AS3020: Aerospace Structures

Module 1: Design of Aircrafts

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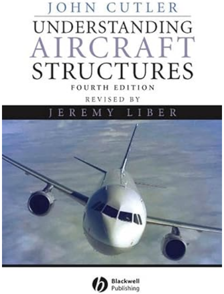
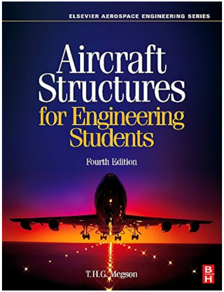


Chapters 1-5,7,9 in Cutler [1]



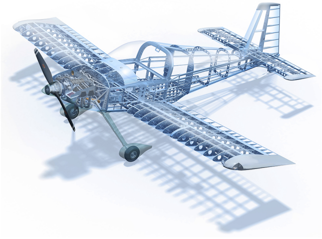
Chapters 12-15 in Megson [2]

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?



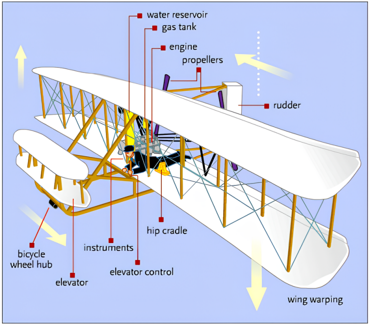
RV-14 Airframe [3]

Textbook References

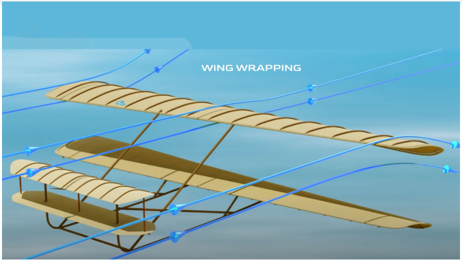
- Chapters 1-5,7,9 in J. Cutler. Understanding Aircraft Structures, Wiley, 2005. ISBN: 978-1-4051-2032-6
- Chapters 12-15 in T. H. G. Megson. Aircraft Structures for Engineering Students, Elsevier, 2013. ISBN: 978-0-08-096905-3.

1.1. Wired Brace Construction: The Wright Flyer

Historical Overview

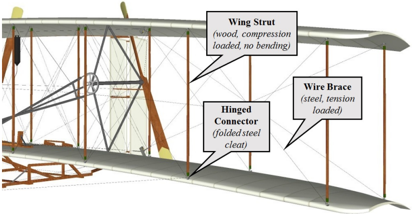


The Wright Flyer, 1903 [4]



The warping wing [5].

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



Wired brace construction [6]

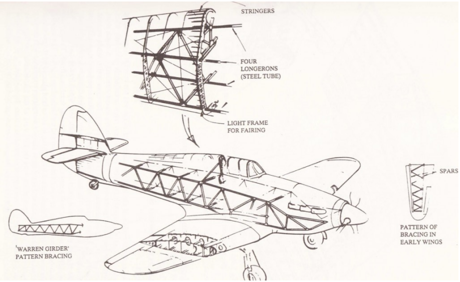
1.2. Braced Fuselage Design

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 [7]

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



Hawker Hurricane frame, 1935 [1]

Warren Truss [8]

Patented truss (∼1840s) formed by equilateral triangles

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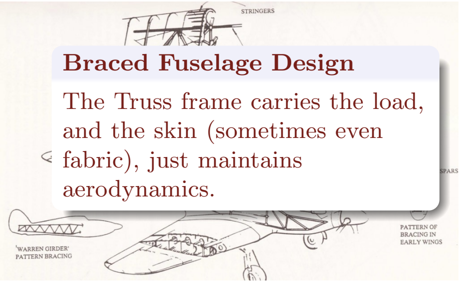


Braced Fuselage Design

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

Hawker Hurricane frame, 1935 [1]

Warren Truss [8]

Patented truss (∼1840s) formed by equilateral triangles

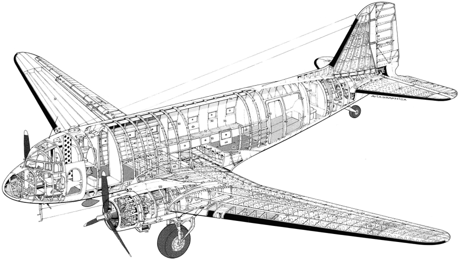
1.3. Semi-Monocoque Design

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 [9]

