Aircraft structures

1. Aerostructure design
2. Structural examples
3. Fasteners and bonding

2B: Aircraft structures supplement

Lecture Presented By: Kevin Kochersberger

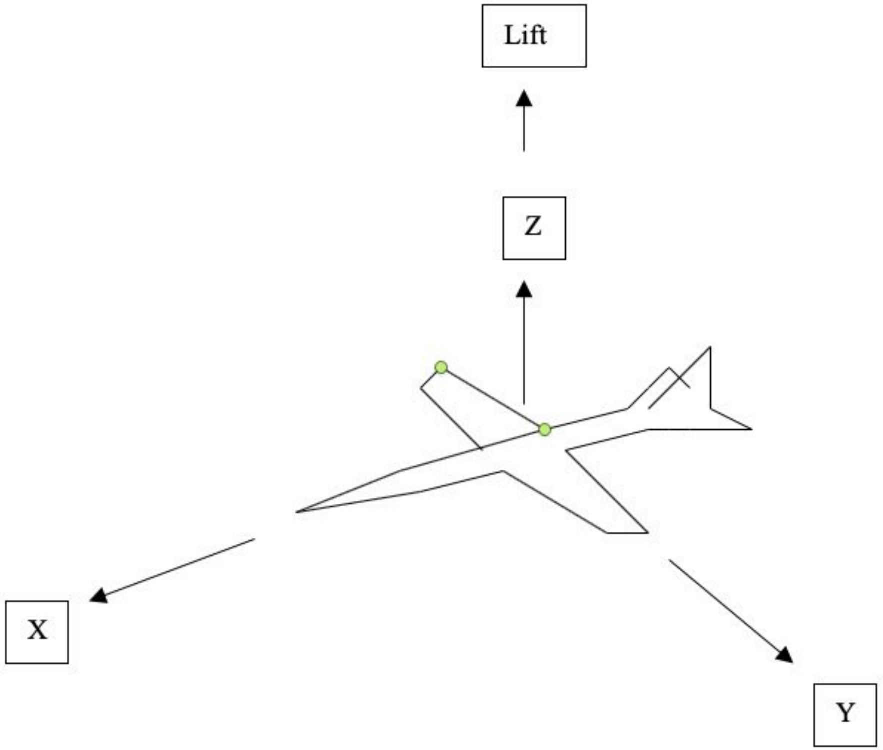
In this lecture you will learn:

- How aircraft structures are designed
- Examples of typical aircraft structures

The design of an aircraft structure starts by considering the loads that must be carried

- A load factor in each orthogonal direction is determined from the flight maneuvers
  - The aircraft is designed to carry these loads without failure
- Load factors in the *x, y,* and *z* directions are expressed as n_x n_y *and* n_z
  - The load factor is a multiplier to the weight (W) of the aircraft

$$\sum F_x = n_x W \qquad \sum F_y = n_y W \qquad L = n_z W$$



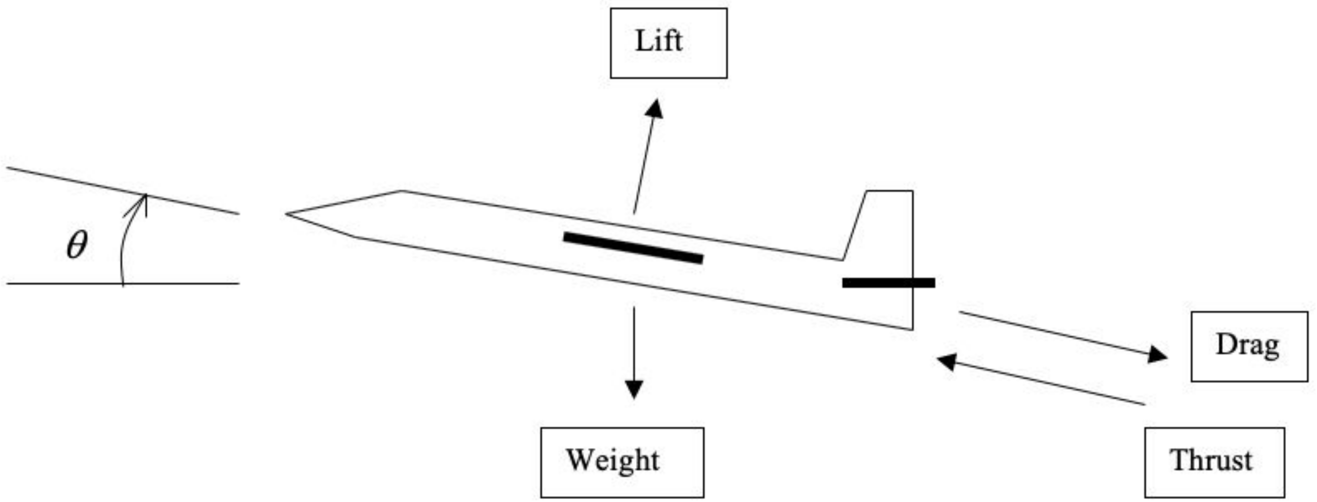
Loading above non-accelerated, level flight is caused by flight loads through maneuvering and gusts

- As the aircraft maneuvers and responds to gusts, it is subject to additional loading

$$n_z = \frac{a_z}{g} + \cos\theta$$

$$n_x = \frac{\sum F_x}{W} = \frac{a_x}{g}$$

$$n_y = \frac{\sum F_y}{W} = \frac{a_y}{g}$$



Vertical gusts cause additional loading which can be defined by considering the vertical component of wind

