

Introduction to Aerospace Structures and Materials

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5. Aircraft & spacecraft structures

5.1 Introduction

To be able to design and analyse aircraft or spacecraft structures, one first has to become familiar with the structural elements and their functions. In this chapter the different structural elements that can be observed in aeronautical structures and their functions are discussed. This explanation is primarily qualitative of nature, but will be further explored in the chapter 6 and 7, where loads acting upon these structural elements are discussed and the stresses that they induce.

5.2 Airframe

The aircraft consists of numerous different elements and components that each fulfill their own function. However, not all elements of an aircraft are considered to be structural elements or fulfill a load bearing function. To distinguish elements that are considered to be part of the structure of an aircraft or spacecraft from other elements, these elements are often referred to as *airframe*.

There are several definitions that can be given for the airframe. An airframe is

- the aircraft or spacecraft without installed equipment and furnishing
- the skin and framework (skeleton) that provide aerodynamic shapes
- the load bearing parts that take up forces during normal flight, manoeuvres, take-off, landing etcetera.
- the parts that together protect the contents from the environment

The reason that these different definitions exist can be attributed to the different types of airframes or structures that can be identified. For example the Fokker Spin, illustrated in Figure 5.1, is completely different in appearance than the military aircraft that are operated these days, see for example the illustration in Figure 5.2 of a Sukhoi SU-25.

Defining airframe as the parts that protect the contents from the environment may be considered applicable for the fuselage and wing structure of a commercial aircraft, but is hardly applicable to the Fokker Spin, where the pilot is only protected from the environment by elements that are not part of the airframe.

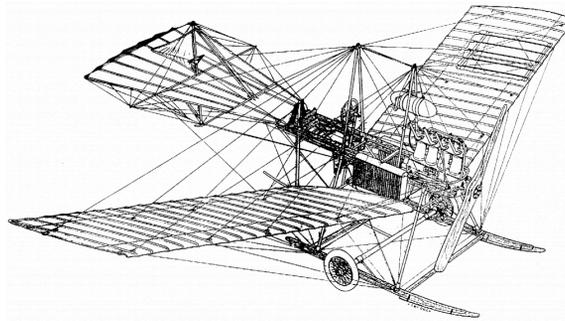


Figure 5.1
Illustration of the Fokker Spin or Fokker Spider. (Anon., n.d., 5-1.jpg. Public Domain.)

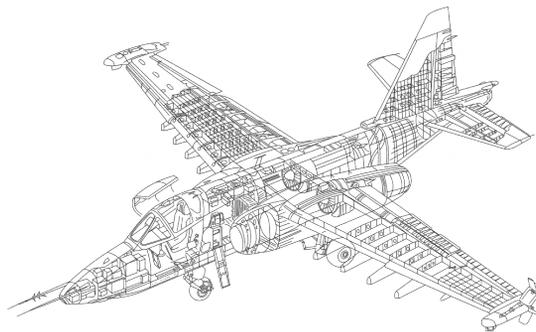


Figure 5.2
Illustration of a Sukhoi SU-25T Fighter Jet. (Altoing, 2011, CC-BY-SA3.0)

Within the airframe a more detailed distinction is made between structural elements that fulfil a critical or a non-critical function. Elements that fulfil a critical function are elements that in case of damage or failure could lead to failure of the entire aircraft or spacecraft. These structural elements are referred to as *primary structures*. Structural elements that fulfil non-critical functions are elements that carry only aerodynamic and inertial loads generated on or in that type of structure. These structural elements are called *secondary structures*.



Figure 5.3

Photo of the shell structure of the cockpit section of the Fokker 100 aircraft (component located in the collection of the Delft Aerospace Structures & Materials Laboratory – TU Delft, n.d., 5-3.jpg. Own Work.)

5.3 Structural concepts

In the past century, different structural concepts have been developed and explored that form the basis of current structural design in both aviation and space. In this section these concepts will be described briefly.

5.3.1 Truss structures

The first structural concept applied in aircraft structures was the truss structure. This structural concept was widely applied at the time in, for example, (railway) bridge structures. Truss structures are made of bars, tubes and wires (wire-bracing of a structure). A famous example of wire-bracing of a structure is the Fokker Spin shown in Figure 5.1.

The aircraft in the first decades of aviation were built with truss structures in which the bars, tubes and wires carried all loads. The skin or fabric coverage did not contribute to the load bearing function.

The elements of the truss structure transfer the loads primarily via tension and compression. Structural rigidity is obtained with the diagonal function, i.e. wires or rods placed under 45°. In Figure 5.4 the diagonal function in the truss structure is illustrated. The concept can be applied in three-dimensions to sustain bending and torsional loading.

The diagonal function can be performed by either wires (only in tension), rods and tubes (tension and compression) and sheet material. The latter solution has led to another structural concept that will be discussed next.

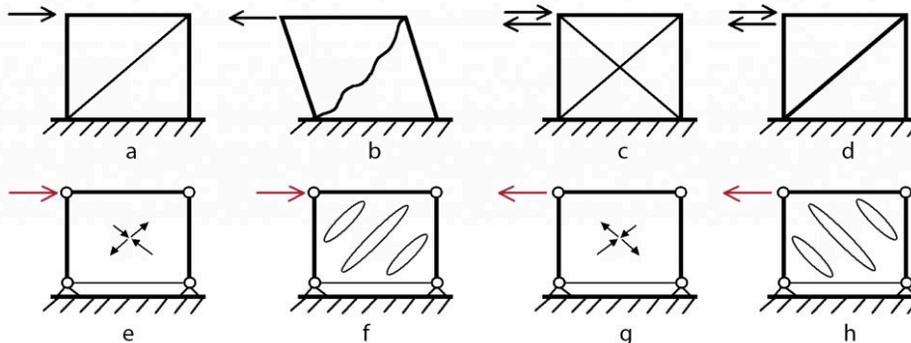


Figure 5.4

Illustration of truss structure concept: diagonal function with wire-bracing (a-c), with rods (d), and with sheet (e-h). (TU Delft, n.d., 5-4.jpg. Own Work.)

Although truss structures were the first structural concept introduced in airframes, this does not automatically mean that the concept has become outdated. In some

modern applications, the introduction of tailored truss structures has led to significant weight savings.

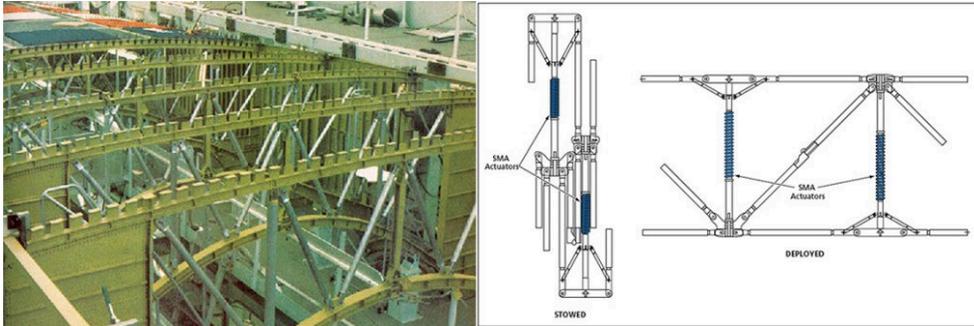


Figure 5.5

Examples of truss structures, left: Ribs in the centre fuselage section of the Space Shuttle using boron-aluminium tubes, (Rawal 2001), and right: deployable truss concept for space applications. Derivative from NASA (2001, 2010), Public Domain.

Such an example is illustrated in Figure 5.5, where the ribs in the centre fuselage section of the Space Shuttle have been constructed partly from a truss structure using boron-aluminium tubes leading to a 45% weight saving over the original baseline design. Truss structures also enable deployment concepts which are of interest for space applications.

5.3.2 Shell structures

With the introduction of metal in aircraft structures a different structural concept was introduced. This concept relates to the application of sheet material in a truss structure to fulfil the diagonal function. In this truss configuration, the sheet performs the diagonal function in shear, whereas the wires and rods only perform that function in tension and compression. For this reason, sheet material is very efficient to reinforce such structure. However, with the introduction of sheet material in the structure, it is no longer considered a truss structure, but rather a thin-walled *shell structure*.

Four functions that can be performed by sheet material are illustrated in Figure 5.6. In addition to tension and compression (also with tubes and wires), sheet material can carry load in shear (diagonal function), but can also seal a structure from its

environment. This is particularly of interest for the pressurization of a structure (including the ability to carry membrane stresses) and for the application of integral fuel tanks.