- 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

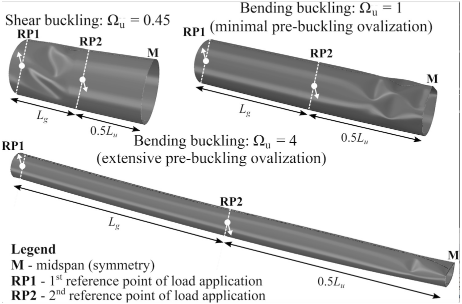


Douglas DC-3 (1933) [10]

1.3. Semi-Monocoque Design

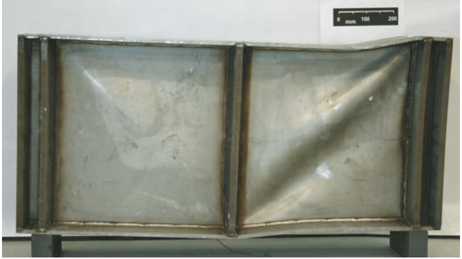
Historical Overview

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



Thin-walled cylinder [11]

- 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 [12]

1.3. Semi-Monocoque Design

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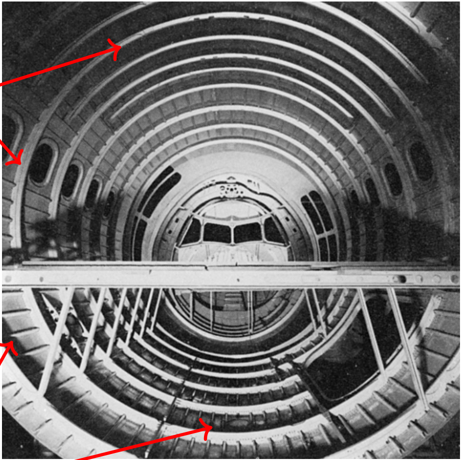
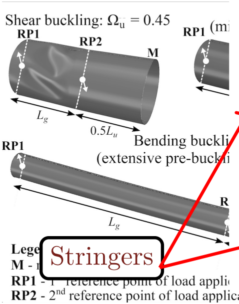


Insides of a fuselage [2]

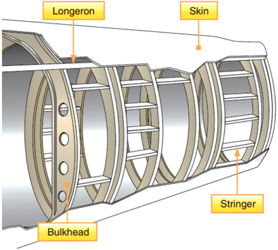


Thin-walled cylinder [11]

Shear buckling [12]

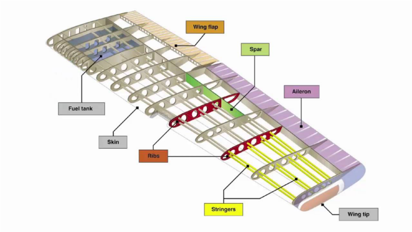
1.3. Semi-Monocoque Design

The Fuselage



Structural members in a fuselage [13]

The Wing



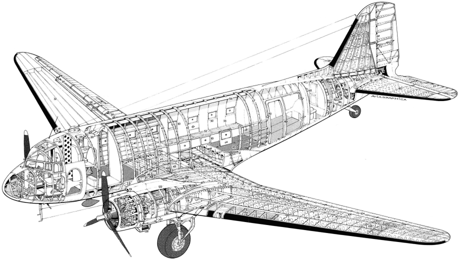
Structural members in a wing-box [14]

- 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)



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Sandwich structures

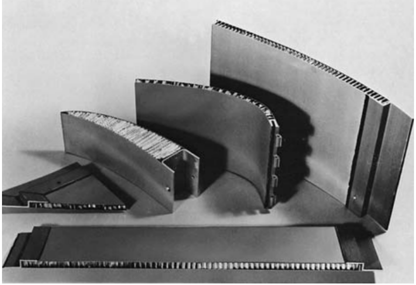

Figure from [1]

