Universidad Carlos III de Madrid

Aerospace Structures
Chapter 1 guide

Abstract

The objective of this chapter is to offer a brief introduction to aircraft and airport structures. The components of aircraft have several functions and support different types of loads. For this reason, an overview of the main load applied to the aircraft is also presented. The structure of an aircraft is composed of several assemblies of components; in this chapter the major components (wing, fuselage and empennage) are described. A brief resume of the method to calculate truss and frame structures is presented.

1. Introduction

A structure can be defined as "the set of resistive elements capable of maintaining their forms and characteristics over time, under the action of an external load”. This definition was established by the Spanish civil engineer Eduardo Torroja. The structure of an aircraft is called “airframe”, the functions of which are: to transmit and resist the loads applied, provide an aerodynamic shape, protect passengers and the payload, and support aircraft systems.

The design process of the airframe can be divided in five steps: specification of function and design criteria, determination of applied load, calculation of internal element loads, determination of allowable element strength, and experimental test.

The design of an airframe requires a structural analysis. This analysis can be defined by the estimation of the effects of external load in the behavior of structures. Several types of structural analyses can be performed: static analysis, damage tolerance, dynamics analysis/impact, and aeroelastic analysis. These analyses cover the different failure modes that can appear in a structure, as shown in the following table. In this subject, only the static analysis is considered.

Mode of failure	Design criteria	Allowables data
static ultimate strength	Structure must support ultimate loads without failure for 3 seconds	Static properties
Deformation of undamaged structure	Deformation of the structure at limit loads may not interfere with safe operation of the element	Static properties and creep properties for elevated temperature conditions
Fatigue crack initiation of undamaged structures	-Fail-safe structure must meet customer service life requirements for operational loading conditions -Safe life components must remain crack free in service. Replacements times must be specified for limited life components	-Crack growth properties -Fracture toughness properties
Residual static strength of damaged structure	-Fail-safe structure must support 80-100% limit loads without catastrophic failure -A single member failed in redundant structure or partial failure in monolithic structure	-Static properties -Fracture toughness properties
Crack growth life of damaged structure	-For fail-safe structure inspection techniques and frequency must be specified to minimize risk of catastrophic failures -For safe-life structures must define inspection techniques and frequencies and, replacement times so that probability of failure due to fatigue cracking is extremely remote	-Crack growth properties -Fracture toughness properties

Authors: Enrique Barbero Pozuelo, Carlos Santiuste Romero, José Fernández Sáez,

2. Aircraft loads

Aircraft loads are forces applied to all the aircraft structural elements. The structural design depends on load and therefore the loads must be determined early in the design. Aircraft loads can be classified as: flight loads, ground-handling loads, static loads, dynamic loads, external loads, and internal loads.

The flight loads may be due to symmetric maneuvers, asymmetric maneuvers, control deflection, or gust loads. The ground-handling loads are those that occur during take-off, landing, taxiing, towing, etc.. There are also special ground loads such as those due to catapulted take-off, arrested landing or landing in water. A dynamic load is one that is a function of time, and introduces an inertial load into the structure. External loads are due to aerodynamic loads, the take-off/landing loads, or those due to the impact of a foreign object. Internal loads are due to internal pressure, engine thrust or component interaction.

The theoretical content of this section is included in one document called “**Loads on structural components”.** This document includes a brief description of the different types of loads and a definition of the models used in design. Also a definition of the concept of load factor is included.

The following readings are recommended for further study of this section.

Suggested reading

- Chapter 3. Aircraft Loads
  M.C.Y. Niu. Airframe Structural Design. Hong Kong Conmilit Press LTD.2005

- Chapter 12 Structural components of aircraft
  H.G. Megson. Aircraft Structures for engineering students. Elsevier. 2007

- Chapter 14 Airframe loads
  H.G. Megson. Aircraft Structures for engineering students. Elsevier. 2007
  Stanford University's Department of Aeronautics and Astronautics.

- Part 2. Loads on Aeroplane Structure.
  N.G. Lakshmi. Aircraft structures. BS Publications. 2010

3. Structural components of aircraft

The major components of a conventional aircraft are wing, fuselage, and empennages (or tail), Fig 1.

http://commons.wikimedia.org/wiki/File:A400M-1957.jpg

Fig.1 Major aircraft components

Wing

The function of the wing is to produce lift. The structures of the wing have to withstand some of the heaviest loads of all aircraft components. The main loads applied on the wing are the aerodynamic loads and the wing's own weight. A wing works as a beam able to support the internal forces (shear, bending, and torsional moments). The major components of the wing are shown in Fig 2.