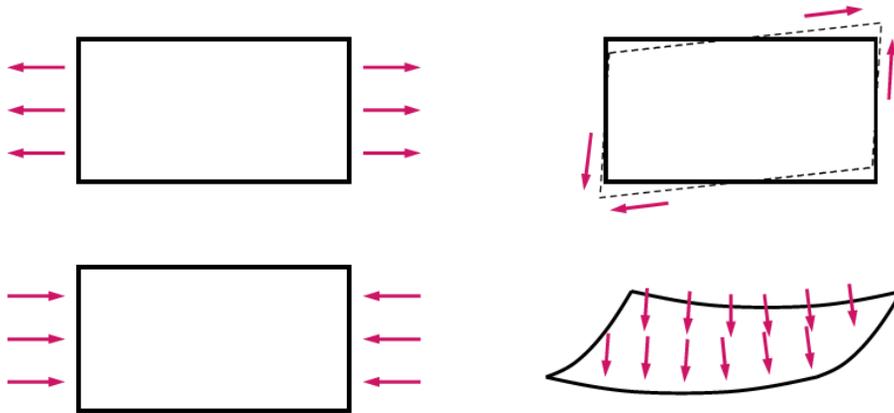


Figure 5.6

Four functions of sheet: tension, compression, diagonal/shear, sealing (air/fuel tight). (Alderliesten, 2011, 5-6.jpg. Own Work.)

To fully exploit the benefits of sheet material, it may be necessary to reinforce the sheet with other elements. Without any additional reinforcement, sheet material can easily carry tensile loads up to its ultimate strength. However, a sheet in compression will bulge out without being able to carry significant compressive loads, see Figure 5.7 (a). Only when the sheet is reinforced or geometrically stiffened, as illustrated in Figure 5.7 (b,c), it is able to carry more compressive load.

Apparently, the sheet stiffness cannot be used when it bulges, but when the sheet is formed into a profile its obtained stiffness can be used in compression. This means that stiffness in the structural context is not only a material property, but also a geometrical property. Figure 5.7 (c) illustrates that the sheet of example (a) can be stiffened by another sheet that is formed into a profile, where the combination of the two sheets becomes a load carrying structure in which the flat sheet carries a significant part of the applied load.

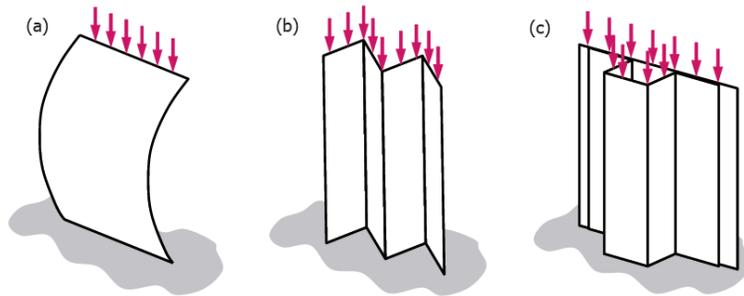


Figure 5.7
Stiffness of sheet material versus geometrical stiffness. (Alderliesten, 2011, 5-7.jpg. Own Work.)

The combination of a flat or slightly curved sheet with stiffeners is called a shell structure. There are multiple stiffener geometries that can be used to reinforce a shell structure. The difference between a sheet reinforced with so-called hat stiffeners and a sheet reinforced with an L-shaped stiffener is illustrated in Figure 5.8. The stability of the hat-stiffener is higher than the L-stiffener, where at certain compressive loads the flange will bulge out, similar to the flat sheet in Figure 5.7 (a), but only at the unsupported edge.

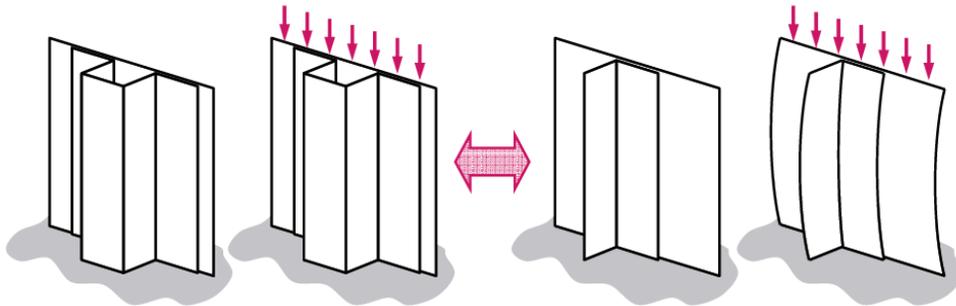


Figure 5.8
Effect of stiffener geometry on deformation induced by panel compression. (Alderliesten, 2011, 5-8.jpg. Own Work.)

For this reason the shape of the stiffener is considered in structural design. Heavy loaded structures, such as, for example, the upper wing panels (upward wing bending causes compression in the upper shell structure) hat-stiffeners are often applied. In shell structures that carry less compressive loads (lower wing panels), often L-

shape or Z-shape stiffeners are applied. An additional advantage is that these stringer shapes enable inspection from all sides, while hat stiffeners cannot be inspected internally.

Another design consideration is the distance between the stiffeners. A single stiffener attached to a flat shell (Figure 5.9) has only a limited and local effect on the stability of the shell structure. Depending on the stiffener geometry an effective width can be determined. Based upon this effective width, spacing between stiffeners must be chosen in the design.

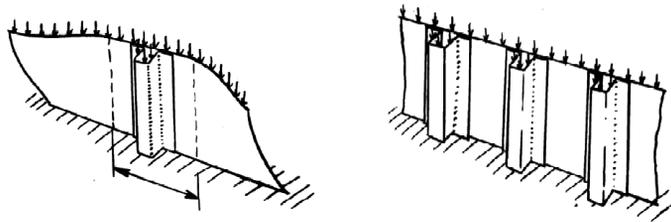


Figure 5.9

Effect of stiffener spacing on stability of panel under compression. (TU Delft, n.d., 5-9.jpg. Own Work.)

Where initially a beam structure was designed as truss structure, where bending was taken up by normal forces in the upper and lower tubes and the diagonal function performed by the diagonally placed elements, the introduction of sheet material has led to more efficient beam concepts. The sheet performing the diagonal function is called the web plate, whereas the elements taking up the (bending) loads by normal forces are called the girders. This beam concept is illustrated in Figure 5.10.

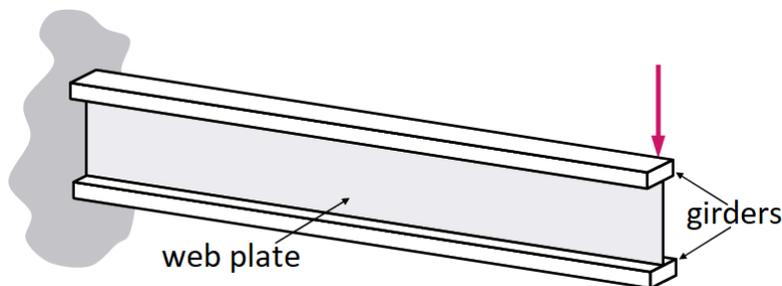


Figure 5.10

Concept of a beam based on sheet web with girders. (Alderliesten, 2011, 5-10.jpg. Own Work.)

An illustration of the application of the beam concept in a fuselage structure is given in Figure 5.11. Here the frames, clips and stringers all utilize the characteristic beam concept with web plate and girders.

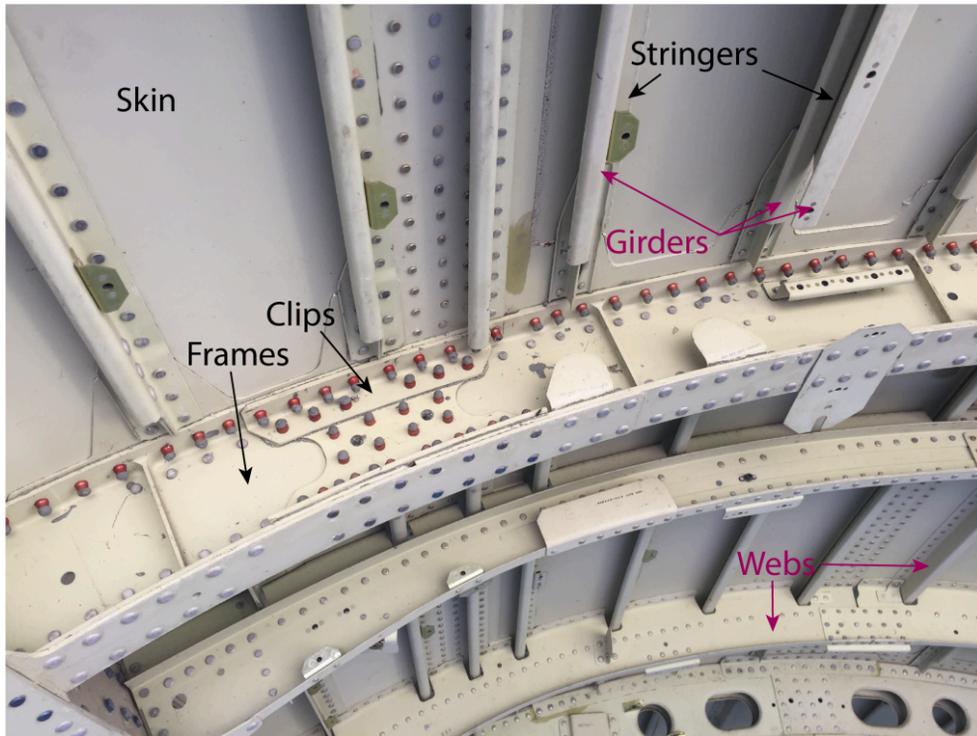


Figure 5.11

Frames and stringers based upon the beam concept. (TU Delft, n.d., 5-11.jpg. Own Work.)