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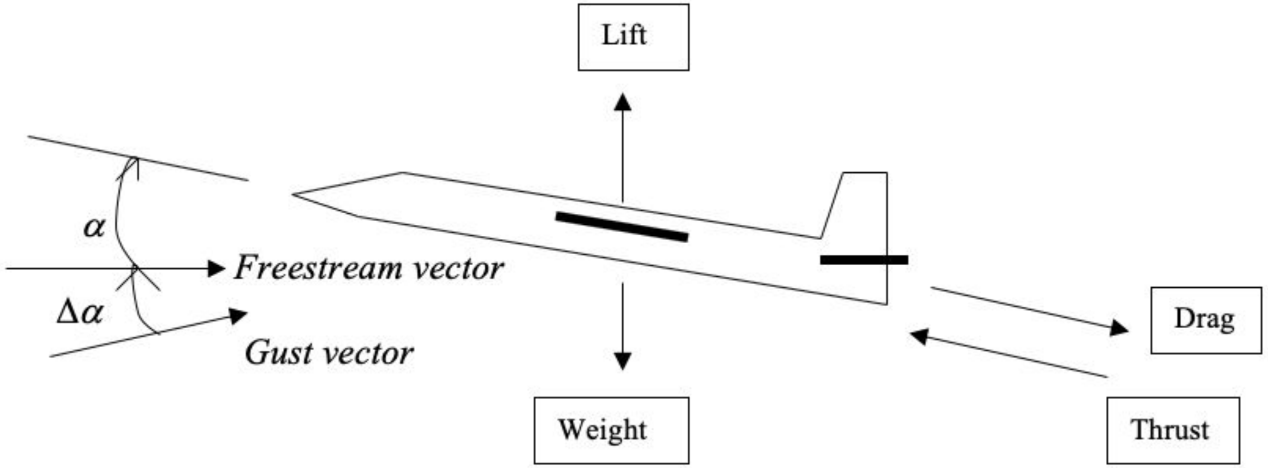
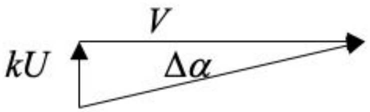
- As the aircraft maneuvers and responds to gusts, it is subject to additional loading
- A vertical gust of magnitude *kU* causes an additional angle of attack on the wing

$$n_z = 1 + \frac{\rho V C_{L\alpha} k U}{2 W/S}$$



The change in angle of attack is related to the *vertical gust velocity U*, the *shape* of the gust, and the *freestream velocity V:*



The relationship between load factor if the aircraft encounters a gust, and aircraft speed, is expressed in a *V – n* diagram

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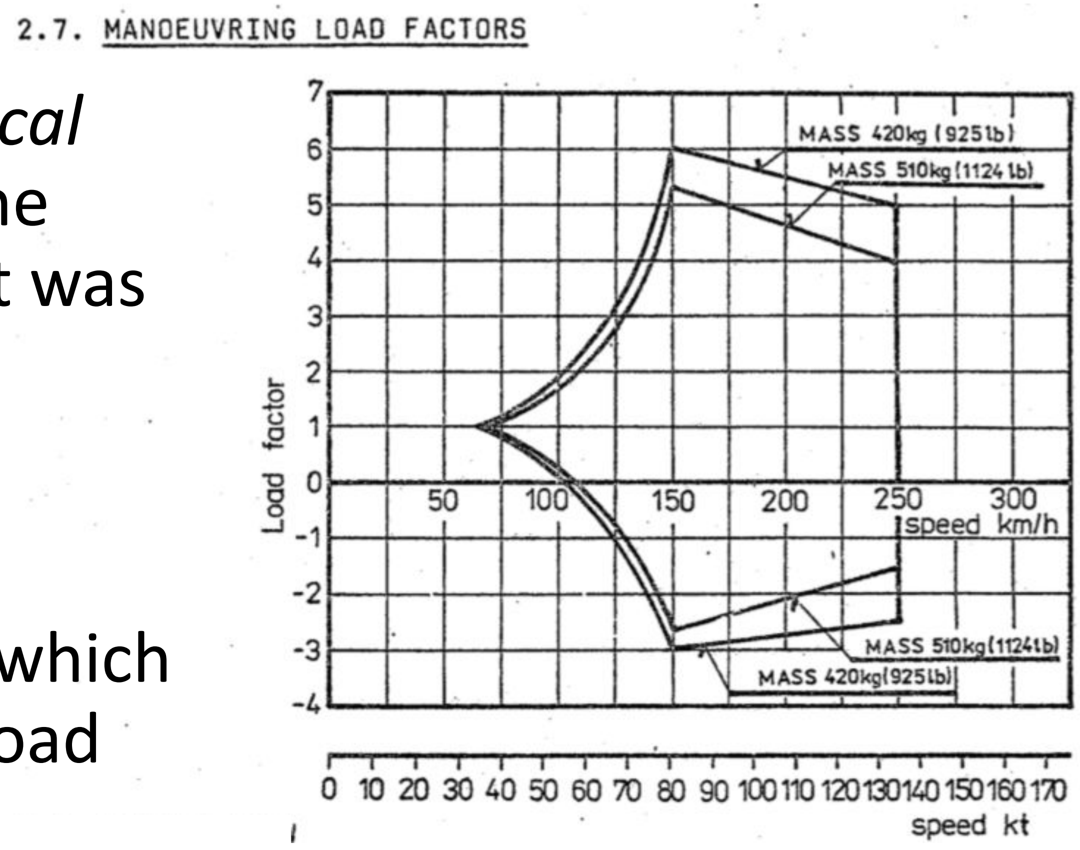
- The V-n diagram shows the *maximum vertical load factor* that would be encountered if the airplane generated the maximum lift that it was capable of generating (at C_L max)
- Note that as the airspeed increases, the potential to generate large loads increases
- The speed of 150 km/h marks the point at which maneuvering must be limited to keep the load factor below 6