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Composite Materials

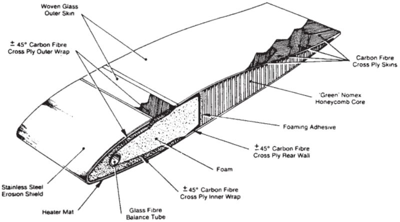

Figure from [2]

1. Historical Overview

Design Overview

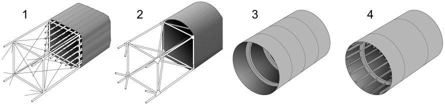

Figure from [3]

The "converged" aircraft

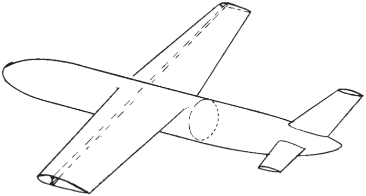

Figure from [1]

Parts of an aircraft

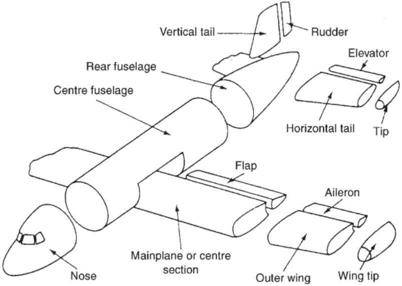

Figure from [2]

1. Historical Overview

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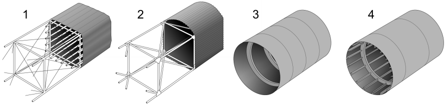

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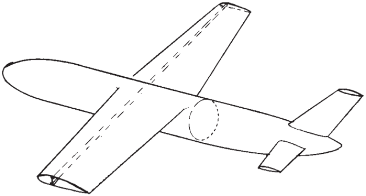

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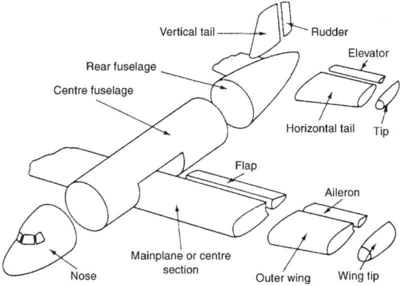


Figure from [2]

- **“Wings”**: Mainplane, tailplane

1. Historical Overview

Design Overview

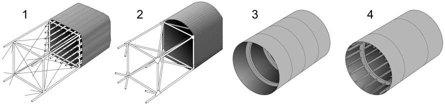


Figure from [3]

The "converged" aircraft

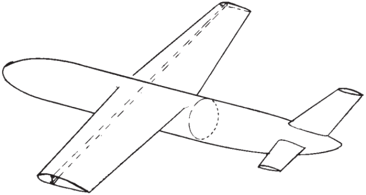


Figure from [1]

Parts of an aircraft

High Lift Devices

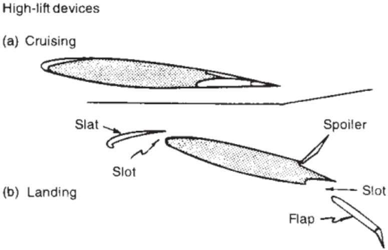
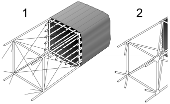


Figure from [1]

- **"Wings"**: Mainplane, tailplane
- **High lift devices**: flaps, ailerons, elevators

1. Historical Overview

Design Overvi



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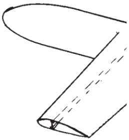
The “converge



F

Dimensions of an Aircraft

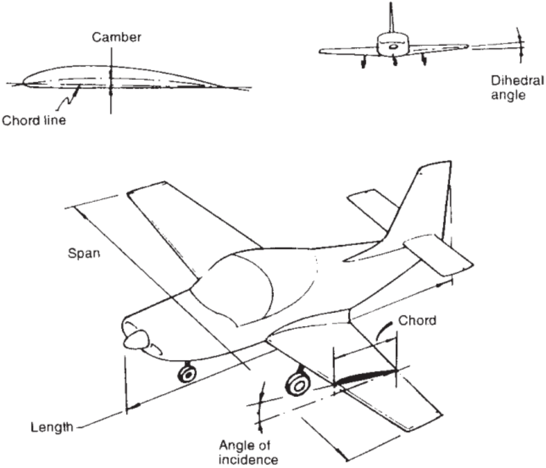
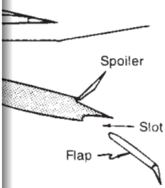