5.3.3 Sandwich structures

An alternative shell structure is the sandwich structure. The sandwich structure contains a low density core in-between two face sheets. This concept basically exploits the same concept as the beam based on web plate and girders. Where the normal forces are carried by the face sheets, the diagonal shear function is provided by the core in-between the facings. However, the sandwich structure carries the loads in two directions. This similarity in concept is illustrated in Figure 5.12.

Sandwich structures are in fact bonded structures because of the adhesion between face sheets and core. There are several core concepts that could be applied. The honeycomb core structure illustrated in Figure 5.13, could be made from either metals or polymers. In composite sandwich structures, polymer honeycombs are being used, while in the past (see Bréguet Atlantic example on the next page) aluminium sandwiches structures used aluminium honeycomb cores. The advantage of honeycomb cores is the low weight due to the high percentage of empty volume.

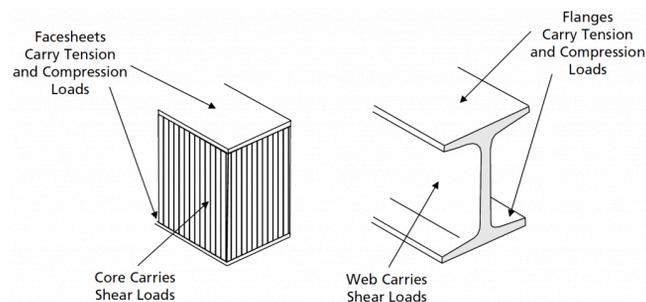


Figure 5.12

Illustration of similarity of concept between beam and sandwich; the girders and face sheets carry the normal forces, while the web plate and core provide the diagonal function. (TU Delft, n.d., 5-12.jpg. Own Work.)

Alternative core solutions are based on the application of balsawood or foams. The foam cores can either be made of polymers or metals.

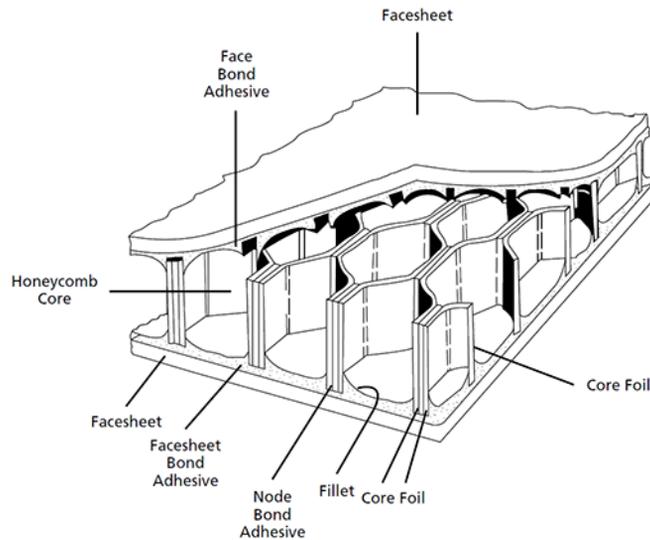


Figure 5.13

Illustration of sandwich concept utilizing the honeycomb core. (TU Delft, n.d., 5-13.jpg. Own Work.)

The advantage of the sandwich concept is the inherent high bending stiffness. For this reason, sandwich structures are often applied as floor concept in passenger and cargo areas of aircraft. To illustrate the benefit in bending stiffness and strength, in Figure 5.15 for a given sandwich lay-up the relative increase in bending stiffness, strength and weight is shown. With adding low density core material, the weight is only slightly increased, while the bending stiffness may increase order of magnitudes.

Example: Sandwich panel concept

The sandwich structure may be considered an excellent structural concept, because it requires no additional stiffening elements providing a smooth surface. However, examples from the (recent) past have also put the emphasis on the drawback of this concept. In 1970 the Bréguet Atlantic, shown in Figure 5.14 (a) revealed substantial corrosion issues related to moisture absorbed by the sandwich structure. One may assume that the sandwich structure is a closed system, but nonetheless, moisture is being picked up by the sandwich

structure, and the moisture remains subsequently trapped inside, see the X-ray photo in Figure 5.14 (b).

To illustrate that this is not a particular problem related to metallic sandwich structures, but to sandwich structures in general, another example is shown in Figure 5.14 (c). On March 6, 2005, an Airbus A310-308 operated by Air Transat designated Flight 961 had to perform an emergency landing after it lost in-flight a composite sandwich rudder of several meters length. Subsequent investigation revealed that moisture absorbed by the sandwich panel trapped between core and face sheets caused rapid delamination of the face sheets from the core, as a result of volumetric increase of the frozen moisture.

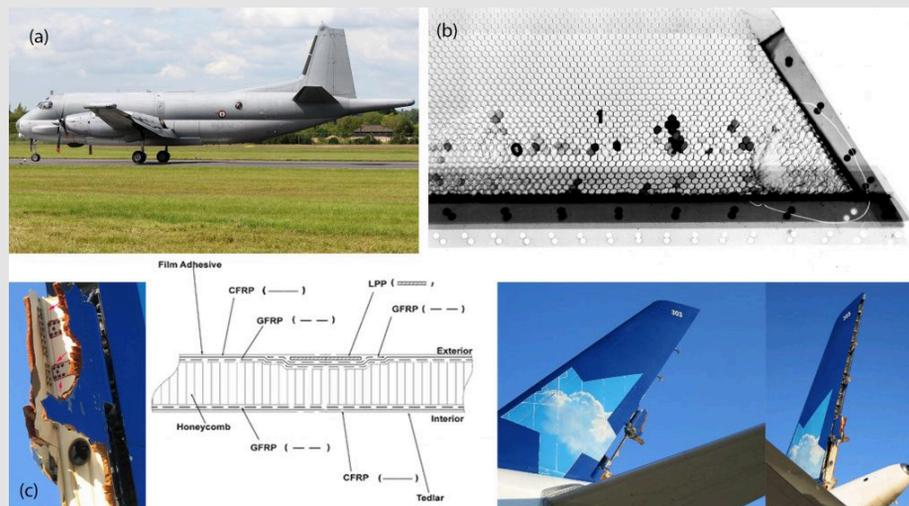


Figure 5.14

Illustration of detrimental environmental influence on sandwich concept: corrosion in metallic sandwich (a,b) and rapid delamination in composite sandwich (c). Derivative from top left: Bidini, (2012), CC-BY-SA3.0; top right: TU Delft, (n.d.), 5-14-b.jpg, Own Work; bottom row: TSB, (2007), Copyright TSB, Use Permitted.

In general, the sandwich concept is an excellent structural concept. However, one should bear in mind that there are several drawbacks related to this concept. First of all, details like the mechanical joints to other structural elements are usually complex and expensive. Simple riveting or use of bolts is not possible, because the soft core

is not able to carry the bearing load induced by bolts, causing delamination between facing and core. The high clamping forces often required for bolted joints is also not possible, because the out of plane stiffness of the sandwich structure is only related to the local stiffness of the face sheet and therefore low.

The second drawback is related to durability and aging of sandwich structures. As explained in the example earlier, the environmental aspect of moisture absorption by the sandwich panels is significant. Experience with for example composite sandwich landing gear doors on Airbus aircraft has revealed that over a few years the weight of such panel may increase by a kilogramme due to the high amount of moisture absorption. Aside from the effect of increased weight on the aircraft performance; it may also impair the structural integrity of the aircraft, similar to the example of the Air Transat aircraft discussed before.