The load factor directly tells us what loads will be applied to the aircraft

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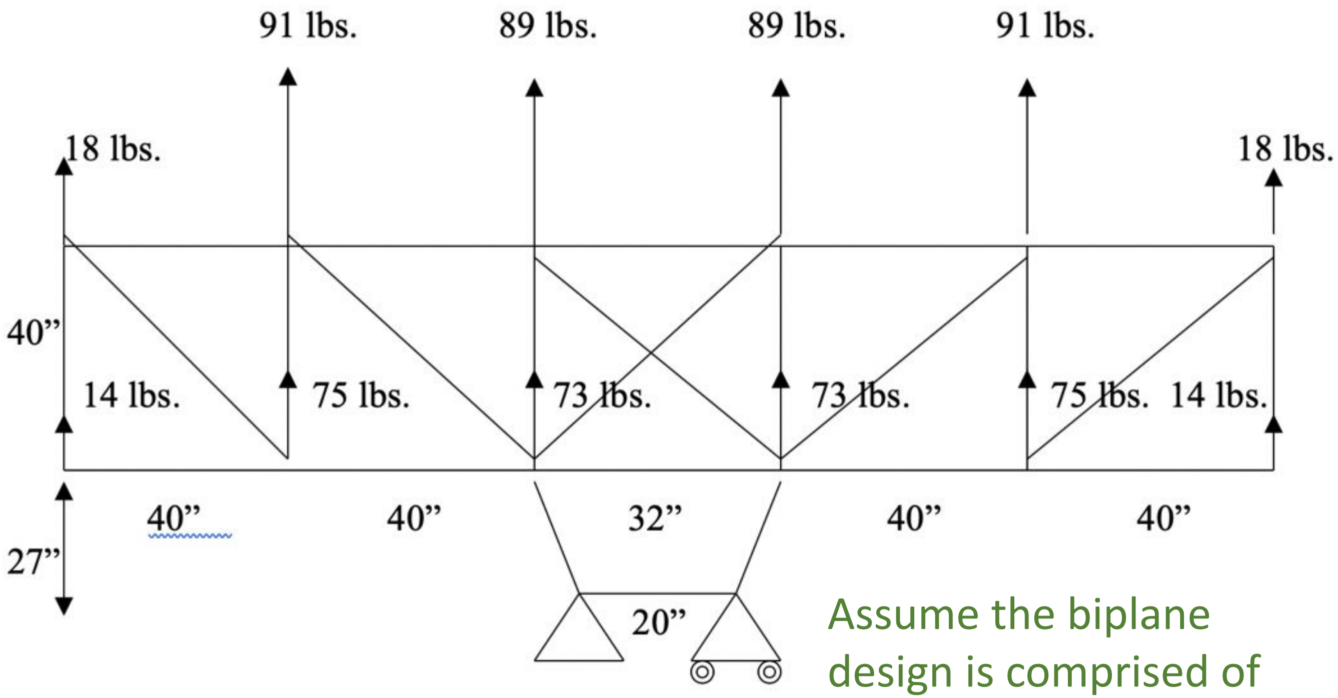
- In the aircraft structural design, it is important to **design the structure to support the design loads** and **include a factor of safety** to ensure the aircraft does not fail
- The **factor of safety (FS)** is typically **1.5 – 2.0** for aircraft
- Simplifying analyses can be performed to ensure the aircraft structure is adequate



Assume the biplane design is comprised of pinned joints with two-force members only

The wing spar carries most of the wing loads

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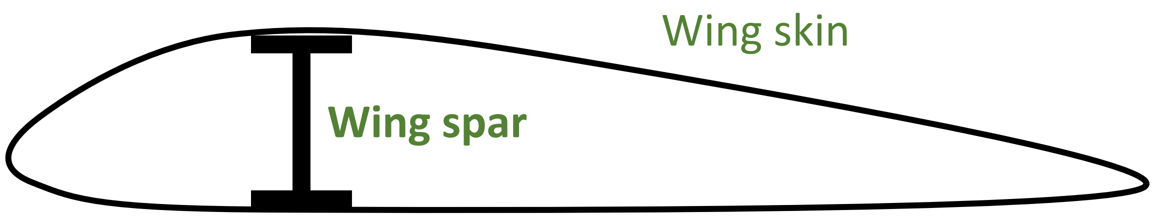
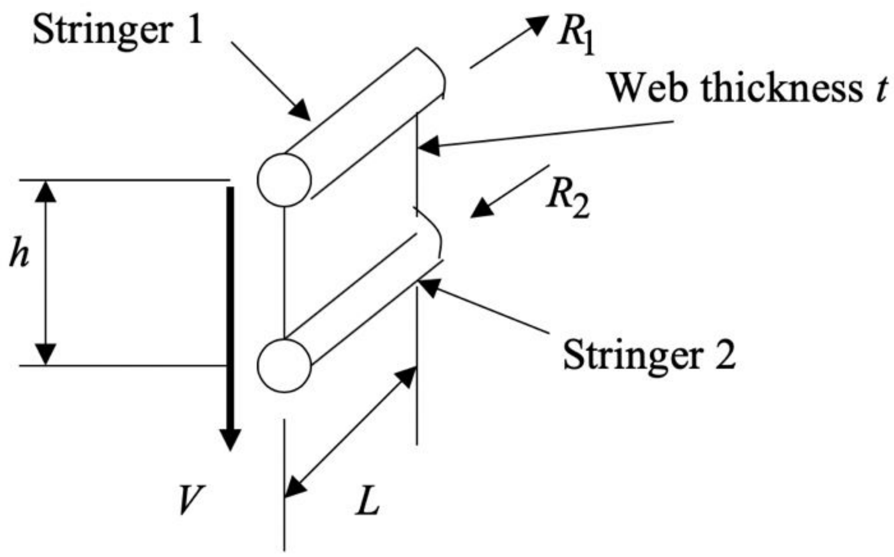
- Many structures in aircraft can be analyzed as beams in bending
- The **wing spar** is comprised of ***flanges or stringers*** on the top and bottom, and a ***web*** in the middle
- The loads generated by the wing in lift are transferred to this spar





A stringer-web structure is commonly found in wings and is a simplified model for analyzing wing spars

The lift can be approximated as a resultant vector in the center of the wing

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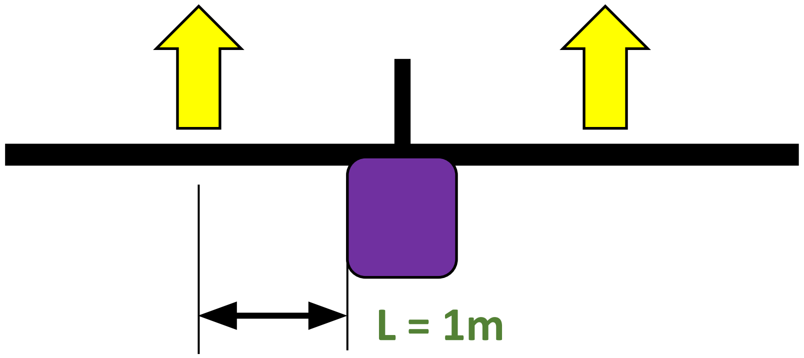
- For the wing spar section shown on the right, if the wing has a 4m wingspan, then we can approximate the max stress in the top and bottom flanges
- In **straight and level flight**, if the aircraft weighs 20 N, then the lift generated by the wings is 20 N
- If the aircraft experiences a maneuver that results in a **vertical acceleration of 3g**, the lift generated by the wings is:



