Structure

What is a structure?

To start with, I would like to introduce the physical body of a horse. If we analyze this, we can distinguish the skin, the nerves, the arteries, the muscles, etc. Each (sub) system has specific functions. E.g.: the arteries circulate the blood in the horse’s body in order to distribute necessary substances like nutrition and oxygen.
One particular physical system of the horse is the ***skeleton***. This skeleton should provide strength and stiffness to its body. It should take up the loads when the horse is moving around. Some parts of the skeleton have a protective function; think about its skull. The bones are also there for provide attachment points for muscles, protection for nerves, etc. This skeleton could be regarded as the “structure” of the horse.

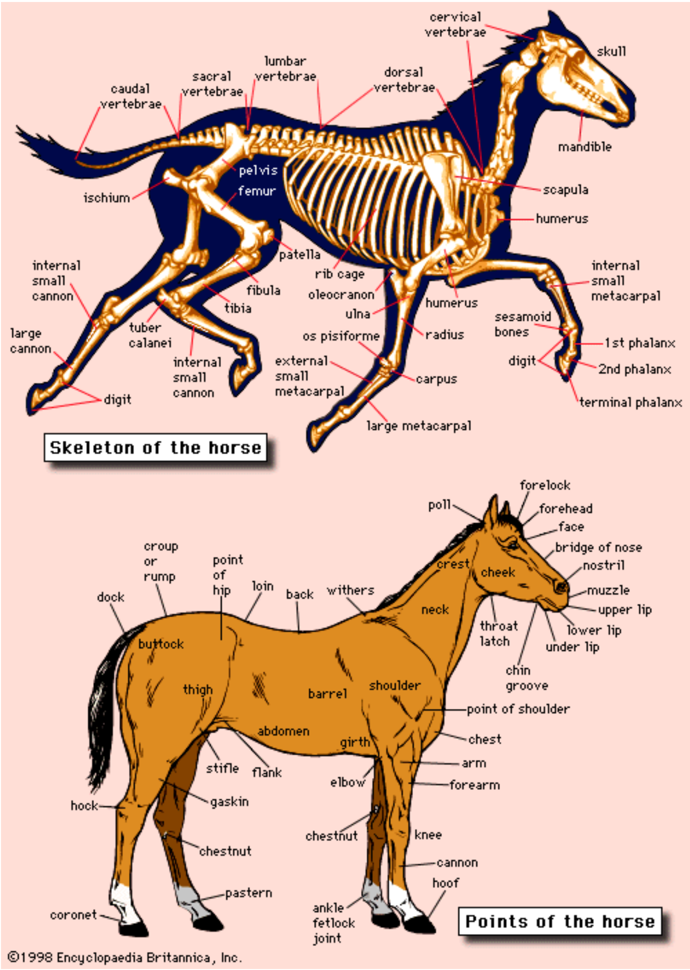


Figure 1. The horse and its skeleton.

An aircraft or spacecraft also have a “skeleton”; a ***structure*** that provides strength and stiffness to the air-/spacecraft, protection, and attachment points for other systems. If we remove all systems like hydraulics, isolation, electric wiring, etc. from the aircraft, the remainder is its structure. As passenger probably you’ll never see the inside of the structure of an aircraft, but the skin at the outside is also part of the structure (see below). Only during the manufacturing process or during heavy maintenance the inside of the structure is visible.

Figure 2. The structure ("skeleton") of the fuselage of a (metal) aircraft.

Functions of a structure.

As mentioned, a structure has a number of functions: it should take care of the loads, protect, and be a framework for the attachment of a large number of systems and elements.
By ***carrying the loads***: during operation an aircraft is loaded by many forces and moments (bending and torsion) resulting from its operation. Think about the flying phase where the weight of the aircraft should be in equilibrium with the lift, about the loads introduced during maneuvers, but also about local loads like impacts, and loads induced by the environment (e.g. by the variation and differences in temperature). In all these cases the structure should "take care of" these loads and the structure should make sure that the loads are in equilibrium.
A structure has also a ***protective function***: it should protect the payload (cargo and/or passengers) against the environment and impacts. At common flying altitudes of 10-12 km the temperatures are as low as -60^0 C and the air density has decreased by about 60-70%. Human beings cannot survive in this environment! The impacts that may occur during operation are bird impacts or impacts of hail stones. Both may cause serious damage to the structure, but the structure should withstand these impacts.
Finally, the structure has the function of a ***framework for attachment*** of multiple systems and elements. All systems like electric systems, control systems, actuators for the movables (like flaps, rudder, undercarriage), interior at a lot more, should be fixed. These systems are attached to the structure which keep the systems in place and support them.

