

Introduction to Aerospace Structures and Materials

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6. Aircraft & spacecraft loads

6.1 Introduction

In the previous chapter, typical aircraft and spacecraft structures have been discussed. The structural elements belonging to the airframe fulfil primarily load bearing functions. After reviewing the structural elements and their characteristics, it is time to consider the loads acting on these structures and elements.

This chapter will review typical loads and load cases for both aircraft and spacecraft. These loads can be divided into concentrated and distributed loads, which each can be divided into static or dynamic loads. These characteristics together with the typical load paths will be discussed in this chapter.



Figure 6.1

The four principle forces considered acting on an aircraft in flight. Derivative from Mr_worker, 2014, Public Domain.

6.2 Externally loaded airframe

To assess the flight performance, an aircraft in horizontal steady flight is typically illustrated with the principle forces that act on such aircraft; lift in equilibrium with weight, and thrust in equilibrium with drag, see for example Figure 6.1. These equilibriums change for various manoeuvres, but are commonly based on the major forces.

However, although sufficient for representing the forces and equilibriums when describing aircraft performance, this presentation becomes insufficient when considering structures and loads acting on those structures. For example, the presentation of Figure 6.1 may be more accurately presented by the illustration in Figure 6.2.

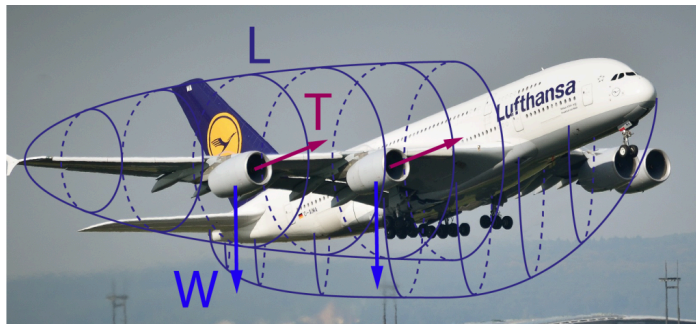


Figure 6.2

Concentrated and distributed forces acting on an aircraft in flight. Derivative from Mr_worker, (2014), Public Domain.

The presentation of Figure 6.1 for instance, provides equilibrium for the complete aircraft, but it does not provide a realistic presentation for the wing structure. For the wing, Figure 6.1 is insufficient as it does not show the forces acting on the wing. In fact, it assumes (equilibrium of) all forces are acting on the centre of gravity. Here, a presentation like in Figure 6.2 seems to give a better picture; the lift generated by the wing is partly compensated for by the weight of the wing and engines, while the thrust is to an even lesser extent compensated by the drag of the wing. The resultants are of course acting on the centre of gravity creating equilibrium with the fuselage and empennage of the aircraft.

In general, the airframe is loaded by a combination of loads, or load cases, which may be attributed to aircraft manoeuvres, gusts, cabin pressure, landing, etc. The loads act on the structure either by concentrated or distributed forces. For example, the thrust is illustrated in Figure 6.2 as a concentrated load, while the wing lift is represented as distributed force acting on the wing. In fact, the engines apply the thrust to the wing via few bolts (concentrated loads), while the lift is a force resulting from pressure multiplied with the area it acts on (distributed force). The consequence of concentrated or distributed loading acting on a structure is illustrated with the example of a beam in bending.

Example: Bending of a beam

Consider the beam illustrated in Figure 6.3 rigidly clamped at one side and loaded at the other side by a concentrated load at the end of the beam or a distributed load decreasing towards the tip of the beam. If both load cases represent the same total force P in vertical direction, then the deflection of the beam for the concentrated and distributed case can be given by

$$\delta = \frac{PL^3}{3EI} \text{ and } \delta = \frac{PI^3}{15EI}$$

respectively, where P is the total vertical load, l the length of the beam, E the Young's modulus and I the area moment of inertia.