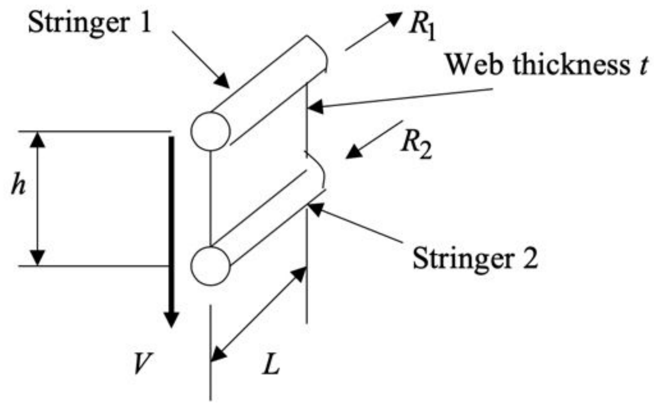
Straight and level flight:

$$Lift = W = 20N$$

3*g* maneuver:

$$Lift = Wn_z = 20N * 3 = 60N$$

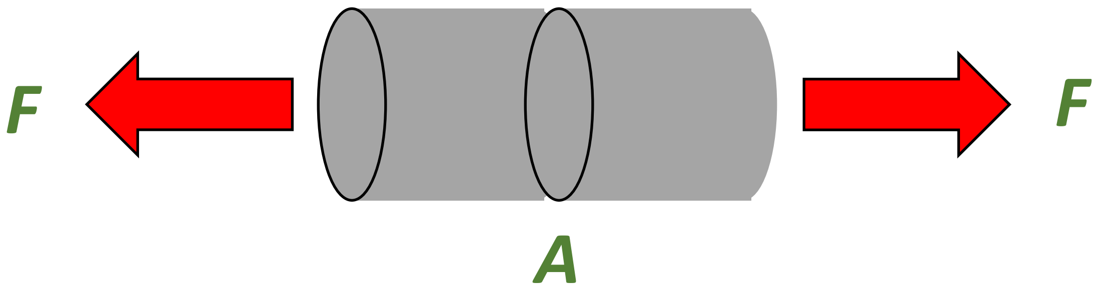
A = x-section area of stringer = 2.5e^{-5}m^2



Wing spar x-section

Stress is the force/area that the spar material experiences

- A factor of safety is applied to account for factors that are not possible to model
  - Manufacturing imperfections
  - Material defects
  - Assembly errors – may cause higher-than-expected loads on the airframe
- If (computed stress)(*FS*) < S_y, the material will not fail



$$\sigma = \frac{F}{A} \qquad FS \leq \frac{S_y}{\sigma}$$

S_y = Material yield strength in MPa

Stress is the force/area that the spar material experiences

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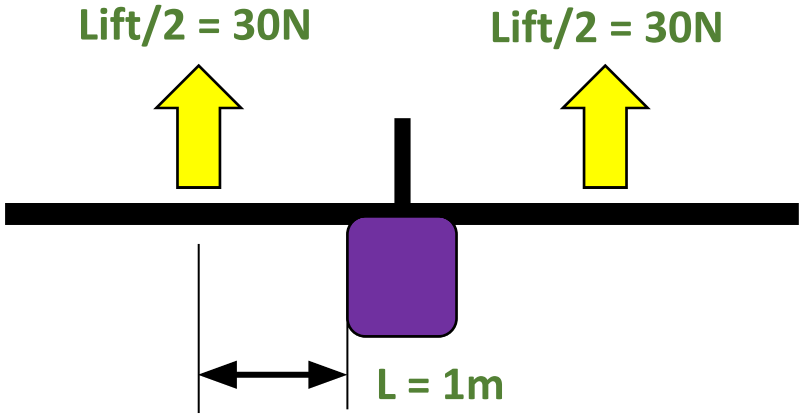
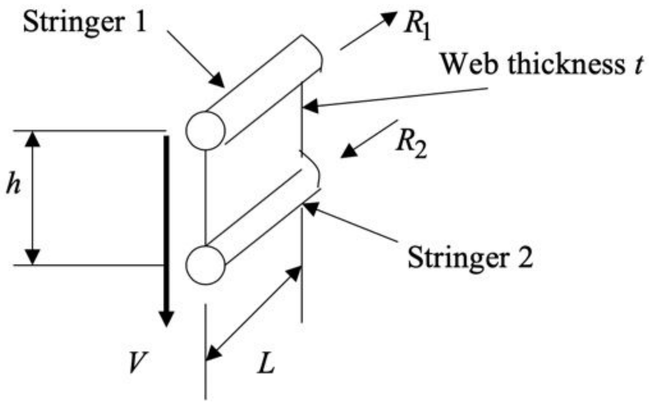
- For the wing spar section shown on the right, if the wing has a 4m wingspan, then we can approximate the **max stress in the top and bottom flanges** as:



A = x-section area of stringer = $2.5e^{-5}m^2$



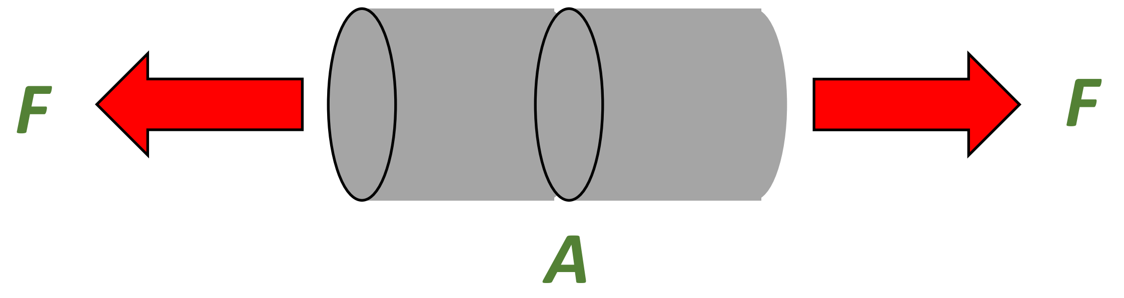
Wing spar x-section

$$\sigma = \frac{Moment * h}{2I} = \frac{Mh}{2I} = \frac{\frac{Lift}{2} * L * h}{2(\frac{Ah^2}{2})} = \frac{Lift * L}{2Ah} = \frac{60Nm}{2 * 2.5e^{-5} * .02}$$

$$\sigma = 60\ MPa$$

The resulting stress is compared to the material strength to determine if the design is safe

- 6061 Aluminum, a popular aluminum used in aircraft structures, has a yield strength $S_y = 290\ MPa$
- If the required factor of safety is *FS = 2,* then we can check to see if the aircraft is designed with adequate strength



$$FS \leq \frac{S_y}{\sigma}$$

$$2.0 \leq \frac{290}{60} = 4.8$$

Because the computed factor of safety (4.8) is greater than the required factor of safety (2.0), the design is good!