Requirements for a structure

In order to comply with the functions mentioned in the previous section, the structure should meet a large number of requirements. The most important ones are described here.

- First, the structure should be strong enough; it should be able to carry the loads (like forces and moments) that the structure will endure during its lifetime. This so-called ***strength*** of the structure depends on the mission of the aircraft or spacecraft. E.g. the loads on fighter jets are much higher than on a civil aircraft: we don't expect a Boeing 747 to carry 9g-loads (as we do for an F-16).
- In the second place a structure should have enough ***stiffness***. Stiffness represents the resistance of a structure against deformation when the structure is loaded. If a large force is applied to the wing of an aircraft, the wing tends to bend or deflect. The higher the stiffness of the wing the smaller this deflection. For structures we require adequate stiffness, not too small but also not too high. When, e.g., the stiffness of the wing of an aircraft becomes too small the large deflections have negative consequences for the shape of the airfoil, and thereby the performance of the aircraft.

- The structure should be a ***lightweight*** structure. The total weight of an aircraft can be divided in three major portions: the weight of the fuel, the weight of the payload and the empty weight of the aircraft. A significant part of the empty weight is the weight of the structure. If this can be reduced, the aircraft could take more fuel (larger range) or more payload (higher income). For space structures this is even more relevant due to the high ratio between weight of the the launch vehicle and the payload (order 100/1).
- The operational life of an aircraft (and its structure) is at least 20-30 years. This requires that the structure should be ***durable***; that means: it should be able to resist all kinds of deteriorating or ageing effects like fatigue, corrosion, and degradation.
- A structure should be ***cheap and cost effective*** as well. Although the structure has to comply with a large number of requirements (much more than the few mentioned here), the aircraft should be affordable (in price) and cheap in operation too. The operational costs are related to repairs, the fuel costs, the turn around time at airports, etc.
- The last requirement mentioned here is the ***availability*** of the aircraft or the ease of its ***maintenance***. If an aircraft part fails or malfunctions, which might happen, it should be fixed or replaced quickly. With respect to the structure, this requirement has consequences for the accessibility or the structure, the joining methods used, the selected materials, etc.

Structural concepts

The aircraft industry is just over 100 years old. In this period a number of different structural concepts have been developed, which will be discussed in chronological order.
One of the first types of structures was the ***truss structures***, made by tubes, bars and wires (wire-braced structures). These structures were used in the first 2-3 decades. In those structures the tubes and wires carried all the loads; the skin, a mere fabric, had no structural significance.
Figure 3 shows 3 simple 2-dimensional truss structures loaded with a vertical load (force) F. The first structure is loaded with the ***external*** force (red); for the second structure also the ***reaction forces*** of the wall (blue) are shown – reaction forces are necessary to keep the structure in its place (in equilibrium); for the third truss structure also the loads per element are presented. Note that some elements don't carry a load.
This simple truss structure is capable of carrying ***tensile forces***, ***compressive forces*** , and a ***bending moment*** (in the plane of the structure). Forces perpendicular to the plane of the structure (and of the paper), can be carried when the structure becomes fully 3-dimensional. In that case the structure is also capable of carrying a ***torsion moment***.

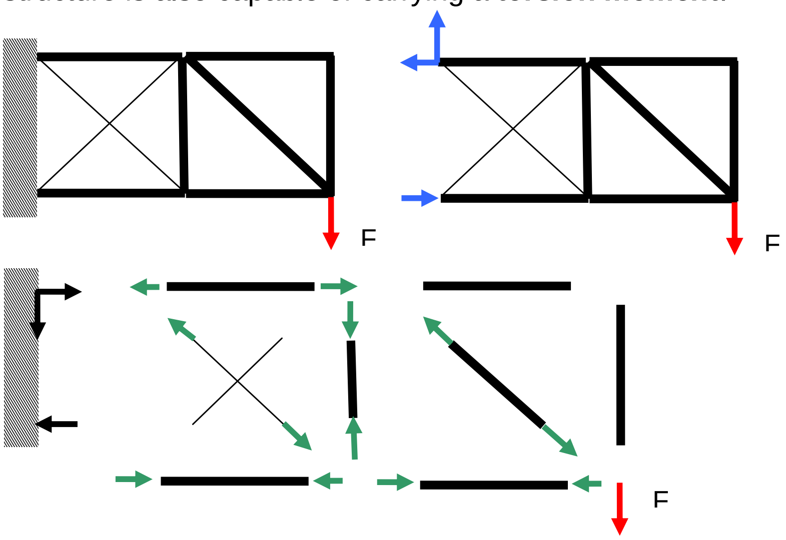


Figure 3. Three pictures of the same truss structure; (1) with the external load only; (2) with reaction forces at the support structure; (3) loads per element.