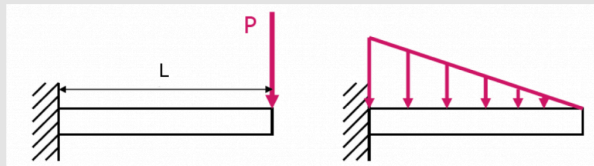


Figure 6.3

Beam bending induced by a concentrated force (left) and a distributed force (right). (Alderliesten, 2011, 6-3.jpg. Own Work.)

6.3 Load path

To understand the meaning of loads acting on a given structure, first the load path must be understood. A load path is a physical trajectory that links the location of applied force and forces elsewhere that provide equilibrium with the applied force. However, this trajectory should be able to carry and transfer the loads. This is illustrated with the point force acting at a certain location in space, as illustrated in Figure 6.4

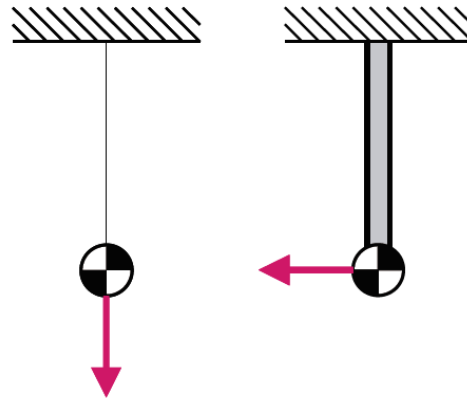


Figure 6.4

Different load paths for a point force acting in space. (Alderliesten, 2011, 6-4.jpg. Own Work.)

For the case where the force is applied downward in vertical direction, there are several solutions to provide equilibrium. A simple cable or rod may be sufficient to be connected between the point force and the wall. In this case the cable or rod represents the load path and it is loaded in tension. For the second case in Figure 6.4, however, the cable may not be sufficient, because the point force would cause the cable to rotate. As a result, equilibrium would not be obtained and thus the cable cannot provide the load path.

The solution in that case may be to connect the point force with a beam to the wall. The beam would resist bending and equilibrium would be obtained not only with a horizontal force at the wall in opposite direction of the applied point force, but as will be explained later in this chapter, also by a set of forces in vertical direction.

6.3.1 Cathedral structures

An illustrative example of load paths is given by looking at old cathedrals. These thin-walled and often tall structures are dimensioned to carry the weight of its own structure in compression. However, because of the thin walls and the tall structure, the addition of the roof structure on top of the walls would result in resultant forces pushing the walls away from each other. Because the walls can only carry load in the plane of its structure, this would lead to collapse of the building. There are two basic methods to avoid this type of failure (see Figure 6.5)

- Using tensile elements to provide equilibrium in the roof structure (inside)
- Using buttresses to provide a load path through the cathedral structure (outside)