Aircraft designs must maximize strength and reduce weight

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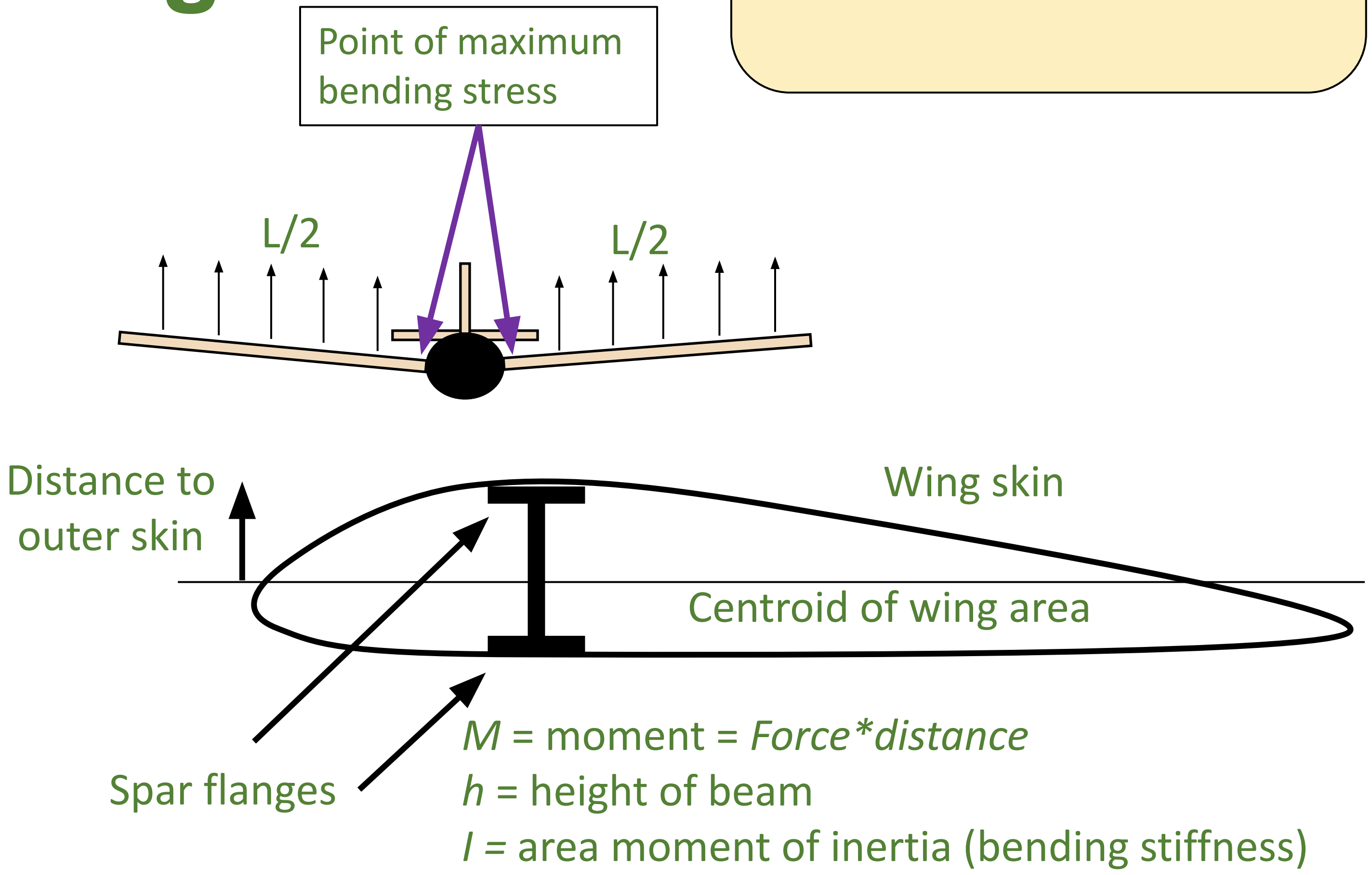
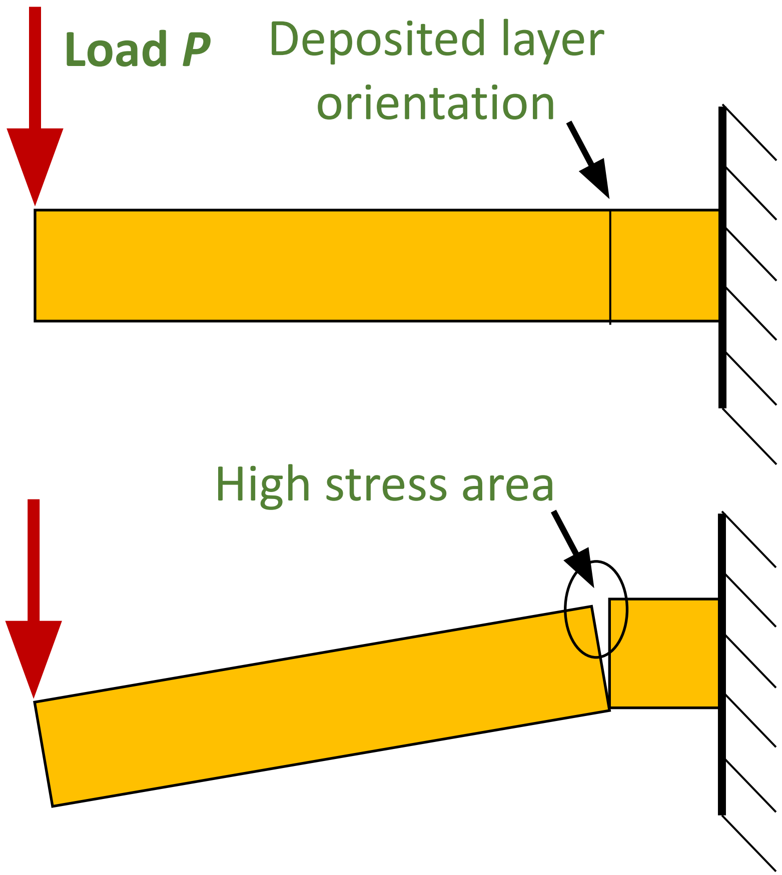
- This is accomplished in a structural design that **maximizes the distance of wing material** from the centroid to the **outer structure**
- Wings are made **strong and lightweight** by designing the wing skin to carry loads like the spar flanges



