Structural Airworthiness

Page 0 Title Page

My name is Danny Heaton and over the next few weeks I have to guide you through the derivation of loads on the aircraft, where they come from (Regulations) and how the Airworthiness Certification process works from the structures point of view.

But where do I start -- What comes first – the chicken or the egg

You will find that aircraft design (like many things in life) is a series of iterations and compromises, it is also complex and complicated.

I like to call the whole process STRUCTURAL AIRWORTHINESS

A good place to start is to have a drawing of the aircraft together with some information about weights and aerodynamics, From the aircraft weight we have some idea which set of regulations we should be using.

Page 1 Aircraft GA

This shows a twin engined light aircraft that is going to be used in the worked example. It is loosely based on an aircraft designed by Britten-Norman called the Sheriff. I have called it KIS (keep it simple) which is what I will be trying to do over the next few weeks.

The prime task of the stress office together with the structures design office is to demonstrate that the airframe structural integrity is maintained under the applied loading as defined in the certification regulations.

But before the stress office can begin their work, they need to know what the loading is on the structure. Experience helps in that one can make a reasonable guess at what the structure looks like and what the loads are likely to be.

Page 2 Introduction

So what are Loads or Loading Actions.

The Structural Design Loads are the Resulting Forces acting on the Aircraft during Take-off, Flight and Landing. They are a function of Aerodynamic, Mass and System effects.
An alternative definition is that Aerodynamics define the outside shape and Stress/Structures define the inside shape and then Loads links these two disciplines.,

I have said AIRCRAFT, but the principles also apply to Helicopters (Rotorcraft) and Space Vehicles (covering both the launch rockets and the space craft)

So the problem of specifying the design loading on a newly designed aircraft structure may appear, at first, to be a very daunting task.

However, as a result of many years of monitoring the accelerations imposed on an airframe, due to manoeuvres and atmospheric gust encounters, it is possible to predict the loading applied to the new structure with considerable accuracy.

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This includes the manoeuvre and gust load envelopes, failure conditions (local or global), and crash conditions. Within the regulations there are defined factors for loading, limit and ultimate and defined factors for analysis, fitting factors and casting factors. There are also statements as to the limitations of analytical techniques and when these must be backed up by testing. The aircraft manufacturer must make a profit to stay in business, hence a secondary task of the stress office is to achieve the structural integrity required for minimum cost and weight. This sometimes leads to conflict.

Fatigue, Damage Tolerance and Failsafe issues are also covered by the regulations, but are not really part of this series of lectures.

Page 3 Design Cases for the Structure

Design Cases cover both overall aircraft and components – so anything I say applies to both.

CS and FAR can be downloaded from the web

See the following web sites for more information

EASA https://www.easa.europa.eu/document-library/certification-specifications

FAR http://www.ecfr.gov/cgi-bin/text-idx?SID=e8dfe8f3a0baf95ea114fdafbaaf018b&mc=true&tpl=/ecfrbrowse/Title14/14cfrv1_02.tpl#0

Page 4 & 5 Certification Specifications (CS)

To cover the different types or categories of aircraft, rotorcraft, sailplanes, engines, equipment and the operational aspects, the civil airworthiness authorities publish a chapter or document for each.
The FAA and EASA lists use a similar numbering system in most instances. These regulations cover airworthiness, operations and licensing

The requirements for Large Aircraft (W>5700kg (12,500lb)) are given in CS-25 or FAR-25, and these are the ones I am most familiar with. Depending on the aircraft size, the following could be relevant

CS-23 for Light Aircraft (W<5700kg (12,500lb))

CS-VLA for Very Light Aircraft

CS-22 for Sailplanes

For Rotorcraft the following are relevant

CS-27 for Small Rotorcraft (W<3175kg 7000lb))

CS-29 for Large Rotorcraft

CS-VLR for Very Light Rotorcraft

There must be similar regulations for Space Vehicles.

I have also been involved with Design Projects for Unmanned Air Vehicles (UAV's) and Human Powered Aircraft (HPA's) and they go through a similar process,

Page 6 CS-25 Contents

CS-25 is divided into sections with Subpart C covering Structure however; note for example that Fuel Tank strength is covered in Subpart E (Powerplant).

