf



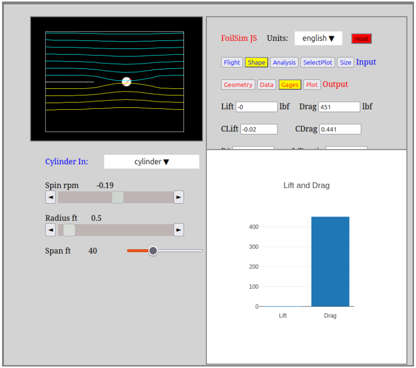
Case 1 Cylinder: 20 ft span, 0.4 ft radius. Drag=19.708 lbf!!

Aside: Airfoils!

- You can do some pretty interesting investigations using the interactive airfoil simulator tool here.



Case 2 Airfoil: 40 ft *span,* 19.9 ft *chord,* 3.98 ft *thickness. Drag*=440 lbf



Case 2 Cylinder: 40 ft *span,* 0.5 ft *radius. Drag*=451 lbf.

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