Figure from [1]



[1]

plane,

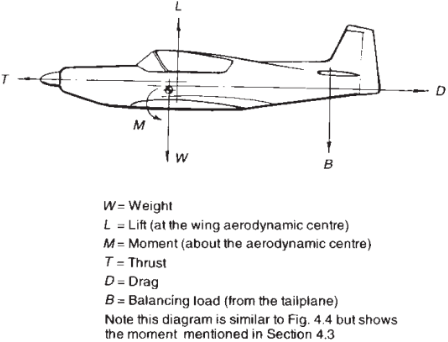
es: flaps,

s

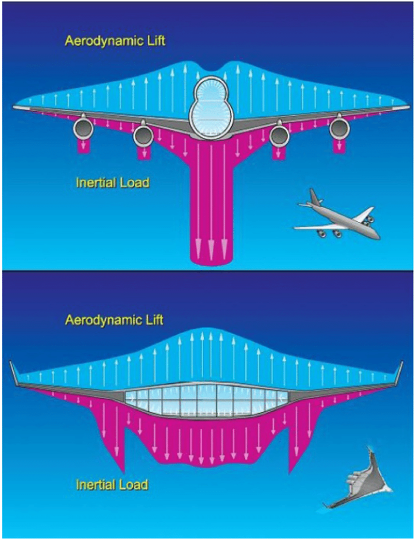
2. Aircraft Loads

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



W = Weight
L = Lift (at the wing aerodynamic centre)
M = Moment (about the aerodynamic centre)
T = Thrust
D = Drag
B = Balancing load (from the tailplane)
Note this diagram is similar to Fig. 4.4 but shows the moment mentioned in Section 4.3



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

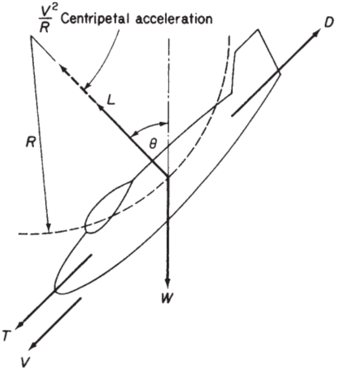


Figure from [2]

Banking

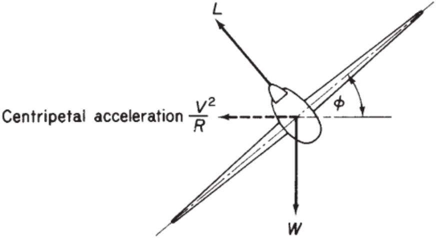
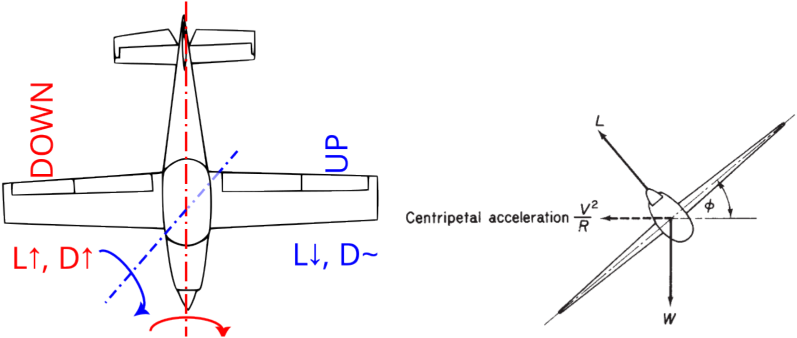


Figure from [2]

2.2. Loads During Maneuvers: “Pure Roll” Banking

2. Aircraft Loads

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



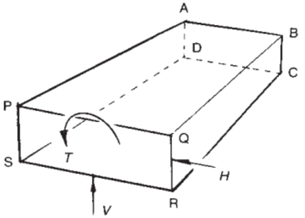
Figures from [2, 16]

2.3. Load-based Design

2. Aircraft Loads

Content from **sec. 5.6.4** in [1].

