Aircraft Structures Summary

1 Introduction

When designing an aircraft, it's all about finding the optimal proportion of the weight of the vehicle and payload. It needs to be strong and stiff enough to withstand the exceptional circumstances in which it has to operate. Durability is an important factor. Also, if a part fails, it doesn't necessarily result in failure of the whole aircraft.

The **main sections** of an aircraft, the fuselage, tail and wing, determine its external shape. The **load-bearing members** of these main sections, those subjected to major forces, are called the **airframe**. The airframe is what remains if all equipment and systems are stripped away.

Old aircrafts had skin made from impregnated linen that could hardly transmit any force at all. In most modern aircrafts, the skin plays an important role in carrying loads. Sheet metals can usually only support tension. But if the sheet is folded, it suddenly does have the ability to carry compressive loads. Stiffeners are used for that. A section of skin, combined with stiffeners, called **stringers**, is termed a thin-walled structure.

A very good way of using sheet metal skin is in a thin-walled cylinder, called a **monocoque** structure. A cylinder with holes, for doors and such, is called a **semi-monocoque** structure.

An **extruded** stiffener is manufactured by squeezing hot, viscous material through an opening of a certain shape. It can usually be recognized by the fact that the thickness is not consistent, especially in the corners. This is relatively expensive, compared to stiffeners made from sheet metal. From sheet metal it is not possible to make complicated stiffeners. Thin sheet metal can be rolled or drawn.

Usually stiffeners are attached to the skin. In an integral structure, the skin and stiffeners have been manufactured from one solid block of material. It is also possible to make some kind of a sandwich structure, in which the skin has a high stiffness due to its spacial structure.

2 The Fuselage

The **fuselage** should carry the payload, and is the main body to which all parts are connected. It must be able to resist bending moments (caused by weight and lift from the tail), torsional loads (caused by fin and rudder) and cabin pressurization. The structural strength and stiffness of the fuselage must be high enough to withstand these loads At the same time, the structural weight must be kept to a minimum.

In transport aircraft, the majority of the fuselage is cylindrical or near-cylindrical, with tapered nose and tail sections. The semi-monocoque construction, which is virtually standard in all modern aircraft, consists of a stressed skin with added stringers to prevent buckling, attached to hoop-shaped frames.

The fuselage also has members perpendicular to the skin, that support it and help keep its shape. These supports are called **frames** if they are open or ring-shaped, or **bulkheads** if they are closed.

Disturbances in the perfect cylindrical shell, such as doors and windows, are called **cutouts**. They are usually unsuitable to carry many of the loads that are present on the surrounding structure. The direct load paths are interrupted and as a result the structure around the cut-out must be reinforced to maintain the required strength.

A typical freighter aircraft will have a much larger door than a passenger aircraft. It is therefore necessary for them to transmit some of the loads from the frames and stringers. Where doors are smaller, the surrounding structure is reinforced to transmit the loads around the door.

In aircraft with pressurized fuselages, the fuselage volume both above and below the floor is pressurized, so no pressurization loads exist on the floor. If the fuselage is suddenly de-pressurized, the floor will be loaded because of the pressure difference. The load will persist until the pressure in the plane has equalized, usually via floor-level side wall vents.

Sometimes different parts of the fuselage have different radii. This is termed a **double-bubble fuselage**. Pressurization can lead to tension or compression of the floor-supports, depending on the design.

Frames give the fuselage its cross-sectional shape and prevent it from buckling, when it is subjected to bending loads. Stringers give a large increase in the stiffness of the skin under torsion and bending loads, with minimal increase in weight. Frames and stringers make up the basic skeleton of the fuselage. Pressure bulkheads close the pressure cabin at both ends of the fuselage, and thus carry the loads imposed by pressurization. They may take the form of flat discs or curved bowls.

Fatigue is a phenomenon caused by repetitive loads on a structure. It depends on the magnitude and frequency of these loads in combination with the applied materials and structural shape. Fatigue-critical areas are at the fuselage upper part and at the joints of the fuselage frames to the wing spars.

3 Wing Contents

Providing lift is the main function of the wings of an aircraft. The wings consist of two essential parts. The **internal wing structure**, consisting of spars, ribs and stringers, and the **external wing**, which is the skin.