From 1930 onwards, metal structures were developed, using metal sheets for structural elements. In those structures, named ***shell structures***, also the skin of the aircraft is made of a metal sheet, which is load carrying. The supporting structure of the skin is made of a number of beamlike elements like stringers, ribs, frames, spars, etc.
The ***concept of a beam*** can be derived from the truss structure if we replace the diagonal wires or tubes by a metal sheet, the so-called ***web plate***. This plate carries the transverse forces by shear loading and the ***girders*** take care of the bending moment (see figure 4).

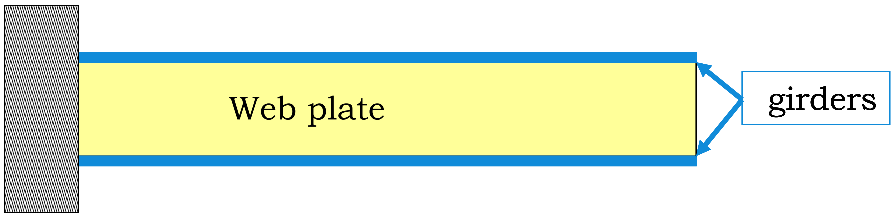


Figure 4. The concept of a beam

A lot of structural elements are based on this concept – see next figure, figure 5.

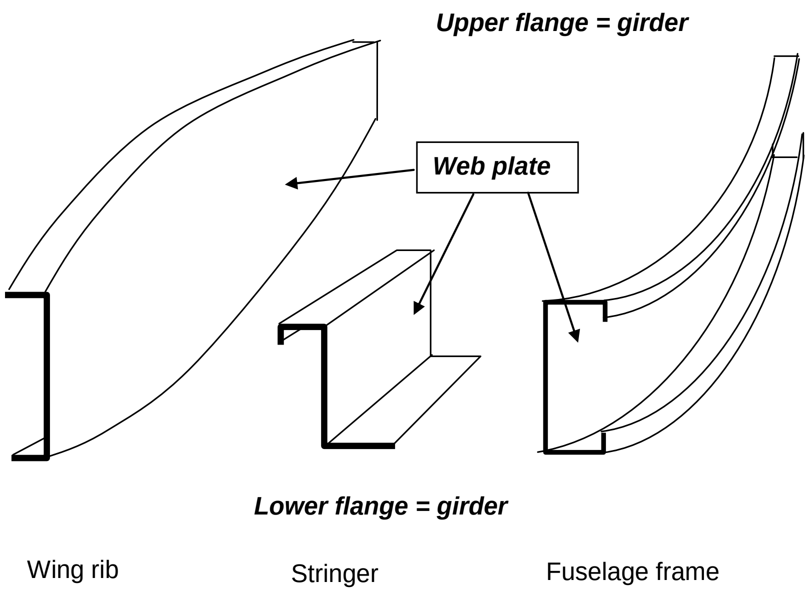


Figure 5. Different structural elements based on the concept of a beam

Today, a lot of structures are still made as shell structures, either made of metal alloys or made of composite materials.
However, composite structures can also be made from sandwiches. A ***sandwich*** can also be regarded as a beamlike element. The most significant difference is that the sandwich acts as a beam in two orthogonal directions, whereas a conventional beam is prismatic (its length is much larger that its width). In a sandwich the face sheets (or faces) carry the bending loads: one sheet for the tension the other for the compression. The core material should carry the transverse (or shear) loads and support the face sheets to prevent the buckling of the thin sheets (in case of compression). The face sheets are bonded to the core material (foam or a honeycomb structure as in figure 6) by adhesive films.