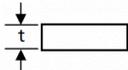
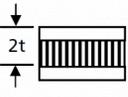
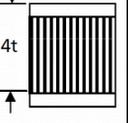
	Solid Material	Sandwich Construction	Thicker Sandwich
			
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2
Weight	1.0	1.03	1.06

Figure 5.15

Effect of core thickness on bending stiffness. (Alderliesten, 2011, 5-15.jpg. Own Work.)

5.3.4 Integrally stiffened structures

The stiffened shell structures can be manufactured by attaching the stiffening elements to the face sheet; this can be done by either using mechanically fastening (riveting, bolting) or by bonding. Another method of manufacturing stiffened shell structures is by taking a thick plate and machining away the material between the stiffeners. This is illustrated in Figure 5.16.

The advantage of the integral concept is the relative low cost of production. Machining, or nowadays high-speed machining, is performed automated and computer controlled, which enables high volume production at relatively low production costs. A second manufacturing benefit of integral structures is the low amount of parts. This reduces the logistic burden in a production facility.

Obviously, this concept leads to a high amount of scrap material. However, that does not add to the manufacturing costs, because nowadays, the metal suppliers are pre-milling such integral components before shipping them to the aircraft manufacturer. The highest amount of scrap metal remains at the metal supplier who can insert that material directly back into their production line.

Another advantage is that with machining the thickness can be tailored continuously, which leads to optimized structures with respect to weight. However, a drawback related to machining is that only simple blade stiffeners can be applied. Complex stiffener concepts cannot be manufactured due to the accessibility of the milling heads.

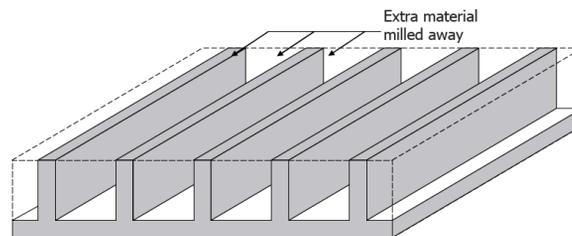


Figure 5.16

Creating an integrally stiffened panel by machining a thick plate. (Alderliesten, 2011, 5-16.jpg. Own Work.)

The difference between the earlier methods of creating a stiffened panel and an integrally stiffened panel is that the latter consists of a single component. Or to put it the other way around, the earlier mentioned concepts of riveting or bonding such panels are build-up structures.

This means that in case of damage or cracks in the structure, the build-up structure contains natural barriers that stop or retard the crack until a new crack has initiated in the subsequent elements. In case of an integral structure, there is no natural barrier, which means that the crack will grow continuously through the panel. As a result, the

integral structure is considered less damage tolerant (i.e. lower ability to withstand damage and damage growth) than the build-up structure.

Because this concept is most cost-effective for thick reinforced plates, like for example lower wing panels, the integral machined panel concept is mostly used on larger aircraft.

5.4 Fuselage structures

The fuselage structure of pressurized aircraft is in fact a thin-walled pressure vessel, exploiting the stiffened shell concept. In a fuselage structure different elements can be identified that together provide strength and geometrical rigidity. These elements are:

- Fuselage skin
- Frames
- Stringers
- Bulkheads
- Splices and joints

The longitudinal stiffness of the structure is created in part by the closed cylindrical shell structure, but to great extent by the application of stringers to the skin panels. Another concept to create that rigidity is by combining stringers into longerons (i.e. heavy longitudinal stiffeners that carry large loads). This concept then has only few longitudinal stiffeners that have a larger cross section. An illustration of such concept is given in Figure 5.17.

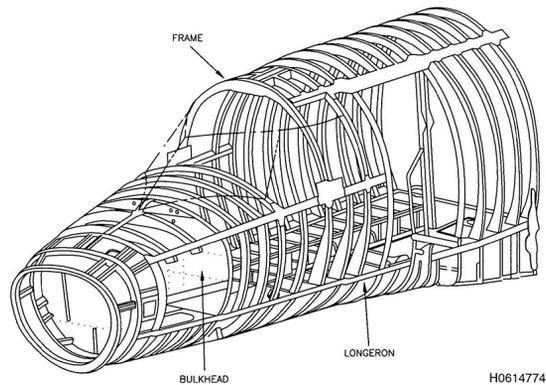


Figure 5.17
 Longitudinal stiffness created with longerons. (Anon., n.d., Public Domain)

Pressurized fuselages require the application of bulkheads at the front and rear end of the fuselage to create an air tight pressure vessel and to maintain the forces related to the pressurization.

5.5 Wing structures

Wing structures contain similar stiffened shell concepts as explained in section 5.3, but due to the different functions to be fulfilled, the elements have a different appearance. In general, wing structures can be divided into:

- Wing skin panels
- Ribs
- Spars

where the assembly of spars and skin require some further elaboration.

A first glance at wing structures reveals that, despite the use of similar elements, a certain design freedom results in different structural appearances. This is illustrated in Figure 5.18 where four structural wing lay-outs are compared.

Some wings contain straight spars from wing root (wing-fuselage connection) to wing tip, while other wings contain kinks in the spars. Such a kink in the spar most often has to be achieved by connecting two spar elements at that particular location.

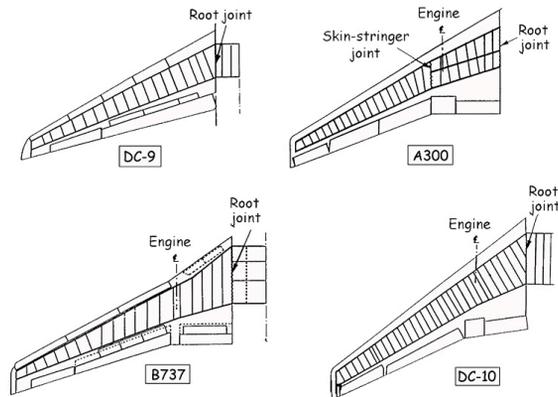


Figure 5.18
Comparison of four wing structural lay-outs. (TU Delft, n.d., 5-18.jpg. Own Work.)

Another aspect that strikes the eye is the orientation of the ribs in the wing structure. Where some wings contain ribs that are placed in flight direction, other wings contain ribs that are placed more or less perpendicular to the spars and wingspan direction.

In general, wing structures are characterised by the significant length the structural elements may have; the wing skin panels and the spars are generally made out of single components if possible. To get an indication of the length of large wings structures, in Figure 5.19 a photo of the A380 wing structure is shown. Because of the length aspect and the logistics related to that, some aircraft have wing structures that are sectioned into, for example, inboard and outboard wings, or centre wings and outer wings, like for example the C-130 Hercules illustrated in Figure 5.19.



Figure 5.19

Left wing of the Airbus A380 and wing structure of a C-130 Hercules (right). Derivative from left: Dr. Brains (2013), CC-BY-SA 3.0; and right: SAP – U.S. Air Force, (2007), Public Domain.

Despite the advantages of sectioning large structures with respect to manufacturing and assembly, a potential disadvantage may be related to the highly loaded joints as a result. For the C-130 Hercules, this joint, often referred to as the rainbow fitting, is a well-known point of concern.

5.5.1 Ribs

The ribs in wing structures provide several functions. First of all, they maintain the aerodynamic profile of wing. Because the aerodynamic profile of the wing is defined in flight direction, this may be an important reason to place the ribs in flight direction.

However, aside from the manufacturing challenges to place the ribs under such angles with the spars that are positioned in wing span direction; there is another obvious reason why placing ribs perpendicular to the spars is preferred.

The length of the ribs is shorter when placed perpendicular to the spars and wing span direction, than when placed in flight direction. The rib placement may be chosen such to minimise weight.

The second function of ribs is to transfer the aerodynamic and fuel loads acting on skin to the rest of the wing structure. The aerodynamic loads are related to the under-

pressure above the upper skin, while the fuel loads act directly on the lower wing skins. These loads are brought into the structures via the ribs.

Thirdly, the ribs provide stability against panel crushing and buckling. This is illustrated in Figure 5.20; without any ribs, the upward bending of the wing would crush the upper and lower wing panels. With ribs at certain length, the upward bending would cause buckling to the upper wing skin, but keep the lower wing skin at distance of the upper wing skin. With the optimal rib spacing, both crushing and buckling are prevented and the shape of the wing is preserved.

A fourth function of the rib that can be identified is the introduction of local loads. Aside from aerodynamic and fuel loads, the wing structure is locally loaded by the landing gear during landing, taxiing and take-off, and, during flight, the engines, flaps and ailerons will locally apply loads to the structure as well. These loads are locally introduced into the structure by the ribs.