Ribs give the shape to the wing section, support the skin (prevent buckling) and act to prevent the fuel surging around as the aircraft manoeuvres. They serve as attachment points for the control surfaces, flaps, undercarriage and engines. The ribs need to support the wing-panels, achieve the desired aerodynamic shape and keep it, provide points for conducting large forces, add strength, prevent buckling, and separate the individual fuel tanks within the wing.

There are many kinds of ribs. **Form ribs** consist of a sheet of metal, bent into shape. **Plate-type ribs** consist of sheet-metal, which has upturned edges and weight-saving holes cut out into it. These ribs are used in conditions of light to medium loading. **Truss ribs** consist of profiles that are joined together. These ribs may be suitable for a wide range of load-types. **Closed ribs** are constructed from profiles and sheet-metal, and are suitable for closing off sections of the wing. This rib is also suitable for a variety of loading conditions. **Forged ribs** are manufactured using heavy press-machinery, and are used for sections where very high loads apply. **Milled ribs** are solid structures, manufactured by milling away excess material from a solid block of metal, and are also used where very high loads apply.

The stringers on the skin panels run in the length of the wing, and so usually need to bridge the ribs. There are several methods for dealing with this problem. The stringers and ribs can both be uninterrupted. The stringers now run over the rib, leaving a gape between rib and skin. Rib and skin are indirectly connected, resulting in a bad shear load transfer between rib and skin. The stringers can be interrupted at the rib. Interrupting the stringer in this way certainly weakens the structure, and therefore extra strengthening material, called a **doubler**, is usually added. Naturally, the stringers can also interrupt the rib. The stringers now run through holes cut into the rib, which also causes inevitable weakening of the structure.

The ribs also need to be supported, which is done by the **spars**. These are simple beams that usually have a cross-section similar to an I-beam. The spars are the most heavily loaded parts of an aircraft. They carry much more force at its root, than at the tip. Since wings will bend upwards, spars usually carry shear forces and bending moments.

Aerodynamic forces not only bend the wing, they also twist it. To prevent this, the introduction of a second spar seems logical. Torsion now induces bending of the two spars, which is termed **differential bending**. Modern commercial aircrafts often use two-spar wings where the spars are joined by a strengthened section of skin, forming the so-called **torsion-box** structure. The skin in the torsion-box structure serves both as a spar-cap (to resist bending), as part of the torsion box (to resist torsion) and to transmit aerodynamic forces.

4 Wing Functions and Attachments

It is usually hard to attach the wing to the fuselage. There is usually a third piece of wing contained within the fuselage. The connection of wings and fuselage are always by way of very strong and heavy bolts. The bolts that are used must be much stronger than necessary, thereby having sufficient lifetime.

Stringers are attached to the wing skin, and run span-wise. Their job is to stiffen the skin so that it does not buckle when subjected to compression loads caused by wing bending and twisting, and by loads from the aerodynamic effects of lift and control-surface movement.

In most aircraft, the wing skin performs several tasks. It gives it the aerodynamic shape, it carries a share of the loads, it helps to carry torsional loads, it acts as fuel tanks and allows inspection and maintenance. Using the skin to carry part of the loads is called **stressed skin**. Almost all aircraft have their wing structure made entirely in metal, or a mixture of metal and composite. The skin may be fixed to the internal structure by rivets or bonding. The volume between the spars is often used for storing fuel.

An alternative to attaching stringers to the skin for stiffness, is a **machined skin**, in which the skin, stringers and spar flanges can be machined from a single piece of alloy, called a **billet**. Advantages are that less rivetting is required, resulting in a smoother surface, lighter and stronger structures are possible, construction faults are less likely, less maintenance is required and easy inspection is possible. However, the costs are relatively high, and replacing parts is difficult.

In commercial aircrafts usually around 25% of the aircraft's maximum operating weight is for fuel storage. Usually most or all of the fuel is stored in the wing, which is divided into several tanks, each one usually having its own pumps. This allows fuel to be moved between tanks in flight, which changes the trim of the aircraft to minimize drag.