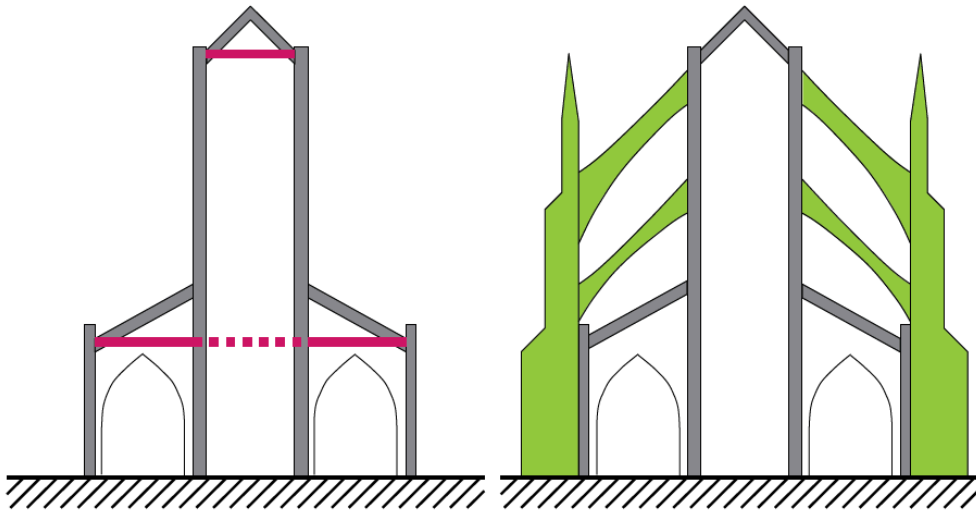


Figure 6.5

Two concepts to sustain the loads from the roof structure's weight. (Alderliesten, 2011, 6-5.jpg. Own Work.)

Because the materials and corresponding production techniques were not yet sufficiently developed to manufacture elements that could be loaded in tension, the designers of these structures used buttresses. The design of buttresses is based on the concept that the resultant force induced by the roof structure can be directed further downward by adding additional forces directed downward. These additional forces are applied by the weight of the buttress structure.

Comparing the different churches and cathedrals, one may observe differences in the design of the buttresses. The weight of the buttresses necessary to provide a resultant force path to the ground can be obtained with three solutions:

- Creating wide buttresses or long flying buttresses to achieve sufficient distance from the central structure to be in line with the load path for the lateral forces
- Creating very thick buttresses to create sufficient weight to provide a resultant load path within the buttress
- Creating very tall buttresses with long decorated peaks of which the weight provides a resultant load path through the relatively thin buttresses.

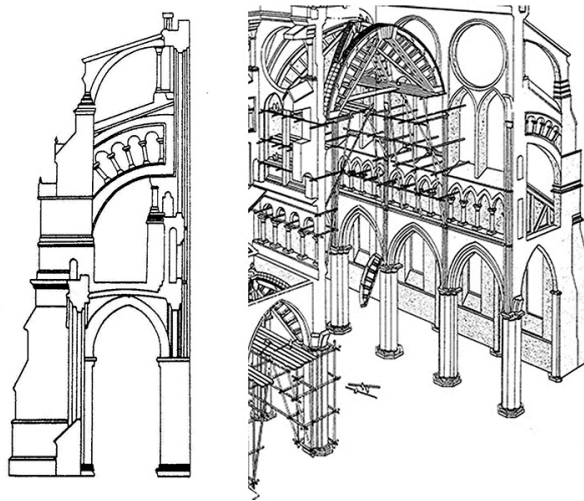


Figure 6.6

Illustration of a central cathedral structure and buttresses to support that structure. Derivative from Roddy, (2007), UC Davis.

6.3.2 Bending of beam structures

Consider the deflection of a beam as illustrated in Figure 6.7. The vertical load applied at the free end of the beam will cause a deflection. Looking at the left hand side illustration in that figure, the load path obviously consists of normal forces at the upper and lower surfaces (or girders) and shear forces in the web plate, see section 5.3.2.

For both cases (a) and (c) in Figure 6.7, the load path is in equilibrium with the applied force in the centre of the cross section. However, for case (b) the shear forces in the web plate are not aligned with the applied force. The distance between the centre of the web plate, see Figure 6.8 (a), and the centre of the cross section will induce a resulting moment. This moment is in fact a torsional moment, which will rotate the beam together with the vertical deflection.

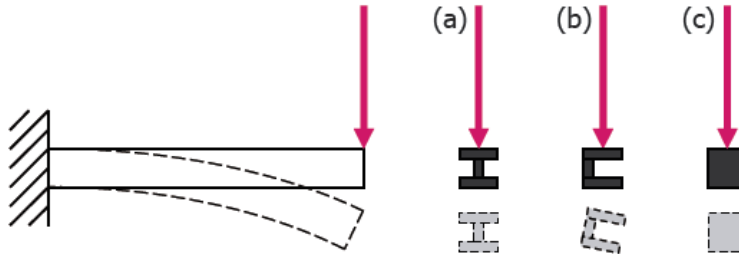


Figure 6.7
Bending of a beam with different cross sections. (Alderliesten, 2011, 6-7.jpg. Own Work).