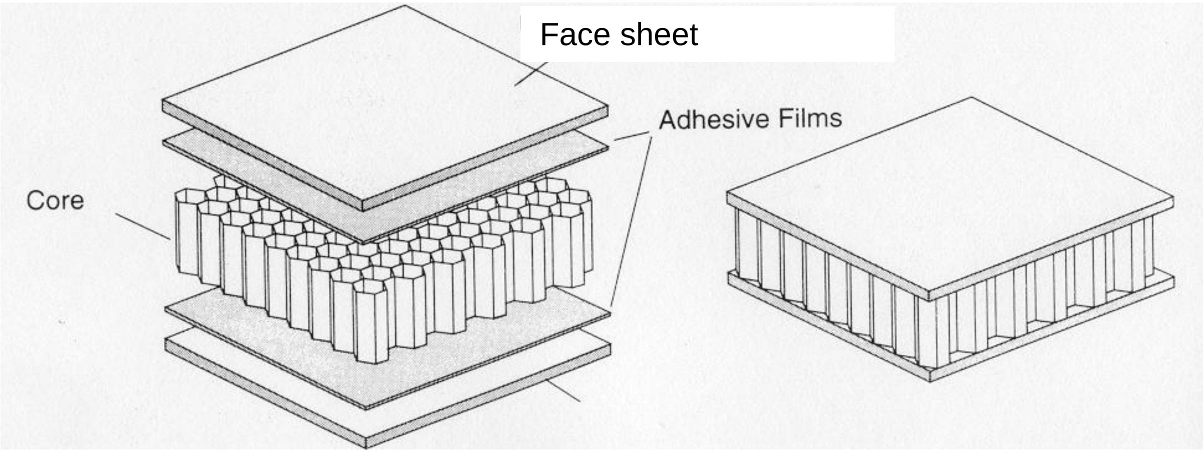


Figure 6. The concept of a sandwich

Besides the beamlike elements which are used all over the structure, an aircraft also has another typical structural "element": the fuselage. In order to fly at high altitudes, the cabin of fuselage of the aircraft needs pressurization. Therefore the cylindrical ***fuselage*** is like a ***pressure vessel***, and the internal pressure causes significant stresses[1] in the skin of the fuselage.

The stress in length direction of the fuselage is $\sigma_{long} = \frac{p \times R}{2t}$

The stress in circumferential or hoop direction is $\sigma_{hoop} = \frac{p \times R}{t}$

These formulas for these stresses are derived in Appendix A.

An aircraft fuselage is pressurized every flight – every flight is a loading cycle. Since most aircraft are operated for 30-40 years (which is equivalent to 30.000-100.000 flights) fatigue is a real issue for the design of a fuselage.
Fatigue is a dynamic loading: the structure is loaded and unloaded many times until failure occurs at a level much lower than the failure strength of the material[2]. By the loading/ unloading sequence the structure deteriorates: cracks originate and these cracks will grow. If no action is taken, these cracks will ultimately cause failure, but maintenance inspections should discover and repair these cracks in time.

[1] Stress = Force per Area [N/mm^2] – see Appendix A for further explanation.
[2] Think about the paperclip which can be broken by bending and unbending it many times.

Materials

What is a material?

The shortest definition of a material could be: “a material is a ***substance, a constituent, or element*** used to build parts, products, and structures”. The ***properties*** of a material do not depend on its geometry, but on its ***composition*** only. Typical examples of materials are metals like steel, aluminum, aluminum alloys, wood, ceramics, and polymers. All these materials have properties which do not depend on its shape: mechanical properties, electrical properties, physical properties, etc.
In the aerospace industry we are looking for ***lightweight*** materials, materials with good to excellent properties but with a ***low density***. The materials should have a good Performance to Weight ratio: for those materials the ***specific mechanical properties*** are high: high specific strength and stiffness (See Appendix B for an example). Typical lightweight materials and their density are: Aluminum alloys (ρ = 2.8 kg/dm^3), Titanium alloys (ρ = 4.5 kg/dm^3), Carbon fiber composites ($\rho \approx$ 1.8 kg/dm^3) and Glass fiber composites ($\rho \approx$ 2.5 kg/dm^3).