Flaps are fitted at the trailing edges. Light aircraft usually have simple flaps, or none at all. Larger aircraft have the more complex split flap or Fowler flap. Most large transport aircraft have double-slotted Fowler flaps. Leading-edge flaps, called **slats**, may be added to increase lift even further. Flaps and slats increase both lift and drag, both being advantageous for landings. **Spoilers** are fitted to the top surface of the wing. When operated, which is usually at touchdown, spoilers increase drag and reduce lift.

5 The Tail

In most aircraft, the sole function of the tail unit is to provide the required stability and control. **Stability** is the tendency of the aircraft to return to its original attitude by itself.

Since an aircraft flies in three-dimensional space, stability and control are required in three direction. These axes are **lateral** (left and right), **vertical** (up and down) and **longitudinal** (fore and aft). For aircraft turns, three manoeuvre cases are used. For **pitch**, which is rotation about the lateral axis, the horizontal tail with elevators is used. For **yaw**, which is rotation about the vertical axis, the vertical fin with rudder is used. For **roll**, which is rotation about the longitudinal axis, the ailerons are used.

The fin provides stability in yaw. When the aircraft is required to yaw, the rudder is deflected. The tailplane provides stability in pitch. When the aircraft is required to climb or descend, the elevators are deflected.

If the position of the centre of gravity varies, or if the aircraft speed is changed, the elevator position necessary to maintain level flight will change. Therefore a small extra control surface is added to each main surface to allow the pilot to **trim** the aircraft.

6 Undercarriage

The undercarriage of an aircraft support the aircraft on the ground, provide smooth taxiing and absorb shocks of taxiing and landings. It serves no function during flight, so it must be as small and light as possible, and preferably easily retractable.

Due to the weight of the fore and aft part of the aircraft, large bending moments occur on the centre section. To carry these bending moments, a strong **keel beam** is present. This reduces the space in which the landing gear can be retracted.

When an aircraft lands, a large force is generated on the undercarriage as it meets the ground. To prevent damage to the structure, this shock must be absorbed and dissipated as heat by the undercarriage. If the energy is not dissipated, the spring system might just make the aircraft bounce up again.

After touchdown, the aircraft needs to brake. **Disc brakes**, which are primarily used, consist of a disc or a series of discs, gripped between pads of friction material. The braking of an aircraft can be supplemented by other forms of braking, such as **air brakes**, causing a large increase in drag, or **reverse thrust**, thrusting air forward.

7 Engines

Aircraft power plants fall into five main types. **Ramjet engines**, for very high speed aircrafts. **Turbo-jet engines**, for high speed aircrafts. **Turbo-fan engines**, for Mach 0.3 to Mach 2. **Turbo-prop engines**, for relatively low speeds. And **piston engines**, for simple low speed aircrafts. Each variant is most suited to a particular aircraft flight speed. The **operating efficiency**, loosely defined as power absorbed divided by the rate of fuel burn, is maximized when the velocity of the air expelled from the jet, fan or propeller is close to the speed of the aircraft.

In turbo-fan engines, some of the exhaust gases are made up of air that has by-passed the engine core or gas generator, and only passed through a fan. They are therefore called **by-pass engines**. The higher the by-pass ratio, the larger the engine's diameter.

Engines can be positioned in many ways. Most transport aircraft have externally mounted engines, leaving the fuselage interior volume clear for payload. Engines can then be rear-mounted, wing-mounted, or a combination of them. Both have advantages and disadvantages. Twin- and four-engined turbo-prop aircrafts will almost inevitable require the engines to be wing-mounted. In combat aircrafts the fuselage is not required to carry an internal payload, so it's an ideal location for the engines.

Twin- or multi-engined propeller-driven aircrafts must have their engines spaced out along the wing to provide clearance between the propeller tips and the fuselage. The closer the engines are to the fuselage, the more noise is generated inside the fuselage, and the further away they are, the more the aircraft yaws if an engine fails.

Wherever the engines are located, they must be supplied with fuel. In twin- or multi-engine installations it is a requirement that the fuel supply can be maintained if any component fails. In case an aircraft should land due to some kind of emergency early on the flight, the aircraft overall weight may be too high for a safe landing. Therefore, the pilot has the possibility to dump fuel.