Concerning the load in the elements of the beam, it has been mentioned before that the forces at the clamped side of the beam are high. The magnitude of these forces depends on the applied load at the other end and the length L of the beam. The longer the beam, the higher the normal forces in the girders at the root.

This equilibrium can be illustrated with Figure 6.8 (b); the applied load multiplied with the length L must be in equilibrium with the product of normal forces and height H . This means that at the end of the beam the normal forces are zero and they linearly build up towards the root. Taking a section of the girder at any location of the beam, as indicated by the square in Figure 6.8 (b), and looking at its force equilibrium, it can be observed that equilibrium is provided by the increase of normal forces and the shear forces that the web plate applies to the girder.

Here, it is evident that the shear forces in the web are constant throughout the web plate. Cutting away a part of the web plate, see Figure 6.8 (c), means that the normal forces in the girders are not increasing in the area where the web plate is removed. Only due to the constant shear forces that the web plate applies to the girders, the normal forces increase. Without the shear forces, the normal forces would be constant.

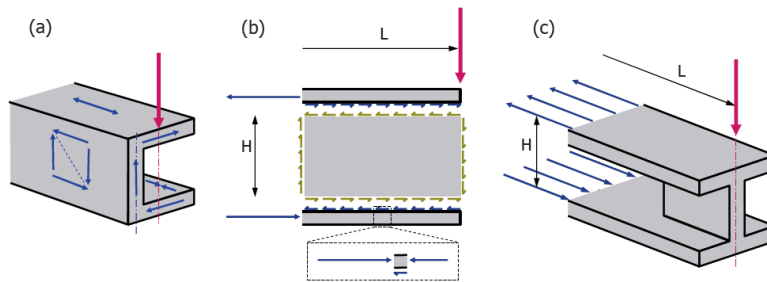


Figure 6.8
Specific aspects related to beam bending (Alderliesten, 2011, 6-8.jpg. Own Work.)

6.4 Loads and load paths in an airframe

It has been discussed a few times, that due to the lift generated by the wing, the wing will bend upward. All lift generated by the wings will be in equilibrium with the weight of the wing and the fuselage. But if the aircraft is considered as two beams that cross, then the lift will provide an upward bending of the wing beam, while the weight of the fuselage beam will cause a downward bending over the wing. This deformation is illustrated in Figure 6.9. Both the lift generated by the wings and the weight of wing and fuselage are considered to be distributed forces acting on the structure.

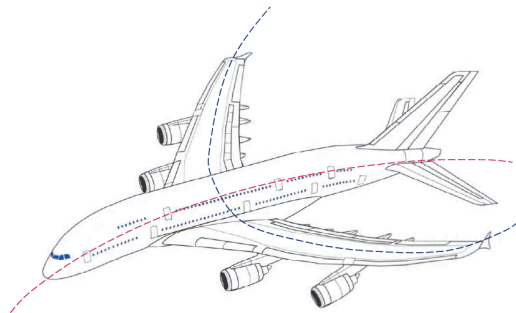


Figure 6.9
Upward wing bending and downward fuselage bending. (Alderliesten, 2011, 6-9.jpg. Own Work.)

Examples of concentrated loads are the forces applied to the aircraft by the landing gears, see Figure 6.10. If the aircraft stands on the platform, the forces introduced by the landing gears are in equilibrium with the total weight of the aircraft.



Figure 6.10

Concentrated forces applied to the airframe by the landing gears. Derivative from Lampel, (2013), CC-BY-SA3.0.

The load path that can be identified in this case starts at the local load introduction of the landing gear, via the rib at that location into the wing structure. Here, the normal forces are carried via the skins, while the shear forces are carried by the web plate of the spars. Although Figure 6.10 only illustrates the load path from the main landing gear towards the fuselage, also part of the load should provide equilibrium with the weight of the wing (and engines) towards the wing tip.