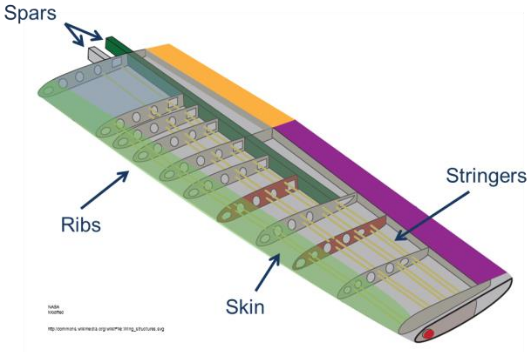


Fig 2. Main components of a cantilever wing

The main structural elements of a wing are the spars. The loads applied to the wing are carried mainly by the spar. Usually the wing is composed by two or more spars. The front spar is located between 15% and 30% of the wing chord, and the rear spar between 65% and 5% of the chord. In a low aspect-ratio wing, as those of a fighter, the structure differs from Fig. 2, and usually a multispar structure is used.

Wing ribs are planar structures, perpendicular to the spars that give the shape to the wing section. Also the ribs transmit the external load from the skin to the spars, and reduce the effective buckling length of the stringers and the skin. The rib spacing is selected after an optimization process (skin+stringer+ribs).

The skin transmits aerodynamic forces to the ribs and spars. The skin represent around 50-70% of the structural weight of the wing and is reinforced by small beams called stringers. Typical cross-sections of stringers are shown in Fig.3.

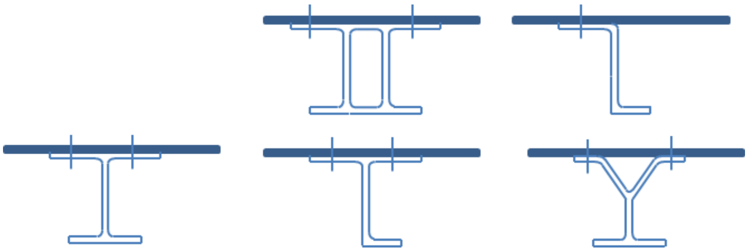


Fig. 3. Typical stringer cross-sections.

The so-called wing box is composed by the rear and front spar, and the top and bottom skin. The spar webs and skin support the shear stress due to the shear force (spar webs) an torsional moment (web spars and skin). The spar flanges support the normal stress due to bending moments.

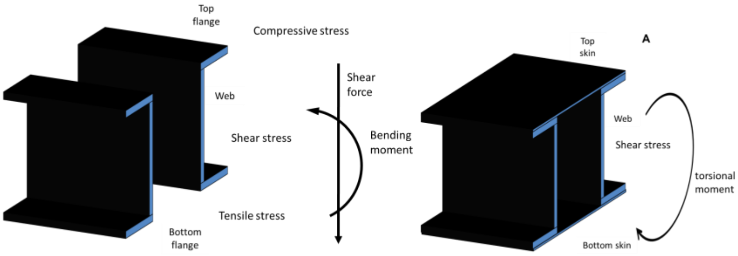


Fig. 4. Load and stress in the wing box

The following readings are recommended for further study of this section.

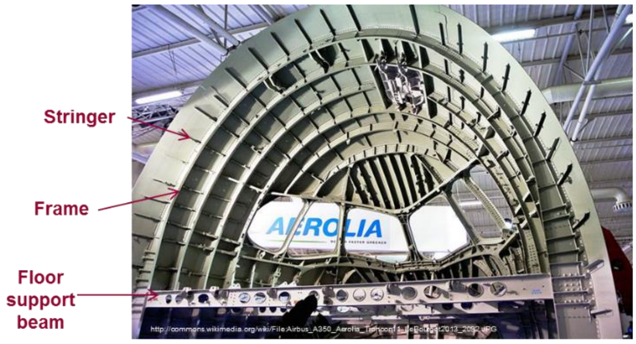
Suggested reading

- Chapter 8. Wing box structure
  M.C.Y. Niu. Airframe Structural Design. Hong Kong Conmilit Press LTD.2005
- Chapter 21 Wing spars and box beams
  H.G. Megson. Aircraft Structures for engineering students. Elsevier. 2007
- Chapter 23 Wings
  H.G. Megson. Aircraft Structures for engineering students. Elsevier. 2007

Fuselage

The fuselage function is to carry the payload and accommodate most of the aircraft system. It also connects the other major structural elements of the aircraft (wing and empennage). The main loads applied on the fuselage are: wing reactions, landing-gear reactions, and internal pressure. The fuselage structure can be classified in two types: non-stressed-skin structures (truss fuselage and geodetic fuselage) and stressed-skin structures (corrugated, monocoque and semi-monocoque fuselage).