Propellers fitted to many aircrafts often have the capability of varying their pitch. If the pitch is controlled automatically, an engine can be operated at constant speed. If an engine fails, the propeller will windmill. This causes extra drag, and may further damage the engine, so the propeller is feathered: the blade pitch is changed until the blades sit approximately in line with the air stream.

8 Aircraft Requirements and Safety

The design process of an aircraft starts with specification of the requirements. An aircraft design is always a compromise. The first and most important requirement of an aircraft part is that it fulfils its function in all circumstances, particularly in critical situations.

The **strength** of a structure is a measure of the risks taken - the acceptance that the structure will fail in extreme conditions. Society sets standards for such risks. We accept that all structures fail in certain conditions. When calculating the loads, we name the force which will just make the structure fail, the **ultimate load**.

Structural failures often occur due to a very large series of normal repetitive loads that cause fracturing of the material: **metal-fatigue**. It is very important to know the rate of **crack-growth** and the **residual strength** (the strength in the presence of cracks) of a structure.

A number of European countries have formulated a set of **Joint Airworthiness Requirements**, the **J.A.R**, which are based on the American **Federal Airworthiness Requirements**, or **F.A.R**. The airworthiness standards define **primary structures**, those that would endanger the aircraft upon failure, **secondary structures**, those that do not cause immediate danger upon failure, and **non load-bearing structures**, which do not carry loads.

There are multiple ways of considering part safety. The **fail-safe** principle accepts that there is a chance that part of the structure fails. However, there should be no chance of the whole structure failing. In the **safe-life** philosophy, the chance of the structure failing within its prescribed lifetime should be zero. If this were to happen, then the chance of the whole structure failing is substantial.

The **stiffness** of a structure is a measure of its resistance to a change in shape when subjected to forces. The stiffness of a complete structure is always a combination f its material properties and its geometry.

Aircraft wings and tail-sections can be subjected to three types of forces, namely aerodynamic forces, elastic forces and mass forces. These forces can work together in such an unfortunate way that they induce a type of vibration known as **flutter**. Flutter only occurs above a certain speed, which we call the **critical speed**. Flutter is caused by two coordinated types of vibration that amplify each other's effect.

Air-transport safety is the responsibility of the manufacturer, the user and the government. As part of this responsibility, the government exercises control over the airfield through the State Air-Transport Service (In the Netherlands this is the Luchtvaart Autoriteit). The Luchtvaart Autoriteit is responsible for monitoring design, manufacturing, use and maintenance of aircraft, education, training and testing of personnel, and operational guidelines, accident investigation, traffic management and traffic regulations.

9 Weight

An optimal structure is as light as possible while having a given strength and stiffness. Therefore the relationship between the total weight and the payload, called the **growth factor**, should be as low as possible. However, this growth factor seems to become more substantial, if the transport system is more advanced.

To reduce weight, materials with a high strength to weight ratio can be used. The relationship of tensile strength and specific weight, $L_t = \sigma_t / w$, is known as the **specific tensile strength** or **break-length**, referring to the length L_t at which a bar of constant cross-section will fail due to its own weight.

It is also possible to choose materials suited for thin-walled structures. Thin-walled structures depend on the stiffness of the material used, together with its specific weight. The E-modulus E is the determining factor, although for composites, the shear modulus G also plays a role. The **specific modulus of elasticity** E/w is measure of a structure's stiffness in relation to its weight.

In compression certain special forms of deformation can occur, namely buckling. The buckling of a sheet of metal takes place at a **critical stress** σ_{cr}, which can be written as $\sigma_t = c \cdot \frac{Et^2}{a \cdot b}$, where c is a constant, t is the thickness, a is the length and b is the width. For two sheets of different material (and therefore different E-modulus but equal surface area) to buckle at the same load, the thicknesses must be related by $t_1/t_2 = \sqrt[3]{E_2}/\sqrt[3]{E_1}$. Taking into account the weight, then the higher the value of the **specific weight stiffness** $\sqrt[3]{E}/w$, the better the material.