Material groups

For the aerospace the following materials groups have relevance for structures:

- Lightweight ***metal alloys*** like Aluminum alloys and Titanium alloys. An alloy is made by adding alloying element to the purified metal in order to increase/adapt the properties of the pure metal. E.g. the adding a few percent of Copper and Magnesium to Aluminum (like in Al-2024) increases the yield strength and ultimate strength values with a factor of 4-6. Generally, metal alloys also have good a processibility, show plastic behavior, and are rather cheap.
- Composite materials. ***Composites*** are materials composed of different constituents, e.g., fibers and a polymer. In the fiber reinforced polymers the fibers provide the strength and stiffness to the material; the fibers are strong and stiff in longitudinal direction. The polymer, acting as a resin/matrix provides the support of the fiber, takes care of the load transfer between fibers, and protects the fibers. Parts made of fiber composites are fabricated with specific processes like filament winding, lay-up and curing, and press forming. A special type of composites are the hybrid materials like GLARE, which are laminates of alternating metal and composite layers.

In addition to these two main groups, there are other groups like (unreinforced) ***polymers and ceramics***, but those are not suitable for structures: Polymers don’t have sufficient strength and stiffness; ceramics are too brittle and have poor processing features.

Requirements for a material

As for a structure, for the material one could assemble a list of requirements too. If you compare these ***material requirements*** with the ***structural requirements***, you would notice that there is a large overlap. But be careful: there are significant ***differences*** between them. Several requirements for the structure are also mentioned for the material: a high strength, a high stiffness, a low weight, durability, and costs. However, one should keep in mind that for compliance to the structural requirements the ***geometry of the structure*** could be changed. E.g. to increase the stiffness of a structure, one can select a material with a higher stiffness, and/or create a stiffer geometry (the shape/design). But, changing the stiffness of the material, represented by its E-modulus, is not possible. Likewise the density is a material constant. Other properties like the strength and the durability can be changed by (slightly) changing its composition (another alloy) or condition (temper).
In addition to the requirements discussed before, two more will be mentioned here:

- The ***manufacturability or workshop properties*** of the material. For the manufacture of aircraft it is very important to have materials that have good workshop properties. E.g. aluminum alloys have a good manufacturability, but titanium alloys don’t. That means that processes like forming and machining (drilling, milling) are easy for aluminum alloys, but difficult for titanium alloys. In composites glass and carbon fiber composites have good/adequate workshop properties, but aramid (Kevlar) fiber composites are very difficult to cut by machining operations, due to the very tough aramid fibers.

- ***Physical properties*** like electrical conductivity and the coefficient of thermal expansion (CTE) are important for specific features of the operation performance. The electrical conductivity of aluminum alloys make it easy to create a (safe) cage of Faraday of the aircraft fuselage. For composites this is more difficult; sometimes extra strips are required for this protection against lightning strike. Also the CTE is important since the aircraft operate between +80^{0}C (a hot day on the airport) and -60^{0}C (at cruise altitude). Large differences in values of CTE of applied materials cause extra problems.

The structure can also be tuned for these requirements, but the material behavior is by far the most dominant factor for these requirements.

Relation Materials – Structures - Manufacturing

Materials are the substances used to fabricate structural elements and structures. So there is a link between the materials and structures.
Materials are retrieved from resources like ***ores*** (metal) and ***oil*** (composites). Once retrieved they are transformed into ***semi-finished products*** like sheets, plates, bars, fibers, powder (polymers). The semi-finished products are further processed into structural elements. For this transformation a huge number of processes are available which can be grouped into: ***casting, forming, machining, and joining processes***. Subsequently, the structural elements are assembled into structures.
The properties of a structures are directly related to the material properties although they are not identical: structural properties are often influenced by the shape/design too.
There is also another relation between material and structure or shape: Not every structure or shape can be made of any material. If we think of the Eiffel tower, the Parthenon, or a surf board, we know that the selected materials (resp. metal, marble and composites) and the shapes of these artefacts are ***compatible***.
A similar relationship exists between the material and the manufacturing process. Metals can be melted, so casting and welding are available production processes for metals. These production processes cannot be applied to e.g. ceramics or to fiber reinforced composites.
The last relationship to mention is the one between the shape (or structure) and the manufacturing process. If we want to fabricate a sheet metal wing rib we may use a forming process. If we replace the same rib by a machined one, the details of the wing shape (local radii, thickness) will be different too. Or the other way around: For a cylindrical shape and a double-curved shape we need different manufacturing processes.
In summary: ***there is a strong interrelationship between the three entities "material", "structure or shape" and "manufacturing process".*** Changing one entity often affects both others. For the best solutions to structural problems one should include all three in the evaluation. This is visualized in figure 7.