Loads on a Box-Structure



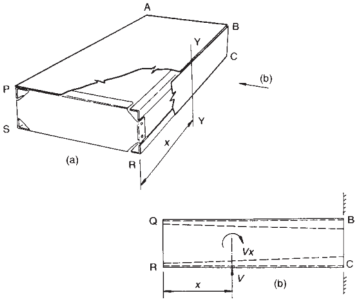
	Type of end load, i.e. tension (+) or compression (–)			
	due to V	due to H	due to T	Type of load in total
Member PA	–	–	0	Large compressive load
QB	–	+	0	Smaller load
RC	+	+	0	Large tensile load
SD	+	–	0	Smaller load
		Type of shear load		
Skin PQBA	0	+	+	High-shear load
QRCB	+	0	+	High-shear load
SRCD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

2.3. Load-based Design

2. Aircraft Loads

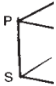
Content from sec. 5.6.4 in [1]

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**.

Loads



d in total
pressive load
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le load
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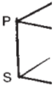
r load
r load

2.3. Load-based Design

2. Aircraft Loads

Content

Loads



d in total

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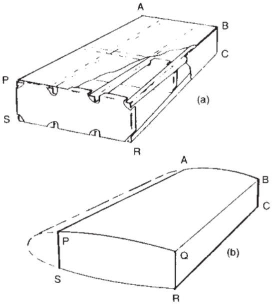
r load

Design modifications due to shear H and Torsion T



- Longitudinal members added to prevent **torsional collapse**;
- Horizontal members added to support shear load H;
- 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

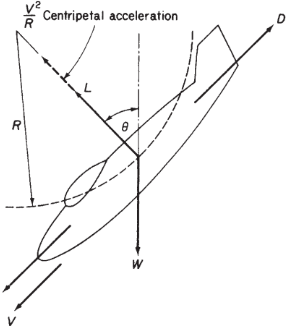
2. Aircraft Loads

- 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 [1], it is mentioned that EASA CS-25 specifies the following for large airplanes:

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

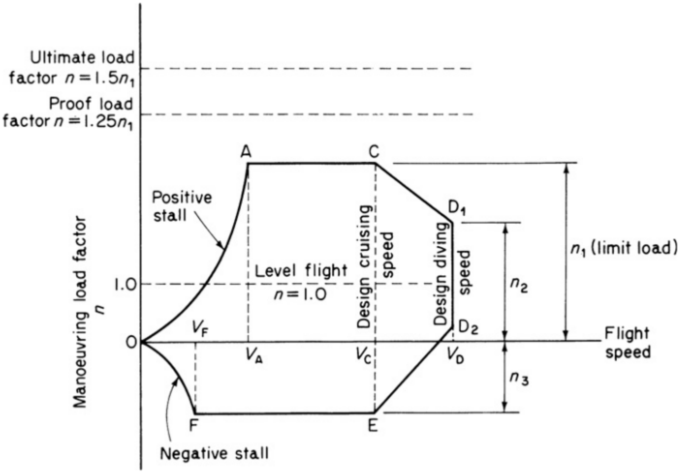


Loads During Steady Pull-Out Maneuver [2]

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 [2]

2.4. Flight Load Envelopes: The V-n Diagram

2. Aircraft Loads

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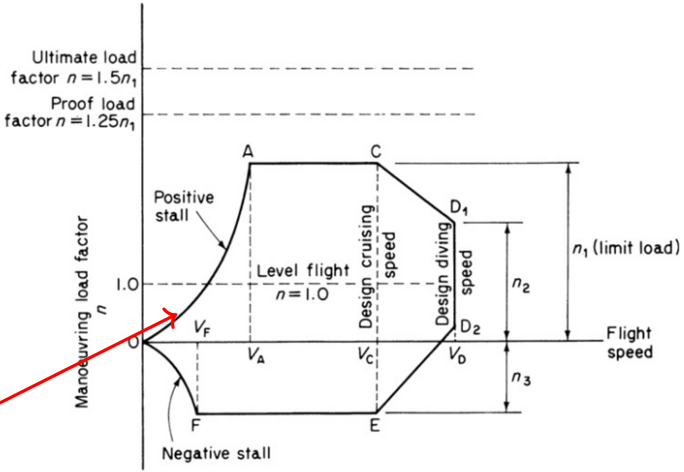