A fifth function is the sealing function in case integral fuel tanks are used in the wing structure. The ribs prevent the surge and splashing by sectioning the fuel tanks in individual bays.

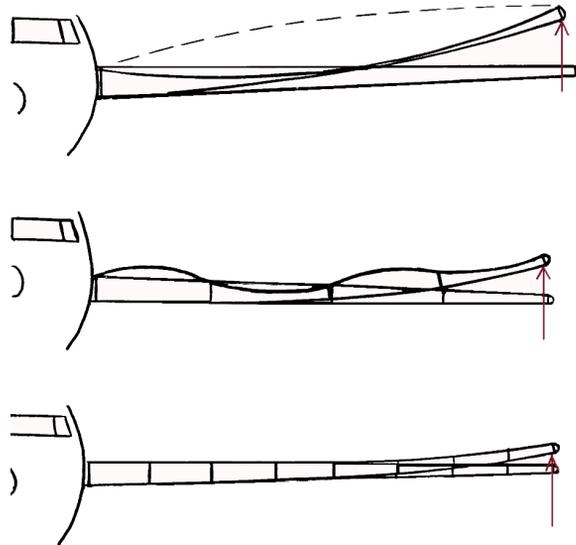


Figure 5.20

Illustration of the rib function; stability against crushing and buckling. (TU Delft, n.d., 5-20.jpg. Own Work.)

Especially the local loads introduced into the wing by the ribs imply that different loads are to be carried by individual ribs. As a consequence, different design concepts or design philosophies may be chosen for individual ribs in the wing structure. This is illustrated with the centre wing box of the C-130 Hercules in Figure 5.19; where, depending on the location in the wing box, different rib designs have been applied.

In general, the selection of rib type and related manufacturing method depends on;

- Loads
- Design philosophy
- Available equipment and experience
- Costs

The loads relate to the functions of a particular rib, i.e. does it only provide stability against buckling and crushing, or are significant loads being introduced locally by, for example, the landing gear? The design philosophy determines the magnitude of the stresses that are allowed in rib structures.

The available equipment and experience is an important aspect in this case. If certain equipment or machines are not available, it is most likely that the rib design that requires this equipment will not be chosen. To some extent it relates to the fourth aspect, costs, if sufficient benefits can be identified, that particular type can still be selected and costs related to acquiring the equipment has to be accounted for.

In case the design loads on the rib are relatively low, one may select the rib type that is manufactured by forming sheet or plate material into a rib. The additional stiffness may be added by adding stiffening profiles to that rib.

In case the loads are relatively high, i.e. near landing gears, a more rigid and stiff design is required. This may be achieved by forging and machining a rib from thick plate material.

A distinct difference between the two rib types is the difference near radii. In case of forming plate material, the minimum bending radius is dictated by the properties of the material. Smaller radii will lead to failure during bending. In case of machining, similar inner radii with smaller outer radii can be achieved by milling, which provide a (geometrically) stiffer connection with the surrounding structure.

5.5.2 Spars

The main function of the spars in a wing structure is to carry the wing bending loads. As explained in section 5.3.2, the spars are beams designed to carry bending by girders carrying the normal forces and web plates that carry the shear forces, see also Figure 5.21.

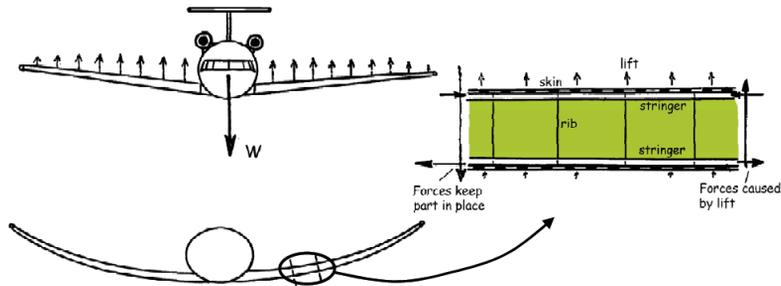


Figure 5.21

Forces in the wing structure as result of upward wing bending. (TU Delft, n.d., 5-21.jpg. Own Work.)

The upward bending illustrated in the lower left part of Figure 5.21, requires some additional attention. Zooming in a bit closer, it is evident that the elements in the wing deform as illustrated in Figure 5.22. To carry the bending loads and to resist against this deformation, the diagonal elements are very important. And as explained before, the diagonal function can also be carried by sheet material, or web plates in this matter.

As a result, the basic form of spars is often the I-beam, in which the girders pick up the normal forces and the web plate the shear forces.

Although the deflection near the wing root is significant smaller than near the wing tip, the loads near the wing root are significantly larger. The equilibrium between the normal forces in both girders of the spar near the wing tip and the upward bending moment, results in relatively small forces. Near the wing root, equilibrium must be provided with the upward bending moment of the complete wing. This results in very high forces near the wing root.

As a result the spar, the girders, and web plate, must be thicker near the wing root than near the wing tip. However, extrusion of an I-beam (see chapter 4 for the extrusion

process) can only be performed on constant cross-sections. A spar with varying cross-section along the wing span cannot be extruded.

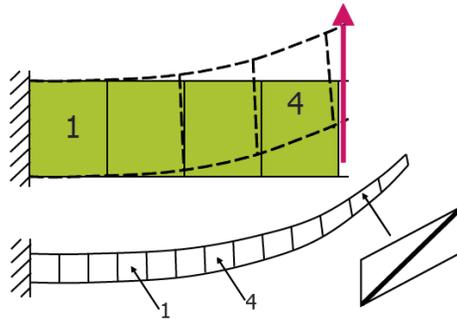


Figure 5.22
Deformation related to the upward wing bending. (TU Delft, n.d., 5-22.jpg. Own Work.)

Design concepts to deal with this manufacturing aspect are based on building up the spar from different elements. Either the girders are separately manufactured and connected to a web plate by riveting for example, or a spar with constant thickness is extruded and subsequently reinforced by bonding additional sheet material to web plate and girders. This is illustrated in Figure 5.23.

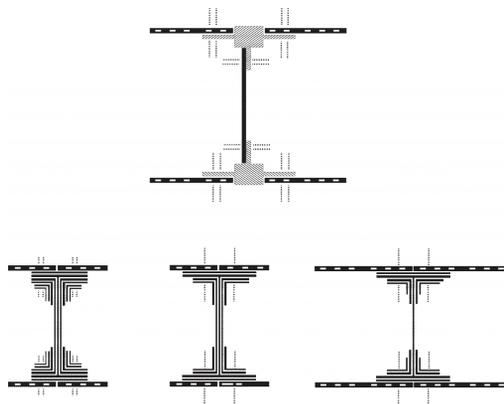


Figure 5.23
Build-up concepts to increase the cross sectional area of the spar towards the wing root. (TU Delft, 2018, 5-23.jpg. Own Work.)

Similar to the discussion of the wing ribs, it can be concluded that depending on the function of particular spars, the loads it has to carry, the design philosophy and the available manufacturing equipment, different spar types can be selected, see Figure 5.24.

This also implies that the spar caps (girders) can be manufactured by extrusion and or machining, or by forming sheet material, see Figure 5.25. The forming concept has less geometrical stiffness compared to the extruded concept.

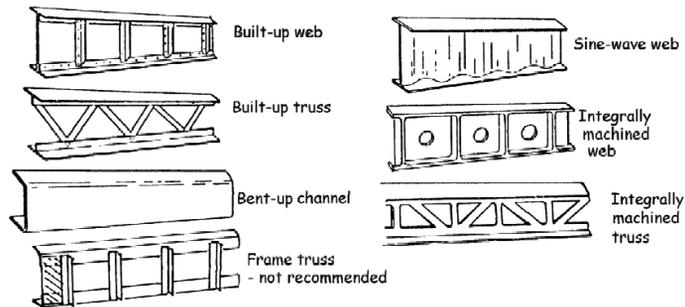


Figure 5.24
Illustration of the different spar types. (TU Delft, n.d., 5-24.jpg. Own Work.)