The designer is forced to approach the problem schematically, either computational or experimental. Analyzing the problem is not possible without simplifications. However, such simplifications also make the model less valid in real life. They therefore contain inaccuracies. This is why the design of such a structure has a built-in **safety factor**. The better the predictive tools, the lower the safety factor necessary, and the lower the final weight of the structure.

10 Aircraft Lifetime and Corrosion

The **lifetime** of an aircraft can be expressed in terms of flight-hours and in terms of flights an aircraft makes. Which is most convenient, depends on the part. For parts like the landing gear and the fuselage (due to fatigue caused by repeated pressurization) it is most convenient to express their lifetime in amount of flights. For parts like the engine, it is most convenient to express the lifetime in the flight-hours.

Corrosion is an unwanted attack on the material, resulting from chemical or electro-chemical reactions with the surrounding environment. Corrosion resistance is an important factor to consider during material selection. There are many forms of corrosion. Besides **general corrosion** there are **galvanic** or **contact corrosion**, which occurs due to a difference in electric potential between touching parts, **intercrystalline corrosion**, where the more active edges of the crystals are attacked while the rest of the crystals remain intact, **stress corrosion**, where mechanical stress increases the chemical activity of the material, and **fretting corrosion**, where wear between surfaces results in corrosion products (hard oxides) increasing the local corrosive effect.

Methods to prevent corrosion include **painting**, which can be relatively heavy, **anodising**, where the aircraft is covered with a stable protective oxide layer, **cladding**, where a layer of pure aluminum is attached during rolling (attaching a less noble material to a more noble material), **cadmium plating**, where a more noble material covers a less noble material, choosing an alternative material, or regular cleaning.

11 Economics and Costs

The **Direct Operating Costs** (**D.O.C.**) of an aircraft can be roughly split up into four equally sized parts, being the cost of ownership, fuel costs, maintenance costs, and various other costs (like salaries of crews, landing permits, insurance, etcetera). **Maintenance costs** are determined by the **real maintenance costs** and lost income due to grounding the aircraft. Therefore downtime has to be kept to a minimum, but not too much at the cost of the real maintenance costs.

Simple shapes, easily worked materials, and standardization all bring down costs. These days, most parts are bought in since that is both cheaper and qualitatively advantageous due to specialization. Costs and accuracy of parts are also coupled. If some part must be made precise, costs and time necessary are high. The manufacturer should therefore not use other tolerances than necessary.

Roughly 35% of the purchase price of the aircraft is incurred through assembly costs. Savings made during assembly can be very important. These are achieved in ways such as **automation**, or by using **integrated structures**. Also experience and learning plays an important role. **Routine forming** leads to smaller groups of workers and shorter delivery times. The first aircraft in a series will be made without routine and will therefore be the most expensive one. Since it cannot be sold at a higher price than later aircrafts, profits can only be made after the **break-even point** (**b.e.p.**), which is the point at which no profits nor losses are present.

12 Loads and Pressures

It's the task of the designer to consider all possible loads. The combination of material and design of the structure must be such that it can carry the loads without failing. Tools that can be used to estimate loads are measurements taken during flight, measurements of a scale-model in a wind tunnel, aerodynamic calculations and test-flights with a prototype. Aircraft structures must be able to withstand all flight conditions and be able to operate under all payload conditions.

A force applied lengthwise to a piece of structure will cause **normal stress**, being either tension or compression stress. With tensile loads, all that matters is the area which is under stress. With compressive loads, also the shape is important, since buckling may occur. If a force is applied at right angles, it will apply **shear stress**, and a bending moment which will cause normal stress. If a force is offset from the line of a beam, it will also cause torsion, which causes shear stresses. **Shear** is a form of loading which tries to tear the material, causing the atoms or molecules to slide over one another.

Stress is defined as load per area, being $\sigma_l = F/A$, where the l indicates the longitudinal direction. The stresses within a structure must be kept below a defined permitted level. Where stress is, is strain. **Strain** is the proportional deflection within a material as a result of an applied stress. It is impossible to be subjected to stress without experiencing strain. For elastic deformation, which is present below the limit load, Hooke's law applies: $\varepsilon_l = \sigma_l/E$.