Let's consider the aircraft as it is standing on the platform. Wind may apply a load on the vertical tail plane as illustrated in Figure 6.11. If the vertical tail plane is considered to be clamped at the fuselage, the deformation may be represented by a beam under bending, as illustrated in the right hand side of the figure. Notice that as the wind applies to the complete surface of the vertical tail plane is considered a distributed load. Because the frontal surface decreases towards the tail tip, the forces most likely will reduce towards the tip.

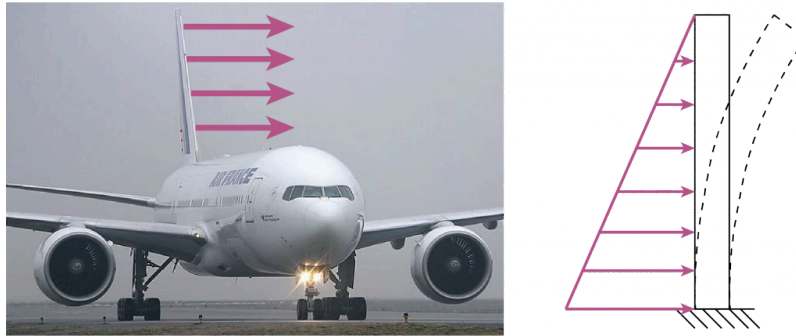


Figure 6.11
Bending moment on vertical tail plane induced by wind. Derivative from Noret, (2012), CC-BY-SA2.5.

Thus the forces are in equilibrium by forces at the root of the vertical tail. However, if the fuselage is considered to be a cylinder which is 'clamped' at the location of the wing, then the bending moment on the vertical tail will rotate the fuselage, as illustrated in Figure 6.12.

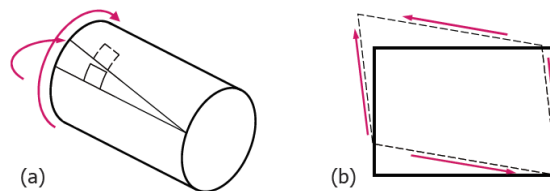


Figure 6.12
Rotation of the fuselage (a) with as result shear deformation of the skin panels (b). (Alderliesten, 2011, 6-12.jpg. Own Work.)

Zooming in further onto the fuselage structure, the fuselage skin panels will deform in shear due to the torsion of the fuselage.

The fuselage was assumed to be 'clamped' in the area of the wing. If the aircraft is standing on the platform, the bending moment on the vertical tail and torsional moment on the fuselage will be in equilibrium with the main landing gear. The reaction forces introduced by the landing gear will be different in magnitude, where the difference between these forces will be providing the equilibrium.

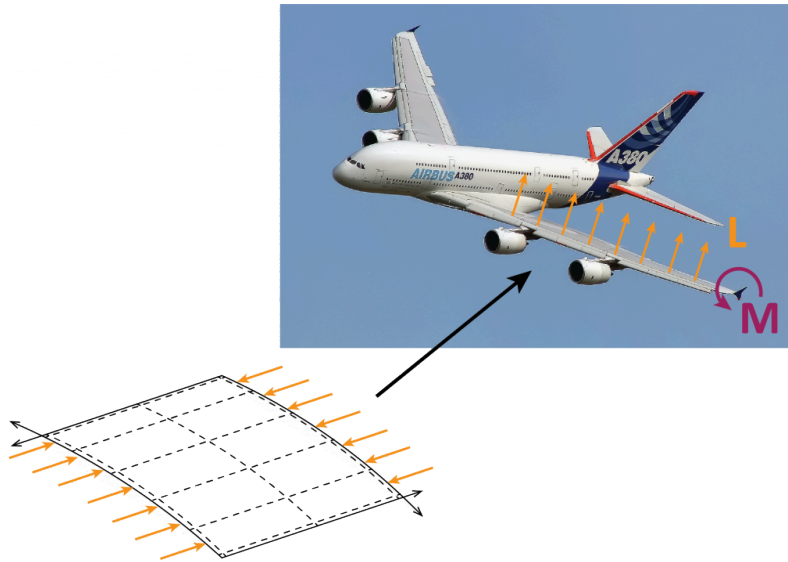


Figure 6.13
Upward bending and rotation of the wing. Derivative from: *lenac*, (2006), Public Domain.