$$\sigma = \frac{Mh}{2I}$$

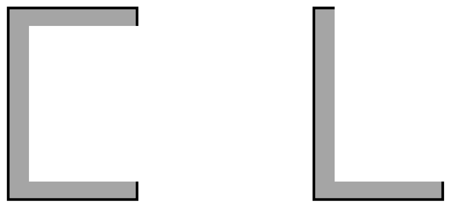
3D printed structures are not always printed in the optimal orientation which results in a reduction of strength

- Care must be taken to print parts so that high stress areas area not unfavorably oriented
- **High loads** that are **perpendicular to the print direction** should be avoided as this is a weak orientation for 3D printed parts
- **Bending loads result in high normal tension loads** at the extreme sides of structures where failure is more likely to occur
- Prints should consider the normal stress due to bending



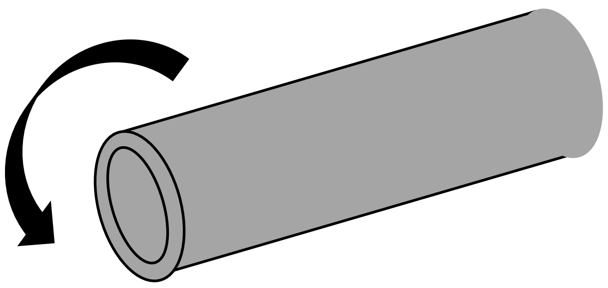
Simple rules can be used in creating strong but lightweight structures

- Torsional loads are best carried by “closed section” structures
  - These are structures that have a cross section which is continuous
  - Open sections (such as L or C shapes) cannot carry torsional loads effectively

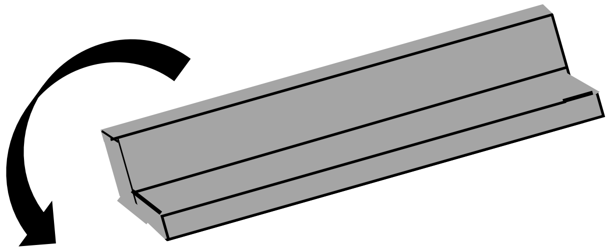


Cross sections that are “open”

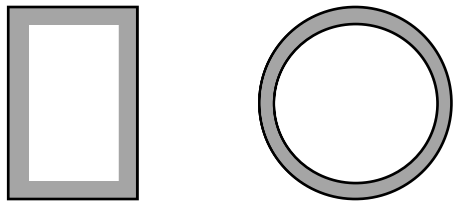
Applied torque T



Good!



Bad!



Cross sections that are “closed”

Simple rules can be used in creating strong but lightweight structures

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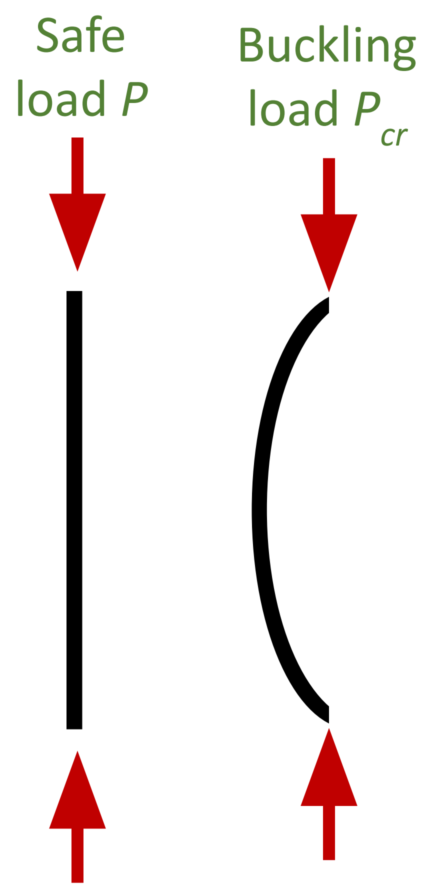
- Thin columns that carry axial loads are **effective in tension** but **not effective in compression**
- Compression loads in thin columns can cause buckling to occur
  - Buckling is a condition of instability of the member and results in a catastrophic failure of the structural member

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2}$$

  - Reducing the column length or load will reduce the likelihood for failure

E = Modulus of elasticity (stiffness of material)
I = Cross section area moment of inertia
K = Column effective length factor (=1 for the pinned example shown)
L = Column length

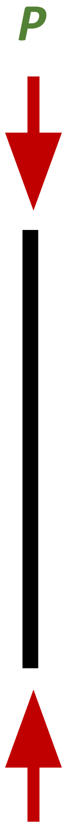


Buckling example

- PLA (Polylactic Acid) is a common 3D printing thermoplastic material
- The datasheet for PLA indicates E = 2.3 Gpa
- If a column is 5 cm long and 4 mm in diameter, determine the critical buckling load assuming pinned connections

$$I = \frac{\pi D^4}{64} = 1.26e^{-11}$$

$$P_{cr} = \frac{\pi^2 EI}{(KL)^2} = \frac{\pi^2 (2.3e^9) 1.26e^{-11}}{(.05)^2} = 114\ N$$



PLA
(Polylactic Acid)