Usually, in modern aircraft a semi-monocoque construction is used. A semi-monocoque fuselage is composed by longitudinal elements (longerons and stringers) and transverse elements (frames and bulkheads) cover by a skin (Fig.5).



http://commons.wikimedia.org/wiki/File:Airbus_A350_Aerolia_Troncon11_leBourget2013_2092.JPG

Fig.5. Element of a semimonocoque fuselage

The longerons support mainly the bending forces and are subjected to axial stresses, while the stringers also support part of the bending forces. The skin supports the shear stresses. The buckling of the skin is restricted by the presence of the stringers. Stringer and skin functions are similar to that in the wing. Longeron and stringer functions are similar to those of spar flanges in a wing.

The frame functions are to maintain the shape of the fuselage and to increase the buckling strength of the stringer. The distance between frames in most airplanes are around 500 mm. The frame function is equivalent to the function of the wing ribs; also the frame reduces the buckling critical length of the stringer and longerons. Bulkhead function is similar to the frame and also provides support to the concentrated load. A special type of bulkhead is the dome, which is used to close the pressurized area of the fuselage.

The following readings are recommended for further study of this section.

Suggested reading

- Chapter 11. Fuselage structure
  M.C.Y. Niu. Airframe Structural Design. Hong Kong Conmilit Press LTD.2005
- Chapter 22 Fuselages
  H.G. Megson. Aircraft Structures for engineering students. Elsevier. 2007
- Chapter 24 Fuselage frames and wing ribs
  H.G. Megson. Aircraft Structures for engineering students. Elsevier. 2007

Stabilizers

Stabilizer construction, especially the horizontal tail, is similar to wing construction. The aspect ratio of the stabilizer is smaller than the wing-aspect ratio, and thus the stabilizer is subjected to lower load levels than is the wing. In civil aircraft the horizontal tail is composed of spar, ribs, and skin. Fighter horizontal stabilizer construction is different, as usually two designs are used: Honeycomb + one spar or corrugated multi-spar.

The following readings are recommended for further study of this section.

Suggested reading

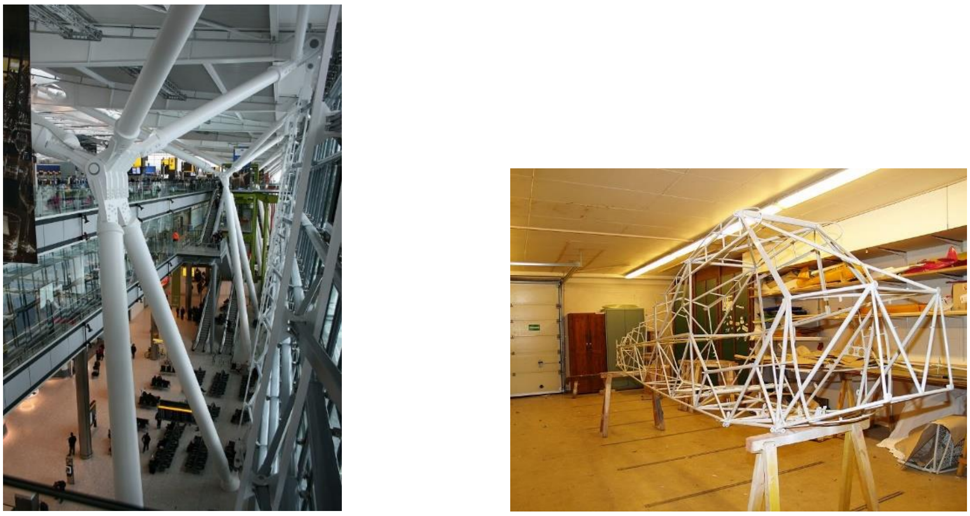
- Chapter 10. Empennage structure
  M.C.Y. Niu. Airframe Structural Design. Hong Kong Conmilit Press LTD.2005

The contents of this section is included in the document entitled “Structural components of aircraft”. The document is divided in three main part, related with the structural description of wings, fuselage and empennages.