A similar discussion may apply to the bending and rotation of the wing in flight. First, the wing may be considered clamped at the root and bending is carried by the upper and lower wing skins in respectively compression and tension forces. The torsional loading will be carried by shear in the torsion box, i.e. both wing skins and both web plates of the spars.

In cruise, the loads will be similar for both wings, which imply that the forces acting on the centre wing box in the fuselage will be equal in magnitude but opposite in sign.

Here, the example of the cathedral structure may explain more specifically how load should be introduced into a structure. Consider the A400M shown in Figure 6.14. The connection between the wing structure and the fuselage structure could be designed in different ways. Two possible solutions are illustrated in Figure 6.15.



Figure 6.14
 Lockheed C-5 Galaxy transport aircraft in maintenance (left) and the centre wing box of a Lockheed C-130 Hercules transport aircraft (right). Derivative of Sapp – U.S. Air Force, (2006, 2011), Public Domain.

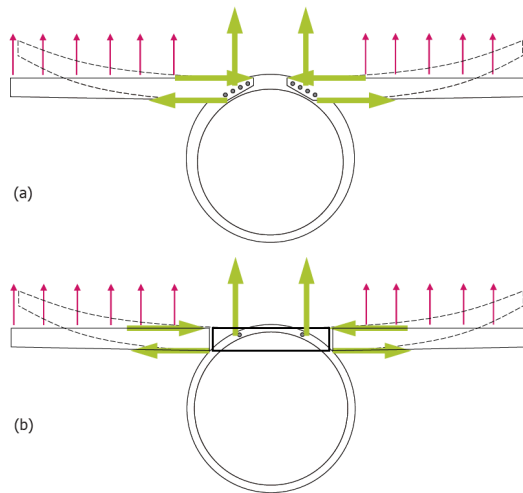


Figure 6.15
 Illustration of two solutions to connect the wing structure to the fuselage structure. (Alderliesten, 2011, 6-15.jpg. Own Work.)

The first solution, Figure 6.15 (a), is not preferred, because it will not only introduce the lift generated by the wing into the fuselage structure, but also all bending deformation as result of that lift. Locally the frames of the fuselage will be highly loaded by tension and torsional forces, which can only be achieved by designing very large and thick frames. But even then, it may be disputable whether the design would suffice.

The second solution, Figure 6.15 (b), is the preferred solution and in fact the solution applied on the A400M and other aircraft. The centre wing box is designed such that the normal forces introduced by the upper and lower wing skin due to wing bending are carried by the upper and lower skin of the centre wing box. Only the lift is introduced into the fuselage structure as vertical force by four attachment points (lugs).

In that respect, this example may be compared to the example of the cathedral structure. The roof due to its weight introduces forces that push the walls away from each other. The solution applied in the past was to guide all these forces through the structure towards the ground using buttresses.

However, a leaner solution resulting in significant less weight would be to provide equilibrium inside the roof for the forces acting outward, and to guide only the vertical component of the weight into the remaining structure, see the left hand side of Figure 6.5.

6.5 Complex load cases

In this section two more complicated load cases for aircraft structures will be discussed: fuselage loads and dynamic loads.

6.5.1 Fuselage loads

In general, one has to be aware that the many possible load cases acting on the structure either as concentrated loads, or as distributed loads, provide a complex picture of areas on the structure that are dictated by different load cases and damage scenarios.