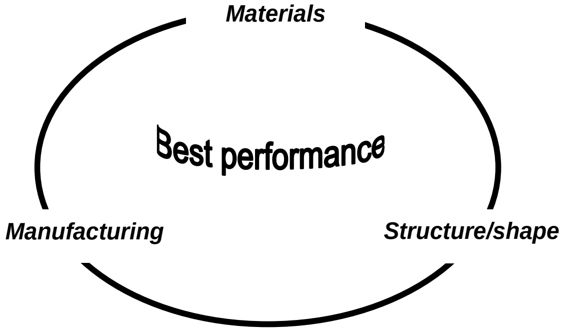
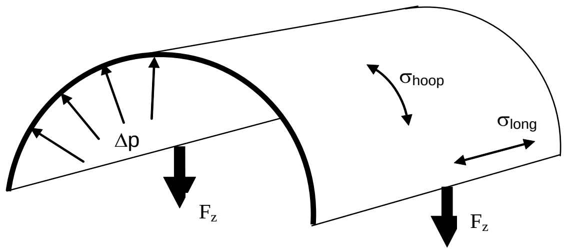


Figure 7. "Best performance is obtained by the right combination of Materials, Shape/structure and manufacturing process."

Appendix A. *Stresses in a pressure vessel (aircraft fuselage).*

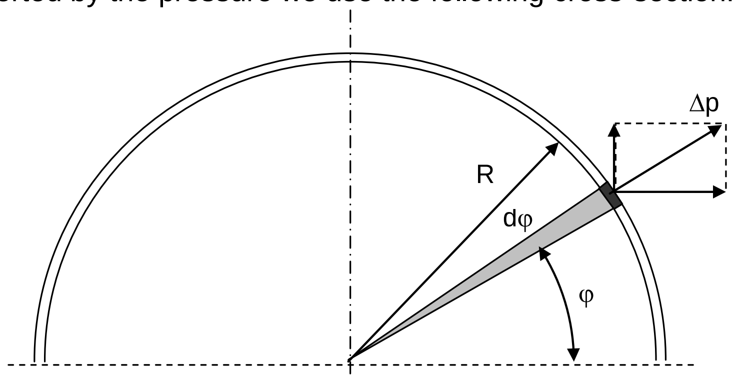
Assume a cylindrical pressure vessel, and we would like to know the values of two stresses[3] σ_{hoop} and σ_{long} in the wall/skin of the pressure vessel.
For the determination of the hoop stress (σ_{hoop}) – stress in circumferential direction – we take a section of the cylinder and cut this in halve (see picture below).
The dimensions of the "halve pipe" are: length L, radius R and wall thickness t.
The cylinder is pressurized, so the pressure inside is larger than the pressure at the outside – therefore, a pressure difference Δp ($p_{inside} - p_{outside}$) is active on the surface of the halve cylinder. The resulting vertical force $F_{\Delta p}$ is in equilibrium with the forces F_z (2x).



For equilibrium (in vertical direction) we need:

$$F_{\Delta p} = \Delta p.\text{surface area of halve cylinder} = 2.F_z$$

For the force exerted by the pressure we use the following cross-section:



$$F_{\Delta p} = .\int(\Delta p).\sin\varphi.(Rd\varphi).L$$

In this equation:

Δp is the pressure on the surface [N/m^2 or N/mm^2]
Sin φ is used since we need de vertical component of the pressure
R$d\varphi$ is a small section of the cross section
L is the length of the fuselage section (L.R$d\varphi$ represents a narrow strip of the fuselage section)
$\int$ the integration symbol is used since we need to sum all contributions
(the integration limits are 0 and π)

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[3] Stress = Force per area [N/m^2 or N/mm^2]. We use stresses in order to make comparisons between materials and/or structures independent from the size/dimensions of the structure or structural elements.
Example: if we have two bars, one (A) with a cross section of 50 mm^2, and one (B) with a cross section of 200 mm^2; if we further tell you that A fails at 10,000N and B at 20,000N, than obviously bar B is stronger. But how about the material of A and B – which material is stronger? For that answer we need the introduction of stress. The stress in A is 10,000N/50 mm^2 = 200 N/mm^2 (or MPa); the stress in B is 20,000N/200mm^2 = 100 N/mm^2. Based on this calculation we conclude: material A is stronger.