4. Structures in the aeronautical sector

Basic knowledge of Strength of Materials are assumed in this section, especially in relation to the calculation of stresses in a cross-section and displacements in beams. In order to reinforced the basic knowledge in Strength of Materials, a study of the Open Course Ware "Elasticidad y Resistencia de Materiales I" (in Spanish) (see suggested readings) is recommended. The students must know all the concepts included in part II of this course: General study of the behavior of resistant elements

Two types of structures made of a combination of beams can been selected in the design of an aerospace structure: truss and frame structures, Fig. 6.



a)
https://upload.wikimedia.org/wikipedia/commons/7/75/London_Heathrow_T5_AB2.JPG

b)
Überflieger89
http://commons.wikimedia.org/wiki/File:Fuselage_Piper_PA18.JPG

Figure 6. Examples of truss and frame structures. a) Truss structure in London Heathrow Terminal 5. b) Example of frame structure: Fuselage

The joints between bars in a truss structure (hinged structure) allow relative rotation about an axis perpendicular to the plane of the structure. Thus, only axial forces appear in the bars if the external forces are applied in the joints. The joints can be made by hinges or by thin plates (welded or riveted to the bars), Fig. 7.

a)
https://upload.wikimedia.org/wikipedia/commons/7/74/T5_Trusses_4.jpg

b)
https://commons.wikimedia.org/wiki/File:THROUGH_TRUSS_VERTICAL-DIAGONAL_INTERSECTION_DETAIL_-_Richmond_Bridge,_US_90A_at_Brazos_River,_Richmond,_Fort_Bend_County,_TX_HAER_TEX,79-RICH,2-25.tif?uselang=es

Figure 7. Types of joints in a truss structure. a) Hinged joint, b) Thin plate.

The simplest stable truss structure is the triangle, made with three bars and three nodes. Stable structures can be design adding two bars and one node, Fig.8.

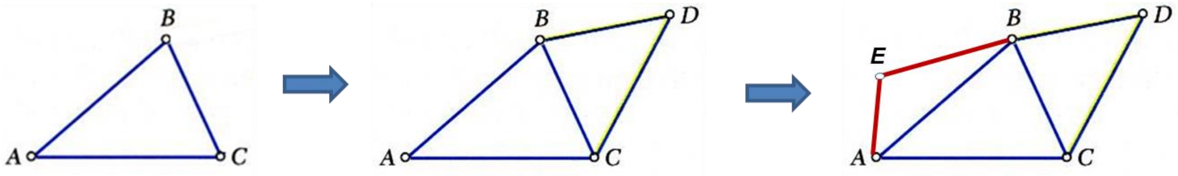
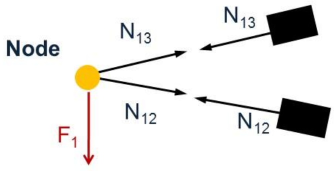


Figure 8. Method to build stables structures.

The axial forces in the bars can be calculated by equilibrium forces in each of the nodes of the structure and supports (in statically determinate structures). In space truss structures, three equilibrium are needed, and in a 2D case (plane structure) only two, Fig. 9.



$$\sum F_H = 0$$
$$\sum F_V = 0$$

Figure 9. Equilibrium in the nodes of a plane truss structure

Once the internal forces on the joint are known, the equations of equilibrium can be applied to the next node. Proceeding in this way in all nodes of the structure the forces of all bars can be calculated.

A frame is a structure with bars joined via fixed joints. The nodes have equilibrium under the influence of eventually all types of internal (mainly axial forces, shear forces and bending moments) and also external loads which may act on the joint. Thus, the bars are subjected to internal axial forces, internal shear forces and bending moments.

The methods to calculate the internal forces, and thus the stresses and displacements, of a frame structure are a generalization of the methods used in beams. In this section only non-traslational frames are analyzed. Neglecting the displacement due to axial forces in bars allows to assume that the nodes of some structures do not move, Fig.10.

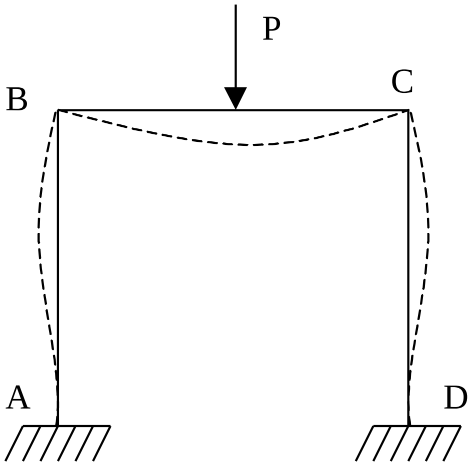


Figure 10. Example of non-traslational frame

A technique to solve non-translational structures consist on decomposing the structure in several bars. The bars, after the decomposition of the structure, must be constrained at their ends via simply supports. The independent bars must be subjected to same conditions they had in the original structure. Thus, the ends of the rods must be subjected to external bending moments which are the unknown of the problem. The compatibility condition is rotations of the end sections of bars that converge at a node must be identical.