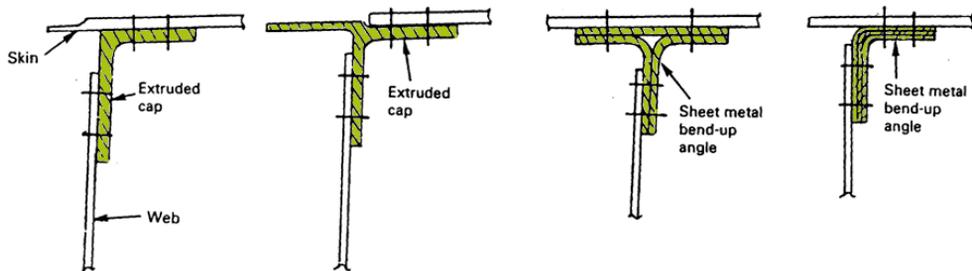


Figure 5.25
Illustration of the spar cap types; extrusion (left) and forming. (TU Delft, n.d., 5-25.jpg. Own Work.) (right)

5.6 Torsion box

The wing is in general loaded by bending and torsional moments. It has been explained that the bending moment can be easily carried by the spars. However, if a wing contains only a single spar, it will not be able to carry the torsional moment, because an I-beam has low resistance against torsion.

In case the wing is equipped with two spars, torsional moments can be carried by differential bending. Differential bending means that torsional deformation is translated to an upward bending of the rear spar and a downward bending of the front spar. In this case, the spar is carrying bending loads for which it is designed.

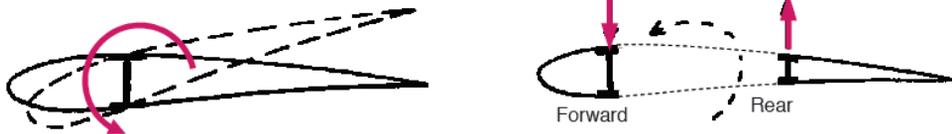


Figure 5.26

Torsional moment in case of single (left) and two spars (right). (Alderliesten, 2011, 5-26.jpg. Own Work.)

However, despite that the resistance to the differential bending is well provided by the spars, torsional moments can be carried more efficiently by a cylinder or closed box, see Figure 5.27. This will be discussed in chapter 6 in more detail. In fact, the cross section does not necessarily need to be cylindrical; any cross section may do, as long as it remains a closed cross section.

A historical example of a single spar wing structure that uses the cylindrical torsion tube is the Blackburn Duncanson, see Figure 5.27.

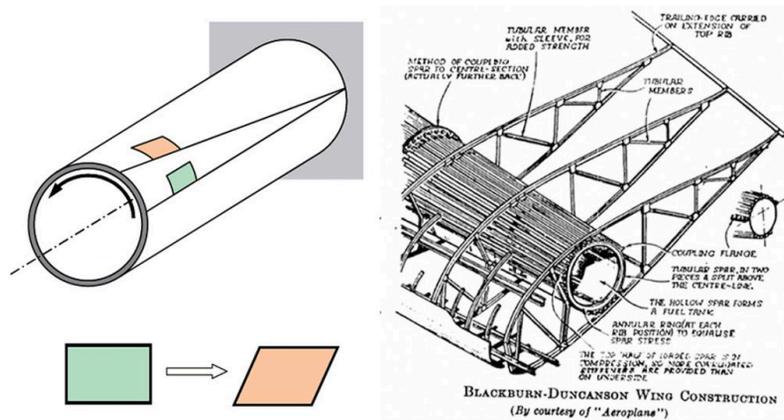


Figure 5.27

Resistance to a torsional moment by a cylinder (left) and the Blackburn Duncanson single cylindrical spar example (right). Derivative from left: Alderliesten, 2011, 5-27-a.jpg, Own Work; and Aeroplane, n.d., 5-27-b.jpg, Own Work.)

The torsional resistance of a closed box structure can be exploited in a wing structure, especially, because the cross section does not need to be circular. This is illustrated in Figure 5.28. Compared to the two spar differential bending concept, the torsion box contains thicker skins. The functions of these skins are to take up the aerodynamic forces and to contribute to the torsion box. In that case they partially take over the bending function of spar caps.

As a consequence the spar caps may have smaller cross sections than in case of the two spar concept. The web plates of the spar will be thicker similar to the wing skins; they contribute to the torsion box and add to the bending resistance.

The stringers in this concept reinforce the upper and lower wing skin and by doing so, also partially contribute to the function the spar caps have in the two spar concept.

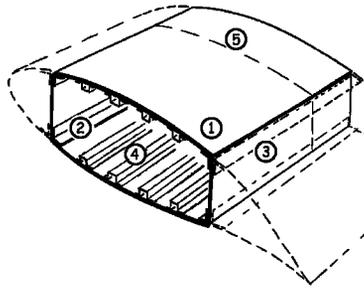


Figure 5.28

Illustration of the different structural elements in a torsion box. (TU Delft, n.d., 5-28.jpg. Own Work.)

The advantages of the torsion box over the two spar concept is that a completely unsupported and load bearing structure can be achieved that does not require support or struts. At given wing span, the wing can be thinner in case a torsion box concept is applied, or similarly, at given wing thickness the wing can be longer. Additionally, by designing the torsion box carefully, the torsion stiffness and the bending stiffness can be engineered separately.

In general, the torsion box concept results in lower structural weight compared to the two spar concept.

5.7 Structural details

Considering the fuselage and wing structures, the elements and their functions have been discussed. However, by creating a three-dimensional structure one will realise that the intersections between the different structural elements require additional considerations. Four examples are discussed here; stringer joggling, stringer couplings at the location where two fuselage barrels are joined, stringer frame intersections, and stringer rib intersections.

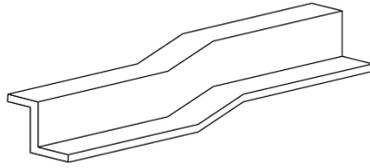


Figure 5.29

Illustration of stringer joggling. (Alderliesten, 2011, 5-29.jpg. Own Work.)

Because the loads are not constant throughout the fuselage structure, the required thickness of fuselage skin panels will vary. The outer surface of the fuselage must be undisturbed for aerodynamic reasons, which implies that thickness steps in the fuselage skin are provided at the inner side of the panel. This can be achieved by either milling thickness step out of thicker sheet material, or by adding additional layers, or so called doublers. These doublers can be riveted or bonded to the skin structure.

The stringers that are attached to the skin have to follow these thickness steps. A common method is to joggle the stringers. Jogging of a stringer implies a shear deformation of the stringer, as illustrated in Figure 5.29.

A fuselage structure is built up from different panels that are connected by longitudinal and circumferential joints. This implies that the panels are manufactured including stringers, but that once the panels are joined in assembly, the stringers can be connected to each other. This is illustrated in Figure 5.30. The joint between the fuselage skin panels is created by adding splice plates at the inner side of the structure, to obtain an aerodynamically smooth surface outside.

These splice plates also cause thickness steps that have to be accounted for by the stringers that are attached to the fuselage skin. When a stringer coupling is used to connect the stringers of both panels, the design of the coupling needs to account for the thickness step.

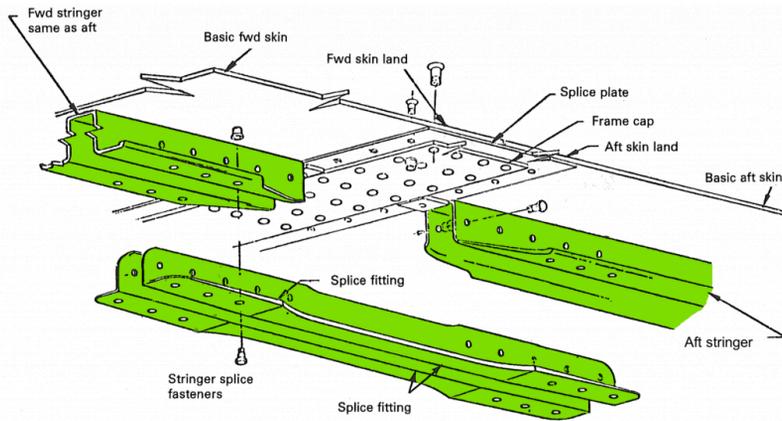


Figure 5.30

Illustration of stringer connection at the joint between two fuselage barrels. (TU Delft, n.d., 5-30.jpg. Own Work.)

Another intersection between stiffening elements that has to be considered is the intersection between stringer and frame. To create the three-dimensional geometry here, there are in general two concepts to provide the intersection. In both cases, the stringers are continuous and not interrupted to have the optimal longitudinal stiffness of the panel.

In the first concept, the frame is locally interrupted to provide an opening for the stringer. This method implies a local weakening of the frame and reduction in bending resistance of the beam. The other concept positions the frame above (floating) the stringers and provides the connection between frame and fuselage skin by castellation or clips. An illustration of both concepts is given in Figure 5.31.