SD3D

Technical Data Sheet

Property	Imperial	Metric
Tensile Properties		
ASTM D638 - Type V		
Property	**Imperial**	**Metric**
Toughness*	7.7 ft·lb/in2	16.2 KJ/m2
Tensile Modulus	293000 psi	2.3 GPa
Ultimate Tensile Strength	7080 psi	26.4 MPa
Tensile Strength at Yield	8840 psi	35.9 MPa
Elongation at Yield	2%	2%
Elongation at Break	4%	4%
3D Printing Properties		
Property	**Imperial**	**Metric**
Expected Max Linear Print Speed	3.54 in/s	90 mm/s
Hardness, **ASTM D2240**	95D	95D
Solid Density, **ASTM D792**	4.48 x 10-2 lb/in3	1.24 g/cc
Impact Properties		
Property	**Imperial**	**Metric**
Notched Izod (machined), 23 C, **ASTM D256**	0.3 f·lb/in	16 J/m
Gardner Impact, 23 C, **ASTM D5420**	10.3 ft·lb	14 J
Thermal Properties		
Property	**Imperial**	**Metric**
Glass Transition by DSC, **ASTM E1356**	134 F	57 C
Glass Transition by DMA, **ASTM D792**	145 F	63 C
Heat Deflection Temperature, **ASTM D648**	121 F	49 C
Coefficient of Thermal Expansion, **ASTM E832**	23 x 10-6 in/inR	41 x 10-6 m/m·K
Heat Capacity, **ASTM E1269**	0.43 Btu/lb/°F	1,800 J/kg·K
Thermal Conductivity, **ASTM C518**	0.9 Btu·in/hr/ft²/°F	0.13 W/m·K

Available Colors

Black, Blue, Green, Grey, Natural, Orange, Red, White, Yellow

Suggested Uses

PLA is one of the most cost-effective FDM printing materials and easiest to process. PLA is best used for complex modeling applications that do not require impact strength or tolerance to heat loads.

*Toughness is not defined in ASTM D638 though can be calculated by taking the integral of the stress-strain curve collected by tensile data.

Visit www.sd3d.com/materials to learn more

Buckling example

- Note that the load carrying capacity is higher when the column is analyzed in tension

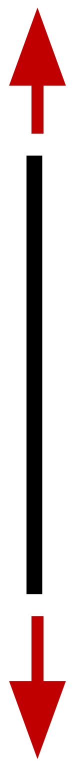
$$\sigma = \frac{P}{A} = \frac{P}{\pi r^2} = \frac{P}{\pi(.002^2)} = 79580P$$

$$S_y = 26.4 \text{ MPa}$$

  - For a factor of safety of 2:

$$2(\sigma) \leq S_y$$
$$\sigma \leq 13.2 \text{ MPa}$$
$$P \leq 166\ N$$

  - The acceptable load in tension is 166 *N vs.* 114 *N* when loaded in compression



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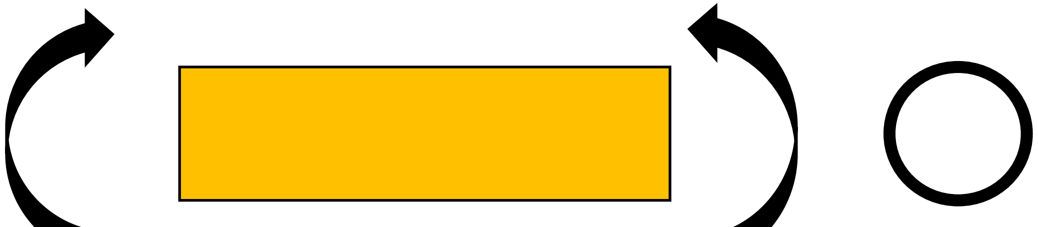
Monocoque design refers to the use of the outer skin of a structure to carry the design loads

- **Structure - monocoque design**
  - The loads are carried through the outer shell of the aircraft
  - This makes a very lightweight, strong structure
  - Aerodynamically it works well for fixed wing aircraft
    - **The DJI Phantom series aircraft are made in this fashion**



Tube structure

Loads are carried in the outer shell efficiently

The construction of an airframe should keep the concept of *load path* in mind

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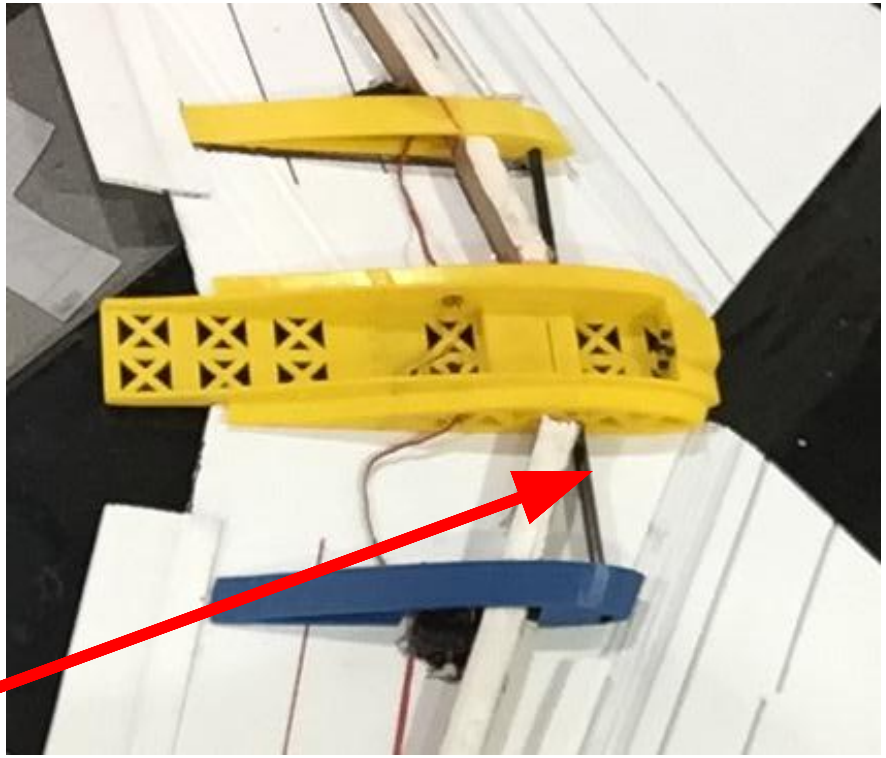
- Load paths refer to the way in which loads are carried throughout an aircraft structure
- It is important to design a structure such that load paths are efficiently guided around the airframe through the main load-carrying members
  - Sometimes a design has failed to take into consideration how loads are transmitted and this can cause an unexpected failure