The theoretical concepts of this section is included in the document called “Structures in the aeronautical sector”. This document is divided in two main part, one focused in truss structures and other focused in frames structures. To explore further the analysis of structures, both truss and frames, the study of the Open Course Ware “Structural Engineering” is suggested, specially chapter 3: Truss structures and chapter 7: frames.

To assimilate the concepts explained in this chapter the student have to solve different problems. In this course two exercises are proposed, focused in the estimation of axial forces in truss structures. Additional exercises can be found in the Open Course Ware “Structural Engineering”.

Finally, chapter 1 includes an auto-evaluation exercise. The students must use this exercise to check if they have a deep understanding of the main concepts of this chapter. This exercise includes different questions that cover the theory explained in chapter 1.

The following readings are recommended for further study of this section.

Suggested reading (previous knowledge)

- Section II. General study of the behavior of resistant elements
  C. Navarro. Elasticidad y Resistencia de Materiales I, Open Course Ware. Universidad Carlos III de Madrid 2008. (In spanish) http://ocw.uc3m.es/mecanica-de-medios-continuos-y-teoria-de-estructuras/elasticidad_resistencia_materialesi

- Section 9. Strength and Stiffness of Structural Elements
  J.J. Wijker. Spacecraft structures. Springer. 2008

- Part III Engineering Theory for Straight, Long Beams B.K. Donaldson. Analysis of Aircraft Structures. Cambridge University Press.2008

- Section 3. Rigid Bodies: Equivalent Systems of Forces
  F.P. Beer, E. Russel Johnston, Vector Mechanics for Engineers. Vol. Static, McGraw Hill, 1994.

- Section 4. Equilibrium of Rigid Bodies
  F.P. Beer, E. Russel Johnston, Vector Mechanics for Engineers. Vol. Static, McGraw Hill, 1994.

- Section 5. Distributed Forces: Centroids and Centers of Gravity
  F.P. Beer, E. Russel Johnston, Vector Mechanics for Engineers. Vol. Static, McGraw Hill, 1994.

- Section 6. Analysis of Structures
  F.P. Beer, E. Russel Johnston, Vector Mechanics for Engineers. Vol. Static, McGraw Hill, 1994.

- Section 7. Forces in Beams and Cables
  F.P. Beer, E. Russel Johnston, Vector Mechanics for Engineers. Vol. Static, McGraw Hill, 1994.

Suggested reading (Truss structures)

- Part 1. Analysis of Trusses and Analysis of Continuum Structures .
  N.G. Lakshmi. Aircraft structures. BS Publications. 2010

- Chapter 2. Truss Structures
  S Krenk, J Høgsberg. Statics and Mechanics of Structures. Springer. 2013

- Chapter 4. Truss Structures
  J.L. Pérez-Castellanos. C. Navarro Ingeniería Estructural, Open course Ware. Universidad Carlos III de Madrid. 2009 (in spanish). http://ocw.uc3m.es/mecanica-de-medios-continuos-y-teoria-de-estructuras/ingenieria-estructural

Suggested reading (frames)

- Chapter 3.Static of beams and frames
  S Krenk, J Høgsberg. Statics and Mechanics of Structures. Springer. 2013

- Chapter 4. Deformation of beams and frames
  S Krenk, J Høgsberg. Statics and Mechanics of Structures. Springer. 2013

- Chapter 6. The force method
  S Krenk, J Høgsberg. Statics and Mechanics of Structures. Springer. 2013

- Section 7. Deformation and Element Methods for Frames
  S Krenk, J Høgsberg. Statics and Mechanics of Structures. Springer. 2013

5. References

H.G. Megson. Aircraft Structures for engineering students. Elsevier

Section B1 Principles of stressed skin construction.

Chapter 12 Structural components of aircraft

Section 12 B2 Airworthiness and airframe loads

Chapter 13 Airworthiness

Chapter 14 Airframe loads

M.C.Y. Niu. Airframe Structural Design. Hong Kong Conmilit Press LTD

Section 3. Aircraft loads

Chapter 8 Wing Box Structure

Chapter 11Fuselage

https://upload.w

R.C. Hibbeler, Structural Analysis, Prentice-Hall, 2006.

Section 1. Types of Structures and Loads.

Section 2. Analysis of Statically Determinate Structures.

Section 3. Analysis of Statically Determinate Trusses.

S Krenk, J Høgsberg. Statics and Mechanics of Structures. Springer. 2013

Section 2. Truss and frames

Section 3. Static of beams and frames

Section 4. Deformation of beams and frames

Section 6. The force methods

Section 7. Deformation and Element Methods for Frames