Similarly to the frame stringer intersection, intersections between stringers and ribs have to be created in wing structures. Figure 5.32 illustrates that for this case there are in general three possible solutions to enable the intersection;

- Both the rib and stringer are uninterrupted
- The stringer is interrupted
- The rib is interrupted

The selection of the most appropriate concept depends on the loads that act locally upon the structure and the manufacturability of the concept.

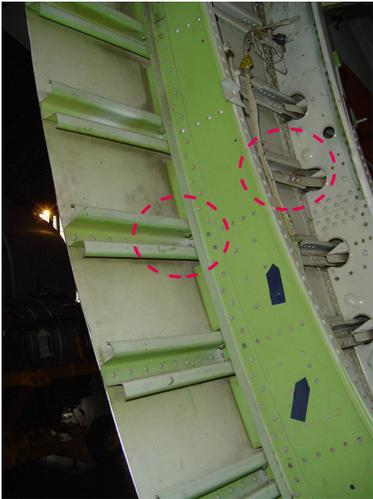


Figure 5.31
Illustration of intersections between frames and stringers in a fuselage panel. (Kolossos, 2006, CC-BY-SA 3.0)

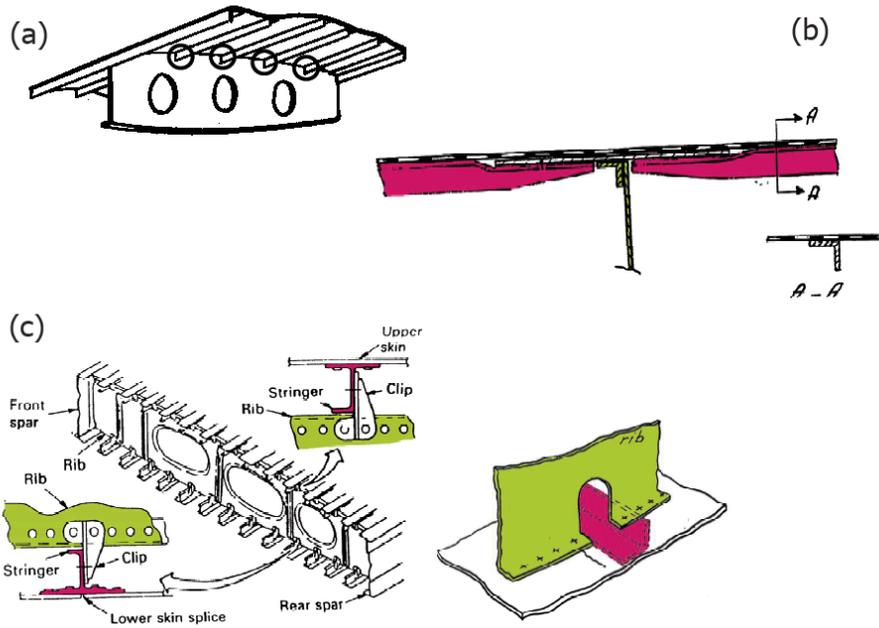


Figure 5.32

Illustration possible rib stringer intersections; both uninterrupted (a), stringer interrupted (b), rib interrupted (c) shows both possibilities: inserts are both uninterrupted, using the clips. The close-up shown on the right is rib interrupted. (TU Delft, n.d., 5-32.jpg. Own Work.)

5.8 Typical spacecraft structures

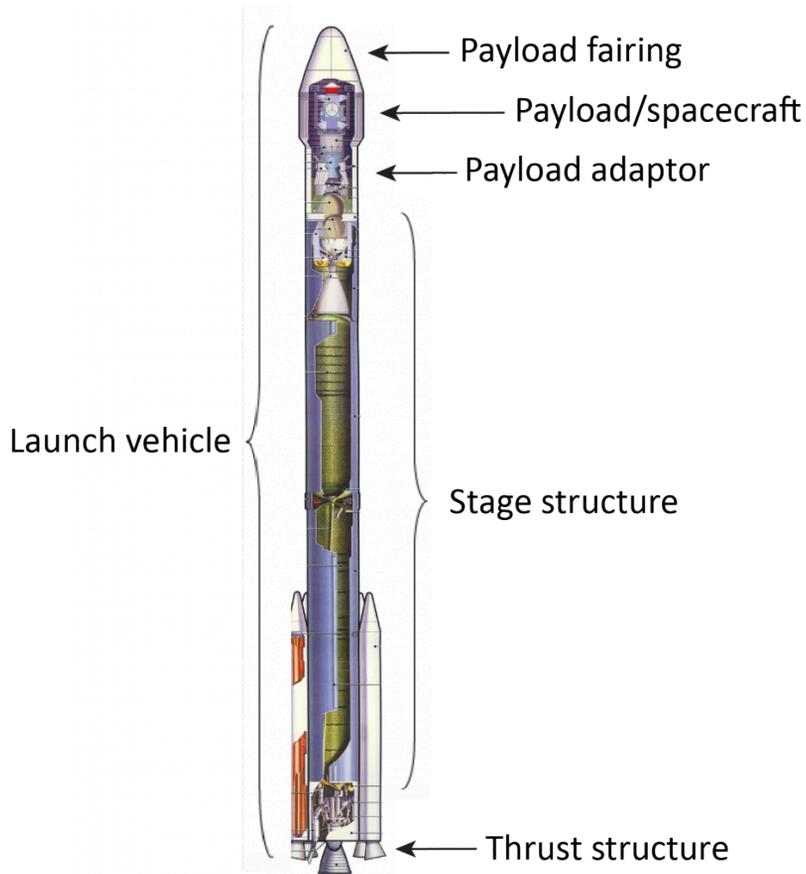


Figure 5.33

Illustration of the spacecraft and launch vehicle (Delta II), with typical components. Derivative from: NASA (2000), Public Domain.

When looking at the spacecraft, one has to take into account that space despite being the operational environment of the spacecraft, does not solely determine the structural design. In fact, the main structural items that can be observed in the spacecraft are dimensioned to sustain all loads related to launch. This means that the forces provided by thrust at the lower end of the launch vehicle have to be transferred

through the structure, including the spacecraft structure. To accomplish this load transfer through the spacecraft structure, two categories of spacecraft structures can be distinguished

- Strutted structures
- Central cylindrical shell structures

Both types of structures will be briefly discussed in this section.

5.8.1 Strutted structure

Part of the launch vehicle is the payload adaptor that is discussed in section 5.9.4. One may assume that the load provided by thrust to be transferred through the spacecraft structure is inserted in to the structure by the adaptor.

One way to create the necessary load paths through the structure is by using struts. These struts basically are a form of truss structure, discussed in section 5.2.1, where the struts are loaded primarily in compression in their longitudinal axis. An example of a truss structure is given in Figure 5.34.



Figure 5.34

Example of a spacecraft utilizing a truss structure. (ESA, 2012, Copyright ESA, Use Permitted.)

An important dimensioning aspect then will be the stability of the trusses, see chapter 8. The trusses should not bulge out in compression, but remain stable to be able to transfer the load to the remaining structure. However, because the primary function of

the trusses is to sustain this particular load case, they can be optimized for this case with particular material and shape solutions, like, for example, the struts in the Space Shuttle ribs mentioned in section 5.2.1.

5.8.2 Central cylindrical shell structure

The central cylindrical shell structure configuration distinguishes itself from other structures, because it has a major central thrust-load-bearing member in the form of a cone of a cylinder (Wertz & Larson, 1999). All load provided by thrust and inserted via the adaptor is transferred through a central cylinder that is primarily dimensioned for this load case.

All systems within the spacecraft are attached at strong points directly to the cylinder or they are attached by combinations of struts, platforms and shear webs. An example is illustrated in Figure 5.35.

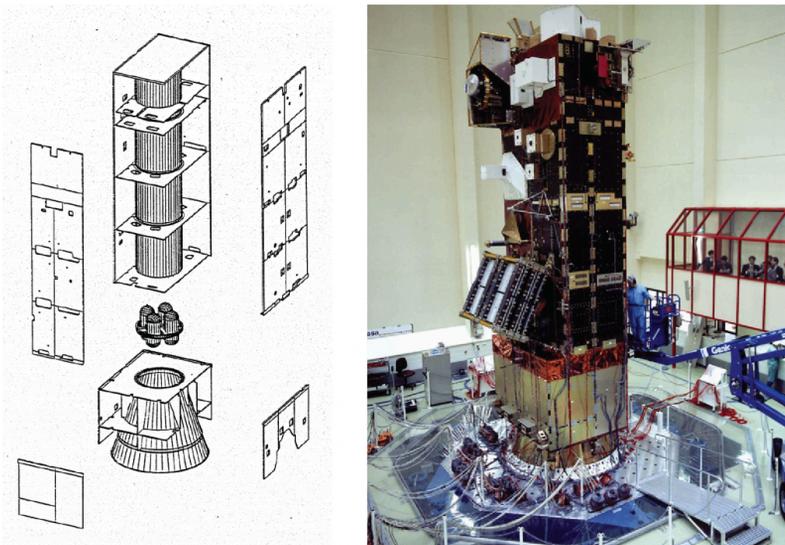


Figure 5.35
Example of a (polar platform) spacecraft utilizing a central cylindrical shell structure. Derivative from ESA, (2002),
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5.9 Typical launch vehicle structures

In this section the four main structural parts of the launch vehicle are discussed: the payload fairing, the stage structures, the thrust structures and the adaptors.