This is illustrated in Figure 6.16. Static ground loads can be significant near the landing gears, but will be less restrictive in other areas. The earlier mentioned downward bending of the fuselage over the wing due to its weight will imply longitudinal tension in the upper part of the fuselage. Together with the circumferential tension as a result of pressurization (which also adds to the longitudinal tension, see next chapter), this will make tension and fatigue dominant

load cases for the upper fuselage. The lower fuselage however, will be predominantly facing compression loads due to the fuselage bending, with as consequence dominant criteria on stability.

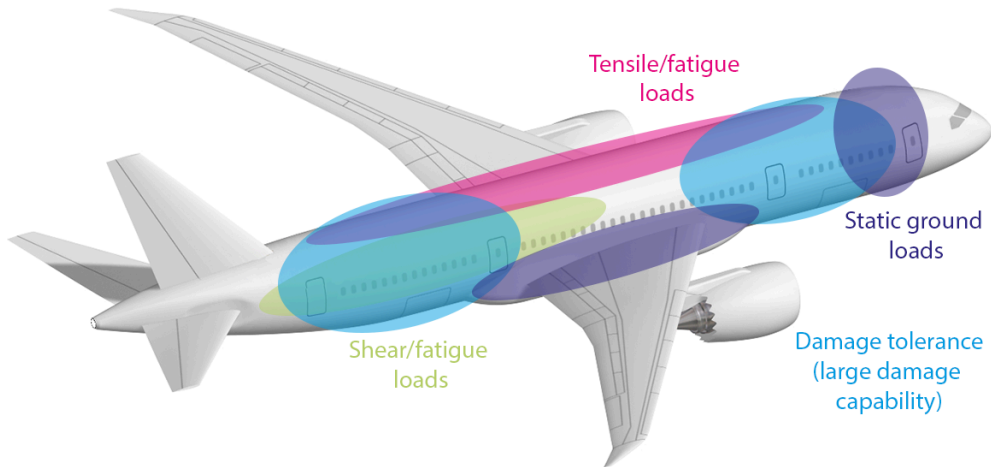


Figure 6.16

Illustration of the dominant load cases and design criteria in the fuselage structure. (TU Delft, 2018, 6-16.jpg. Own Work.)

The aft side fuselage shells will face shear and fatigue loads, introduced by the loads introduced by the empennage. One example of the bending of the vertical tail plane has been discussed at the beginning of this section.

6.5.2 Dynamic loads

The discussion of loads and load paths in this chapter has been limited implicitly to quasi-static loading, i.e. an external load is applied to the structure and equilibrium must be provided. However, in an aircraft not all loads are quasi-static. Some loading appears to be very dynamic of nature. Although fatigue, discussed in chapter 10, relates to cyclic loading, it relates in most cases still to quasi-static loading. For example, the pressurization cycle (equivalent to a single flight) may be analyzed as a single load cycle in an almost constant fatigue loading spectrum over the year. Nonetheless, the load cycle itself is considered quasi-static.

Sometimes interaction of aerodynamic forces, structural elastic reactions, and inertia of components may induce oscillations of aircraft components. These oscillations may be quite significant and severe. One example of these oscillations may be flutter, which may lead to destruction of components if not anticipated for.

Another example is buffeting caused by airflow separation from one component onto another. A well known example here is the buffeting issues related to the two vertical tails of the F18 Hornet.

Because the oscillations may increase if natural frequencies of the structure are approached, the design has to take into account the damping properties of the structure or component. In addition, the design should account for natural frequencies and attempt to keep the natural frequencies outside the range of potential frequencies of oscillations. An example of this approach is discussed for spacecraft structures in chapter 8.

6.6 Load and load cases for spacecraft structures

Spacecraft in general face different types of loading compared to aircraft. A distinction has to be made between the loads related to handling and pretesting, the loads related to launching and the loads occurring once the structure is in orbit.

The load cases considered prior to launching are the handling and transportation loads as well as the vibration and acoustic test loads.

The static and dynamic loads during launching can be categorized by:

- Quasi-static
- Sine vibration
- Acoustic noise and random vibration
- Shock loads

The consequence of these loads for design is discussed in detail in chapter 8. In orbit the spacecraft will experience shock loads, structurally transmitted loads, internal pressure and thermal stress. These are generally much lower than launch loads and are not discussed in detail in this book.