A narrow sheet will undergo lateral contraction when subjected to a tensile force F. A **lateral contraction** is a negative strain perpendicular to the direction of F, according to $\varepsilon_d = -\mu\varepsilon_1 = -\mu\sigma_l/E$, where d indicates the lateral direction. μ is the coefficient of lateral contraction, also known as the **Poisson's ratio**. Hooke's law becomes more complicated in the case of stresses occurring simultaneously in two perpendicular directions, in which the following applies: $\varepsilon_l = \sigma_l/E - \mu\sigma_d/E$ and $\varepsilon_d = -\mu\sigma_l/E + \sigma_d/E$.

Now look at a wide sheet pulled in the direction of its shorter axis by a force F. Clamping of the sheet prevents lateral contraction, which means $\varepsilon_d = 0$ and therefore $\sigma_d = \mu\sigma_l$. Due to this additional lateral stress, the longitudinal force is smaller, being: $\varepsilon_l = (1-\mu^2)\sigma_l/E$.

Another example of bi-axial stress is found in the skin of a cylindrical pressurized cabin. The hoop-stress (around the fuselage) is σ_1 while the axial-stress (in the direction of the length) is σ_2. If R is the cylinder radius, t the wall thickness and p the pressure, it can be shown that $\sigma_1 = pR/t$ and $\sigma_2 = pR/2t$. The hoop-stress is therefore twice as large as the axial stress.

The pressurized cabin has important characteristics. Failure is catastrophic, the limit load occurs during every flight and the fuselage is not only subject to pressurization forces. The static strength of the fuselage therefore incorporates a larger safety factor: $j = 2$. So the structure should be able to sustain twice the pressure usually present.

Another example of bi-axial stress if the condition within a spherical pressure-vessel, where the stress is $\sigma = pR/2t$ in all directions. The sphere is therefore the lightest structure possible for a pressurized vessel. The rear bulkhead of the cabin is usually spherical.

13 Fuselage Loads

The fuselage will experience a wide range of loads from a number of sources. The weight of the fuselage structure and payload will cause the fuselage to bend downwards from its support at the wing, putting the top in tension and the bottom in compression. In manoeuvring flight, the loads on the fuselage will usually be greater than for steady flight. During negative g-manoeuvres, some of the loads are reversed. Also landing loads may be significant. The structure must be designed to withstand all loads cases. The bending loads are higher when the weight is distributed towards the nose and tail. Therefore, aircraft are loaded close to the centre of gravity.

The larger part of passenger and freighter aircraft is usually pressurized. The cabin altitude is usually changed quite slowly, beginning pressurizing long before 2500m, which is the normal cabin pressure altitude during cruise, is reached. Combat aircrafts have no need for pressurization of large areas of the fuselage. Particular problems occur in areas where the fuselage is required to be non-cylindrical. Internal pressure will generate large bending loads in fuselage frames. The structure in these areas must be reinforced to withstand these loads.

Because fuselages are pressurized for safety, the designer must consider what will happen if the pressurization is lost. The damage due to depressurization depends on the rate of pressure loss. For very high rates, far higher loads would occur than during normal operation.

Doors and hatches are a major challenge when designing an aircraft. Windows, being small, do not create a severe problem. Depending on their design, doors will or will not carry some of the load of the fuselage structure. On the floor of the fuselage also very high localized loads can occur, especially from small-heeled shoes. Therefore floors need a strong upper surface to withstand high local stresses.

14 Wing Loads and Other Loads

A wing produces lift as a result of unequal pressures on its top and bottom surfaces. This creates a shear force and a bending moment, both of which are at their highest values at the point where the wing meets the fuselage. The structure at this point needs to be very strong, to resist the loads and moments, but also quite stiff, to reduce wing bending. The wing will be quite thick at this point, to give the maximum stiffness with minimum weight.

An advantage of wing-mounted engines is that their weight is close to the area in which the lift is produced. This reduces the total fuselage weight, reducing the shear force and bending moment at the wing root.A correct position of the fuel-load also results in a smaller moment at the wing root. Fuel load close to the tips reduces this moment. Therefore the order in which the tanks are emptied is from the root to the tip. The tailplane, rudder and ailerons also create lift, causing a torsion in the fuselage. Since the fuselage is cylindrical, it can withstand torsion very effectively.