5.9.1 Payload fairings

The payload fairing is an important part of the launch vehicle. It protects the payload during launch and ascent against the aggressive environment, i.e. aerodynamic heating and pressure. Once the launch vehicle is outside the atmosphere, the fairings are disposed, exposing the payload to the environment. The consequence of the fairing disposal is that the to be accelerated mass will decrease, which increases the efficiency of the thrust.

5.9.2 Stage structures

Rocket launchers typically consist of multiple stages, which each contain a rocket propulsion system with several subsystems within the structure. These stages can either be placed in sequence, i.e. on top of each other, or in parallel. The main stage forms the core of the launcher, while booster stages are often placed in parallel to increase the thrust during the initial part of the ascent. The booster stages are illustrated in Figure 5.33.

Different design concepts could be chosen for the stage structure. The two most important design concepts can be characterized by whether the fuel tanks are part of the load bearing structure, or not.

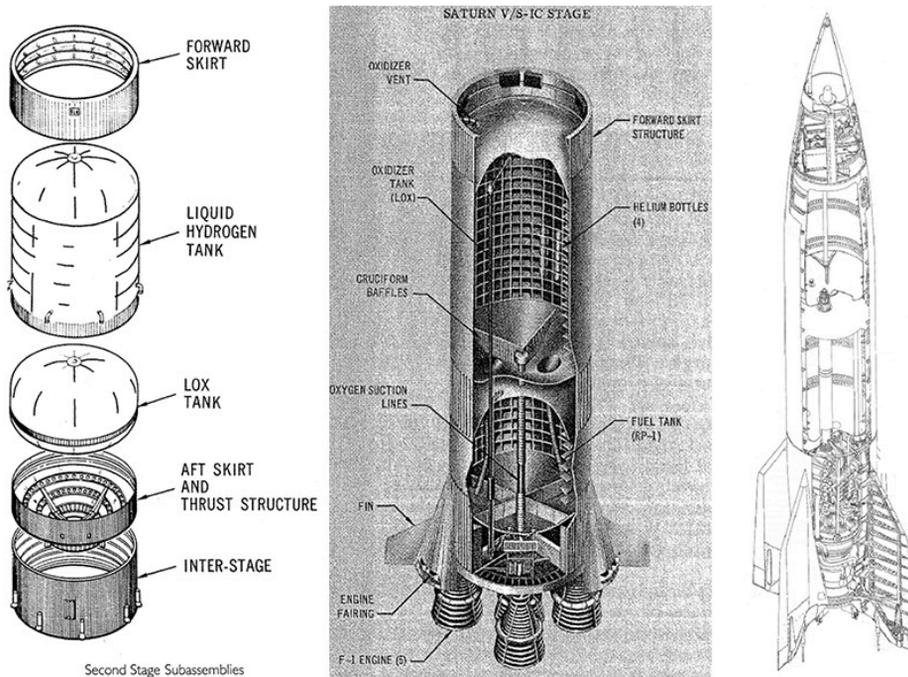


Figure 5.36

Illustrations of typical stage structures: Saturn, fuel tank part of the structure (left) and V2, fuel tank not part of the structure (right). Derivative from NASA, (n.d.), Public Domain.

The exploded view in Figure 5.36 illustrates the assembly of the structural components in case the fuel tanks are part of the load bearing structure. The structural components are connected with interface structures to transfer the load from one component to another. The skin concept is usually referred to as semi-monocoque, i.e. load bearing skin containing internal stiffeners, as explained earlier.

The design concept in which the fuel tanks are not part of the primary structure contains an external skin that is separated from the internal tanks by longerons and circular stiffeners, this is illustrated in the right part of Figure 5.36

5.9.3 Thrust structures

The thrust structure is an important part of the launcher as all loads introduced by the propulsion system is transferred via this structure into the main stages of the

launcher. The high loads (Ariane 5 about 15000 kN at take-off \sim 1500 tons) are introduced rather concentrated and must be distributed into the stage structure via a conical structure, as illustrated in Figure 5.37.

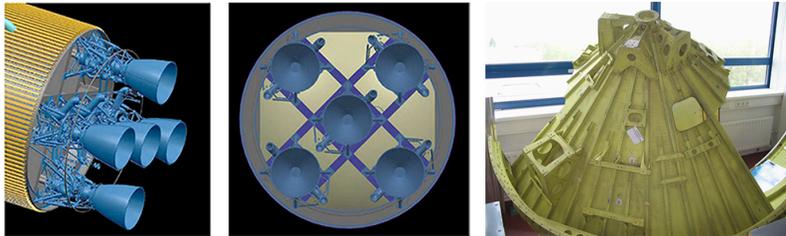


Figure 5.37

Illustrations of ARES V thrust structures (left -NASA, 2007, Public Domain) and section of the Ariane 5 HM60 conical thrust structure (engine mounted on top of cone) (right – TU Delft, n.d., 5-37.jpg, Own Work)

5.9.4 Adaptors

A similar function of transferring loads, as mentioned for the conical structure that is part of the thrust structure, has to be fulfilled by the adaptors. This part is located in the upper part of the structure and has the primary function to transfer the loads from the stages into the spacecraft or satellite located in the payload area under the fairing.

Hence similar conical shapes can be observed, as illustrated in Figure 5.38, where instead of the load distributed to a wider area, the loads are rather concentrated into the primary structure of the spacecraft, especially when the spacecraft applies a central cylindrical shell design, see section 5.8.2.

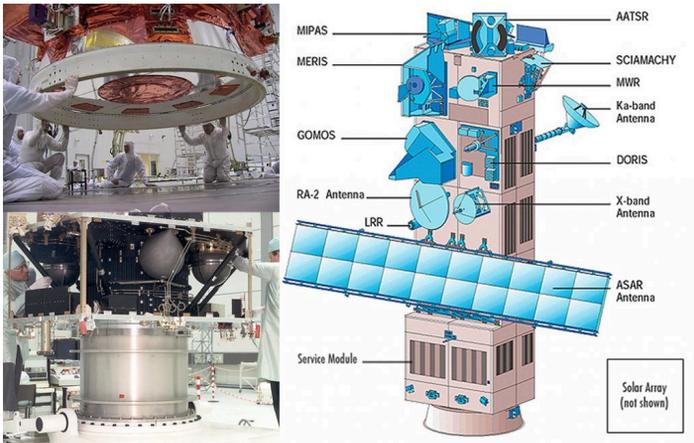


Figure 5.38
Illustrations of adaptors (lower left image shows the Hipparcos main structure and fuel tanks, upper left image shows the adaptor for the Envisat shown right). Derivative from ESA, (2002), Copyright ESA.

Introduction to Aerospace Structures and Materials

Dr.ir. R.C. (René) Alderliesten

This book provides an introduction to the discipline of aerospace structures and materials. It is the first book to date that includes all relevant aspects of this discipline within a single monologue. These aspects range from materials, manufacturing and processing techniques, to structures, design principles and structural performance, including aspects like durability and safety. With the purpose of introducing students into the basics of the entire discipline, the book presents the subjects broadly and loosely connected, adopting either a formal description or an informal walk around type of presentation. A key lesson conveyed within this book is the interplay between the exact science and engineering topics, like solid material physics and structural analysis, and the soft topics that are not easily captured by equations and formulas. Safety, manufacturability, availability and costing are some of these topics that are presented in this book to explain decisions and design solutions within this discipline.



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Dr. Alderliesten obtained his MSc and PhD degree both at TU Delft, and holds since 2012 the position of associated professor within the department of Aerospace Structures and Materials at the faculty of Aerospace Engineering, TU Delft. His expertise is fatigue and damage tolerance of metals, composites and hybrid materials, with the emphasis on proper understanding the physics of damage growth. Dr. Alderliesten introduces Aerospace Structures & Materials in the first semester of the BSc curriculum, while teaching Fatigue of Structures & Materials in the first semester of the MSc both at TU Delft and at the University di Bologna.



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