$F_{\Delta p} = \Delta p.R.L.\int_0^{\pi} \sin \varphi.d\varphi = \Delta p.R.L.[-\cos \varphi]_0^{\pi} = \Delta p.R.L\ [1 - (-1)] = 2.\ \Delta p.R.L$

If, in addition, we transform the force F_z into stresses, we get:

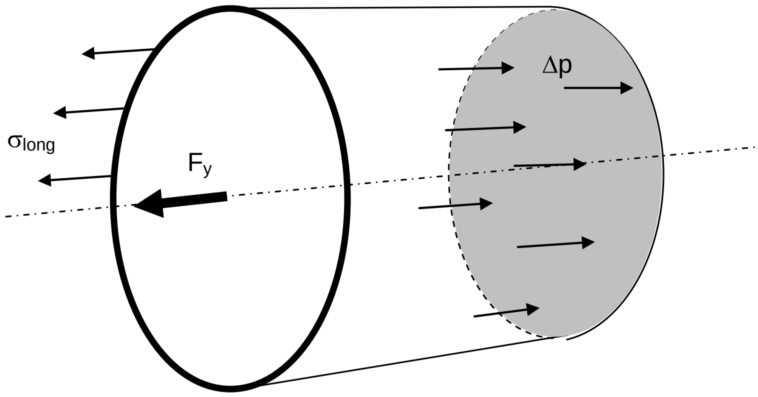
$F_z = \sigma_{hoop}.L.t$

For equilibrium we get:

$2.F_z = F_{\Delta p}; \quad \rightarrow \quad 2.\sigma_{hoop}.L.t = 2.\ \Delta p.R.L$

$\rightarrow \quad \sigma_{hoop}.t = \Delta p.R. \quad$ or $\quad \boldsymbol{\sigma_{hoop} = \Delta p.R/t}$

The formula for the longitudinal stress (σ_{long}) can be retrieved as follows (see figure below):



The section of the cylinder is closed with a cap. Whether this cap is curved or flat, does not matter. The equilibrium equation is:

$F_y = \Delta p.A_{cap}$

F_y is the (resultant) reaction force in the cylinder to the internal pressure
Δp is the pressure difference ($p_{inside} - p_{outside}$)
A_{cap} is the surface area of the cap ($= \pi R^2$)

It is very easy to write the force F_y as:
$F_y = \sigma_{long}.A_{edge} = \sigma_{long}.2\pi R.t$

So: $F_y = \sigma_{long}.A_{edge} = \sigma_{long}.2\pi R.t = \Delta p.A_{cap} = \Delta p.\pi R^2$

$\rightarrow \sigma_{long}.2\pi R.t = \Delta p.\pi R^2 \quad \rightarrow \boldsymbol{\sigma_{long} = \Delta p.R/(2t)}$

Note that $\quad \sigma_{hoop}/\sigma_{long} = 2$

Appendix B Example: Specific strength of a simple tension bar.

Problem: If I have to transfer a tensile load from point A to point B, using a tension bar, which material (Steel or Aluminum) offers the lightest solution?
Tensile load = 1000 kN
Length of the bar is 2m.

Steel properties:	Yield strength	= 550 N/mm^2
	Failure strength	= 800 N/mm^2
	Density	= 7.8 kg/dm^3
Aluminum properties:	Yield strength	= 280 N/mm^2
	Failure strength	= 450 N/mm^2
	Density	= 2.8 kg/dm^3

Solving the problem:

We assume that plastic deformation is not allowed; therefore, the maximum allowed stress in the tension bar is set by the yield stress.

The minimum required cross section for

the steel bar is:	1000kN : 550 N/mm^2 = 1818 mm^2
aluminum :	1000kN: 280 N/mm^2 = 3571 mm^2

The weight corresponding to these bars is:

the steel bar :	20dm x 0.1818dm^2 x 7.8kg/dm^3 = 28.4 kg
aluminum :	20dm x 0.3571dm^2 x 2.8kg/dm^3 = 20.0 kg

The aluminum provides the lightest tension bar - difference is 42%.

This result could also be obtained by the following:

We have to compare the performance/weight ratios for both materials.
In this case: the required load divided by the weight:

$$\frac{F}{W} = \frac{\sigma_y \times A}{\rho \times A \times L} = \left(\frac{\sigma_y}{\rho}\right) \times \left(\frac{1}{L}\right)$$

Since L is equal for both options, we have to check the ratio σ_y/ρ.

For steel this ratio is	70.5
For aluminum	100

Again aluminum proves to be better by 42%.

NOTE. This ratio (σ_y/ρ) is only valid for tension. For other load situations like compression or bending, other ratios should be used.