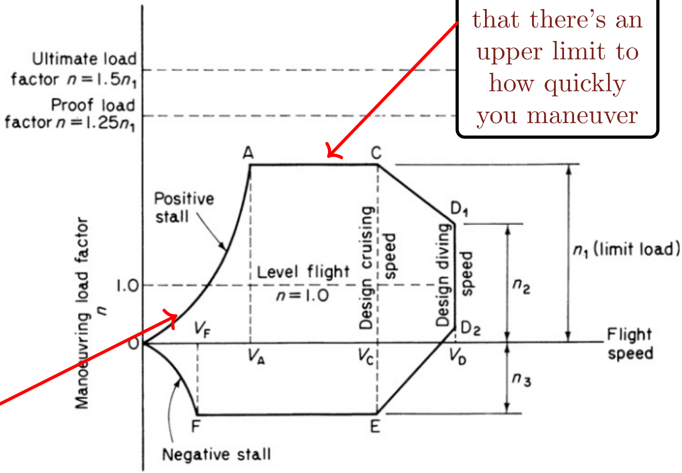
The wings can't carry the aircraft to the left of here

Flight Envelope from [2]

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

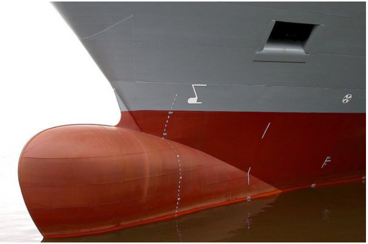
The wings can't carry the aircraft to the left of here

Flight Envelope from [2]

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
  - Listing out reasons will be part of your first assignment! ;)



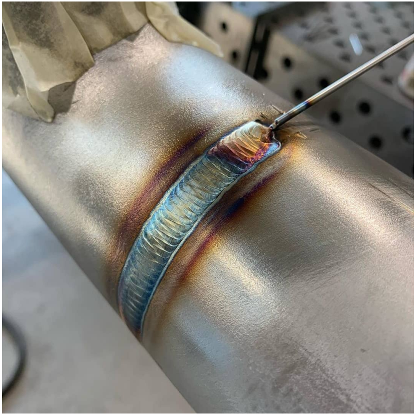
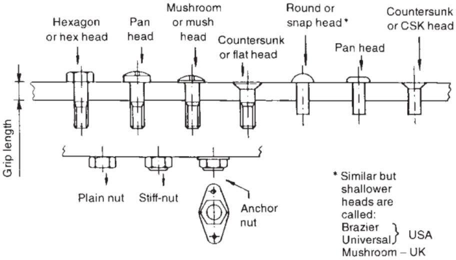


Figure from [17]

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**

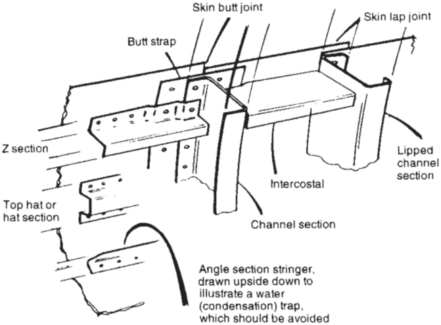


Types of fasteners [1]

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**



Detail on skin attachment to frame [1]

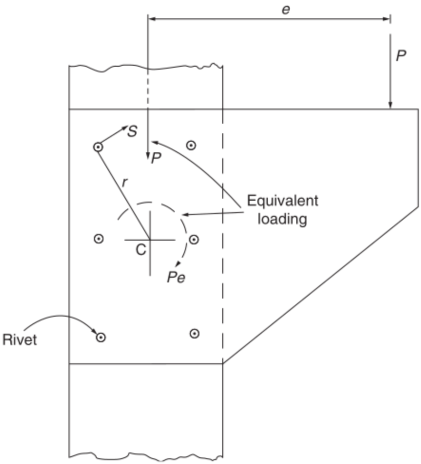
3.3. Strength of a bolted joint

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

$$S = \frac{Pe}{\sum r^2} r$$



Eccentrically loaded joint [2]