Also the landing gear can generate side loads causing torsion of the fuselage. But the main force caused by the landing gear is an upward shock during landing. For this, shock absorbers are present, absorbing the landing energy and thus reducing the force done on the structure. The extra work generated during a hard landing results in a very large increase in the force on the structure. This is why the absorbers are designed with a safety margin by taking into account a vertical speed 1.25 times higher than the maximum vertical speed during landing.

15 Load Factor, Load Requirements and Gust Loads

The loading conditions are characterized by the airspeed and load-factor n. This **load factor** is defined as $n = L/W$, where L is the lift force and W the force caused by weight. For straight steady flight $n = 1$, for flying upside down $n = -1$ and for manoeuvring $n \neq 1$ for the aircraft as a whole. In a turn with bank angle φ, the load factor is $n = 1/\cos\varphi$.

The aircraft's requirements are based on loads that are very unlikely to occur during its lifetime. The chance that they will occur during the lifetime should be very small. The **nominal** or **limit load** B_n is the load which should only occur once (or only a very few times) during the lifetime of the aircraft. Also, the users require that the aircraft should not be damaged to the point of permanent deformation after such an incident.

Obviously, an aircraft must not fail at B_n. We therefore make use of a safety factor. This factor is derived from two major influences, being $j_1 = 1.2$ to account for the variation in the material quality and dimensions, inaccuracies in the calculations and internal stresses, and $j_2 = 1.25$ to account for exceptionally large forces which may occur but are less likely than B_n. These two factors combine to form the overall safety factor $j = j_1 \cdot j_2 = 1.5$ which is used to define the **ultimate load** $B_u \geq j \cdot B_n$. The chance that the ultimate load will occur is not zero, however, and if it were to occur then the aircraft would most probably fail.

Air gusts can come from any direction and have any magnitude. The gust loading is dependent on flight condition, load condition, altitude, aerodynamic characteristics of the wing and the gust speed itself. The certification regulations stipulate a set of extreme gust-speeds that must be withstood at a number of characteristic airspeeds.

16 Metal Fatigue and Stress Concentrations

Metal fatigue occurs through the application of a very large number of relatively small cyclic forces. Safety can not be proven by calculation alone in the case of fatigue. Tests will often show a large deviation in results and van never fully simulate the real-life conditions of the aircraft's service life. For these reasons, and aircraft may be tested for three times its life-expectance. In order to be able to withstand such testing, many aircraft components may be made stronger than is strictly necessary to meet the static strength requirements. Such parts are termed **fatigue-critical**.

The highest stresses are found around the edges of a hole. The relation between the maximum stress σ_{max} and the average stress σ_{avg} is the **stress concentration** K_t such that $K_t = \sigma_{max}/\sigma_{avg}$. K_t is always 3 for round holes. The effects of stress concentrations are largest at the hole edges, and usually wear off at a distance of three times the hole diameter. What is also interesting is that an increase in cross-sectional area will also create stress concentrations. Rounding the corners at the change in thickness can reduce the concentration factor.

At very high stress concentrations, material might start to plastically deform. This reduces the stress concentration factor K_f, which is the stress concentration factor in the case of plastic deformation (So $K_f < K_t$). The amount in which this happens depends on the material. Materials with a high **notch sensitivity** are generally brittle materials, while ductile materials are less sensitive to notches.

If σ_{avg} is a cyclic stress with a small amplitude, then the corresponding σ_{max} will be K_t times as large. The Wöhler-curve shows that the number of cycles of a tensile force on a material before failure occurs is dependent on the amplitude of the cyclic force. Therefore fatigue often occurs at the same places as stress concentrations. Fatigue does not occur below a certain stress amplitude, called the **fatigue limit**.

The **residual strength** is the strength of a part after cracks have occurred. This depends on the **critical stress** σ_{cr}. For a crack with length $2a$, the critical stress is $\sigma_{cr} = K_{I_c}/\sqrt{\pi a}$ where K_{I_c} is a material constant called the **stress intensity factor**.