An early-generation EcoSoar shows the carbon spar that passes through the middle of the fuselage body, carrying loads between the wings and not loading the 3D printed fuselage directly

Wing construction methods

- Carbon epoxy is a common aircraft construction material because it is strong and lightweight, and it can be molded into a desired shape
- The methods of carbon epoxy construction include wet layup and pre-preg molded construction
- Carbon is typically in the form of a cloth, and epoxy is a two-part system that cures to a hard finish
  - The combination of carbon and epoxy results in a very strong finished product

Wing construction methods

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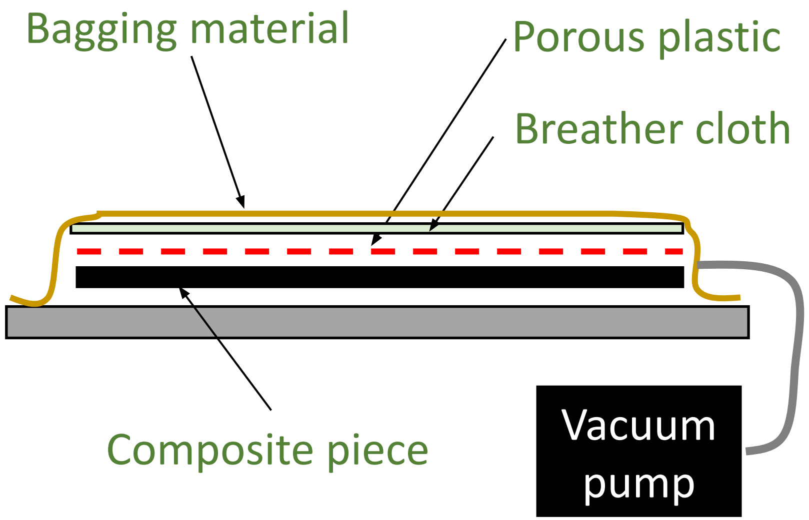
- ***Wet layup*** is a technique of laying down carbon cloth in the desired shape and applying epoxy so the system cures in the desired shape
- It is relatively simple to create complex shapes
- Forms can be used to improve the quality of the epoxy construction, and vacuum bagging is typically used to apply pressure and remove excess epoxy

Two carbon tubes joined in a T-joint by laying up carbon cloth and applying epoxy



Vacuum bag to apply pressure to carbon on mold

Wing construction methods

- A method by which the part shape is first produced by machining wax (easy to machine) is commonly used:
  - The part shape is produced in an easy-to-machine material
  - An external mold is created by laying up fiberglass epoxy on this part
- The fiberglass mold is then used as a form to lay up the final carbon epoxy product

The wax plugs on the left are machined using a CNC mill. Fiberglass-epoxy is vacuum-bagged to the plug to create a fiberglass mold (right). Carbon epoxy is laid up in the fiberglass mold and vacuum bagged. The finished product is a high tolerance carbon part

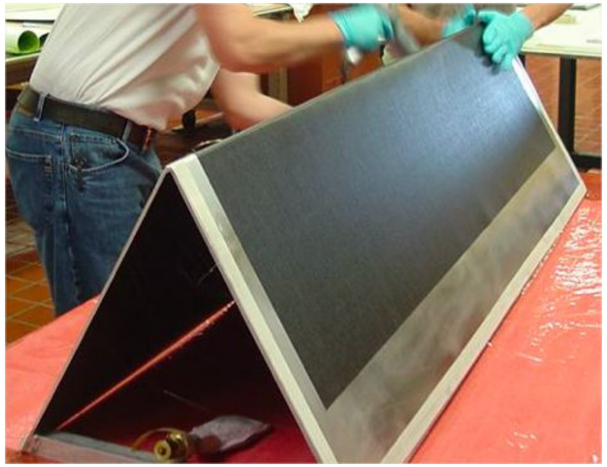
Wax plugs

Fiberglass mold

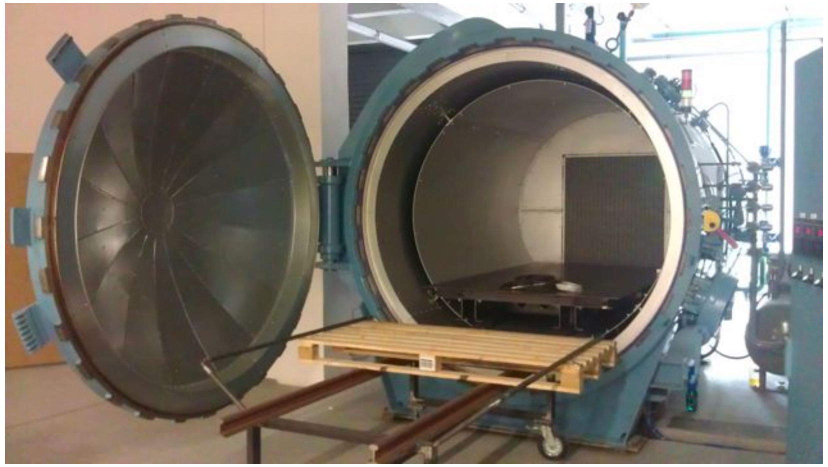
Carbon epoxy propeller

Wing construction methods

- **Pre-preg molded construction** uses carbon cloth which is pre-impregnated with epoxy and laid into a mold which holds the structural shape under applied pressure
  - The pre-preg material must be refrigerated to prevent premature curing
  - Once it is exposed to room temperature or elevated temperature, it cures to a hard finish
  - The Boeing 787 has carbon epoxy wings that are cured in an autoclave



Pre-preg material is applied to a mold



https://brebeckcomposite.wordpress.com/tag/brebeck-composites-s-r-o-team/page/3/

The part is placed inside an autoclave (a high temperature pressure vessel) to cure

Finished parts are held to a much higher tolerance