4. Tutorial Session

Joint Strength Computation

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

“Modes” of failure

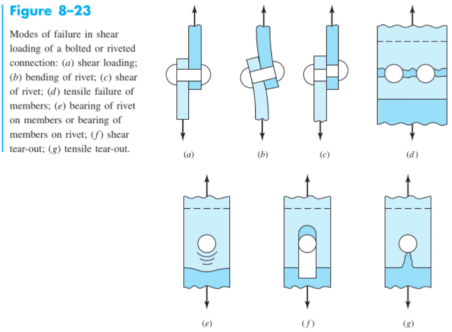
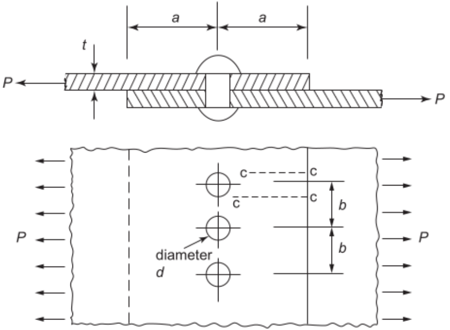


Figure 8–23

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 [18]



Simple Lap Joint [19]

4. Tutorial Session

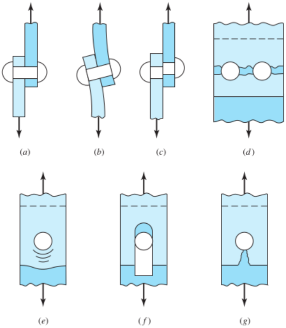
Joint Strength Computation

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

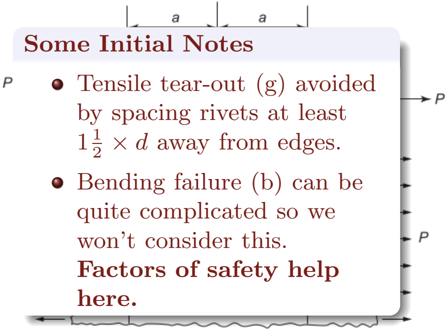
"Modes" of failure

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 [18]



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 [19]

4. Tutorial Session

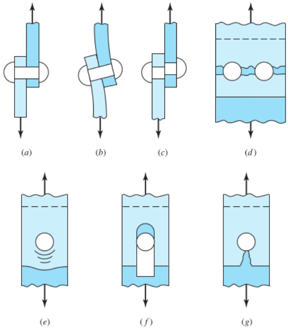
Joint Strength Computation

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

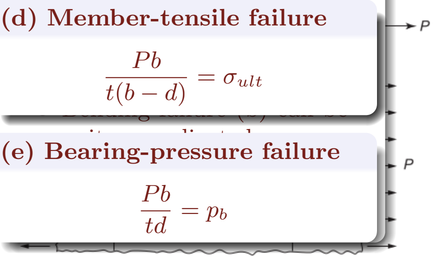
"Modes" of failure

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 [18]



(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

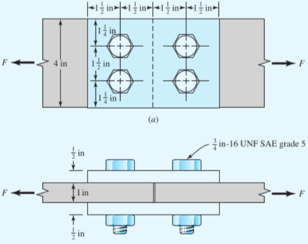
$$\frac{Pb}{2at} = \tau_2$$

4. Tutorial Session

Joint Strength Computation

Example 1 [18]

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.



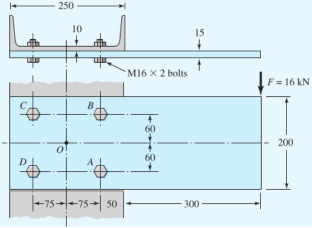
(a)

(b)

Example 2 [18]

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



References I

[1] J. Cutler. Understanding Aircraft Structures, Wiley, 2005. ISBN: 978-1-4051-2032-6 (cit. on pp. 2, 3, 5, 6, 11–18, 21–24, 29, 30).

[2] T. H. G. Megson. Aircraft Structures for Engineering Students, Elsevier, 2013. ISBN: 978-0-08-096905-3 (cit. on pp. 2, 3, 8, 9, 11–17, 19, 20, 24–27, 31).