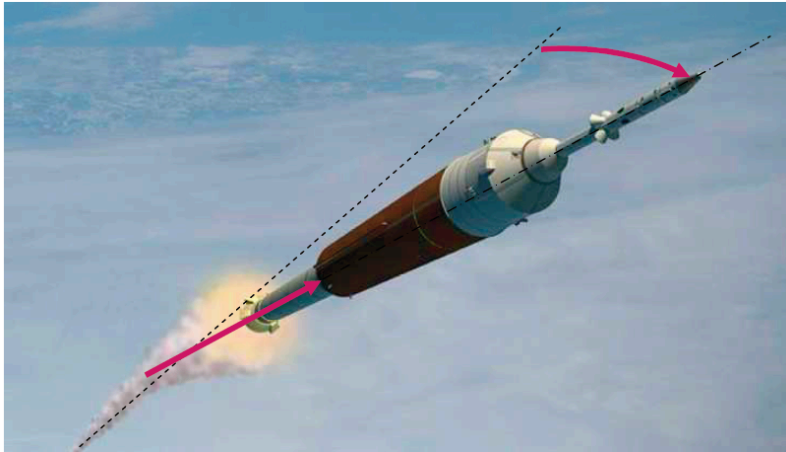


Figure 6.17

Illustration of the axial and lateral loads and movements. Derivative of NASA (2006), Public Domain.

The steady state loads can be directed either in axial direction of the launching vehicle or perpendicular to that direction (lateral direction). The main load case acting in axial direction is the thrust generated by the engine of the launching vehicle. Wind gust and vehicle manoeuvres are generally oriented in lateral direction.

One important distinction one has to make here is the primary axis of the spacecraft (satellite, etc) with respect to the primary axis of the launching vehicle. The explanation of axial loads and lateral loads may seem obvious for the case illustrated in Figure 6.17, but when designing a spacecraft, it depends on the orientation of the spacecraft with respect to the launching vehicle, see Figure 6.18.

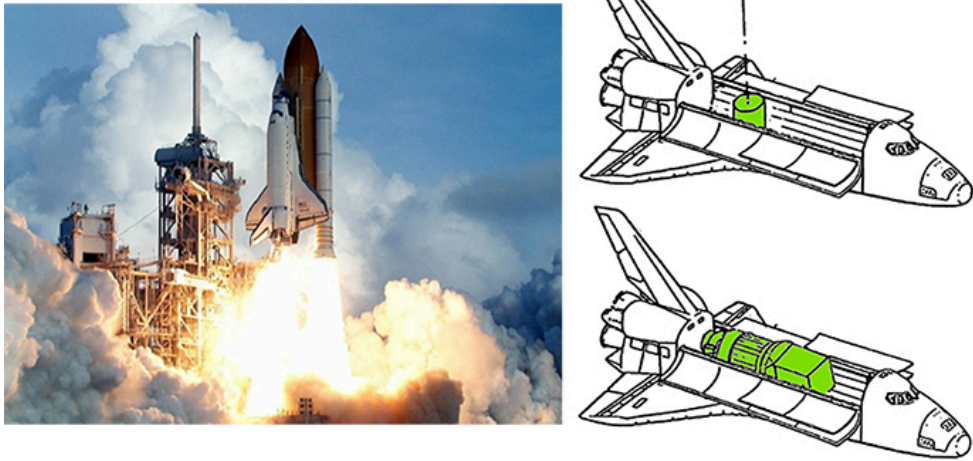


Figure 6.18
Illustration of spacecraft orientation with respect to launching vehicle. Derivative of NASA, (2000), Public Domain.

The upper case in the right hand side of Figure 6.18 has its primary axis perpendicular to the maximum acceleration, whereas the lower case has its primary axis parallel to the maximum acceleration. The design of the spacecraft will be different for both scenarios.

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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