[3] "Airframe". Wikipedia, (June 2024). URL: `https://en.wikipedia.org/w/index.php?title=Airframe&oldid=1228362623` (visited on 08/05/2024) (cit. on pp. 3, 14–17).

[4] *NOVA | Wright Brothers' Flying Machine | Pilot the 1903 Flyer (Non-Interactive) | PBS.* URL: `https://www.pbs.org/wgbh/nova/wright/flye-nf.html` (visited on 08/05/2024) (cit. on p. 4).

[5] *History of First Flight.* URL: `https://www.lesics.com/history-of-first-flight.html` (visited on 08/05/2024) (cit. on p. 4).

[6] *Flyer Fatality – Solution.* URL: `http://niquette.com/puzzles/flyerfts.html` (visited on 08/05/2024) (cit. on p. 4).

References II

[7] *Team of Volunteers Finish Building WWI Plane after More than 20 Years.* July 2022. URL: `https://rollingout.com/2022/07/27/team-of-volunteers-finish-building-wwi-plane-after-more-than-20-years/` (visited on 08/05/2024) (cit. on pp. 5, 6).

[8] *STRUCTURE Magazine | The Warren Truss.* URL: `https://www.structuremag.org/?p=8715` (visited on 08/05/2024) (cit. on pp. 5, 6).

[9] *Lyman-Morse Builds New in Wood and Glue - Professional BoatBuilder Magazine.* URL: `https://www.proboat.com/2017/08/lyman-morse-builds-new-wood-glue/` (visited on 08/05/2024) (cit. on p. 7).

[10] *Douglas DC-3 Cutaway Drawing in High Quality.* Feb. 2019. URL: `https://conceptbunny.com/douglas-dc-3/` (visited on 08/05/2024) (cit. on pp. 7, 11–13).

References III

[11] *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.* URL: `https://shellbuckling.com/presentations/unstiffenedCylinders/pages/page_345.html` (visited on 08/05/2024) (cit. on pp. 8, 9).

[12] N. Saliba and L. Gardner. "Experimental Study of the Shear Response of Lean Duplex Stainless Steel Plate Girders". Engineering Structures, **46**, (Jan. 2013), pp. 375–391. DOI: `10.1016/j.engstruct.2012.07.029` (cit. on pp. 8, 9).

[13] *22.12.2. Monocoque Type.* URL: `https://www.abbottaerospace.com/aa-sb-001/22-aircraft-specific-design-features-and-design-methods/22-12-53-fuselage/22-12-2-monocoque-type/` (visited on 08/05/2024) (cit. on p. 10).

[14] *22.16.2. Main Wing Box.* URL: `https://www.abbottaerospace.com/aa-sb-001/22-aircraft-specific-design-features-and-design-methods/22-16-57-wings/22-16-2-main-wing-box/` (visited on 08/05/2024) (cit. on p. 10).

References IV

[15] P. Okonkwo and H. Smith. "Review of Evolving Trends in Blended Wing Body Aircraft Design". Progress in Aerospace Sciences, **82**, (Feb. 2016). DOI: `10.1016/j.paerosci.2015.12.002` (cit. on p. 18).

[16] *The Aircraft Drag Polar*. Aug. 2017. URL: `https://aerotoolbox.com/drag-polar/` (visited on 08/06/2024) (cit. on p. 20).

[17] #WhyWeWeld. *Getting Started with TIG Welding*. June 2020. URL: `https://medium.com/@whyweweld/getting-started-with-tig-welding-82ac654ca949` (visited on 08/05/2024) (cit. on p. 28).

[18] R. G. Budynas, J. K. Nisbett, and J. E. Shigley. Shigley's Mechanical Engineering Design, Tenth edition. Mcgraw-Hill Series in Mechanical Engineering. New York, NY: McGraw-Hill Education, 2015. ISBN: 978-0-07-339820-4 (cit. on pp. 32–35).

[19] T. H. G. Megson. Structural and Stress Analysis, Fourth edition. Oxford, United Kingdom ; Cambridge, MA: Butterworth-Heinemann, 2019. ISBN: 978-0-08-102586-4 (cit. on pp. 32–34).