Book 1 gives the regulation and Book 2 gives an Acceptable Means of Compliance.

Having introduced the topics of Airworthiness and Loads, we will now look at them in more detail.

This list of contents is typical of the fixed wing and rotorcraft CS's.

CS-25 is now asking for rational analysis of loading conditions (e.g. time histories). At the beginning of a project there is not enough information available to do this kind of analysis or calculation. The advice is to look at earlier issues or amendments of CS-25 and/or look at CS-23 Amdt 4 (or even CS-VLA).

Page 7 Airworthiness (1)

Virtually all manned aircraft, including private, public and military, have to satisfy a specific set of airworthiness regulations during design, manufacture, and testing (rig, ground and flight) before they can be awarded a Type Certificate of Airworthiness. The Type Certificate covers the overall aspects, while each individual aircraft has its own Certificate of Airworthiness. They will also have to satisfy the Specification for the aircraft agreed/contracted with the customer (airline or government), as this can give rise to other requirements. This also applies to Unmanned Air Vehicles (UAV's).

In UK, airworthiness requirements are regulated by two authorities:

1. Civil Aviation Authority (CAA) for private and public transport aircraft;
2. Ministry of Defence via QinetiQ for military aircraft.

Originally the CAA issued its own regulations called British Civil Airworthiness Requirements (BCAR). However, in 1970 there was a need to move away from national to international requirements following collaboration projects like Concorde and Airbus, so several European Countries got together and formed the Joint Airworthiness Authority (JAA) and issued Joint Aviation Regulations (JAR). This has now (Oct 2003) been replaced by the European Aviation Safety Agency (EASA) which issue Certification Specifications (CS).

In the United States of America, the Federal Aviation Administration (FAA) issues Federal Aviation Regulations (FAR)

Other countries each had their own airworthiness regulations but now there are virtually only 2 sets of regulations that need to be considered and are almost the same. It should be noted that FAR's and CS's are legal documents and are very similar in wording, application and interpretation.

The words 'similar in wording' needs a little further explanation. At a meeting several years ago discussing manoeuvre loads, the 8 manufacturers present, each had different methods/interpretations and agreements with the Airworthiness Authorities. This situation still exists and is probably world wide.

These regulations have evolved over a period of time and are still evolving. Any changes are made such that the new/revised rule gives an equivalent level of safety to the previous definitions

The Ministry of Defence in the UK issues Def Stan 00-970 which gives the general requirements. The detailed requirements and specification are contained in another document which is usually classified as secret.

The United States of America issues Mil Specs for general requirements.

In addition to these regulations, many manufacturers apply their own design cases to cover previous experience, potential weight growth etc.

Until the aircraft satisfies the necessary regulations, it will not be issued with the C of A. It must not be flown publicly without this certificate (or if a military aircraft, released for general service use). During flight testing each flight is cleared separately or by the use of a Special or Restricted Category C of A.

Page 8 Airworthiness (2)

The regulations cover all aspects of the aircraft design and operation e.g. aerodynamics, performance, stability and control, electrical, hydraulic, fuel and other systems and in particular, regulations for structural strength, stiffness and fatigue life. The size of gust and the maximum inertia (or "g") loading that the aircraft has to withstand are defined in the regulations. As well as analysis there will be testing (structures and system rigs) to demonstrate conformity with the regulations. There will be flight testing to demonstrate handling characteristics and performance. The airline will have been provided with guaranteed miles per gallon figures so the manufacturer needs to know they have achieved the required performance when they build one.

During construction of the aircraft, close control is maintained by inspection (quality control) to ensure that all parts and assemblies are manufactured according to the drawings (which in today's world may be electronic). The drawings and all design calculations must be open to inspection by the AA. This exercise of showing that the regulations have been met is known as 'conformance'. What usually happens is that the manufacturer makes a statement against each paragraph of the regulations. The statement might be a document reference covering several paragraphs or topics. For structures a summary of the reserve factors will be included.

The certificate for each individual aircraft is usually renewable every 3 years, subject to regular aircraft inspections and maintenance. The C of A is only valid if strict adherence is observed for all manoeuvre and other operational limitations listed in the certificate and also detailed in the Flight Manual.

<u>Page 9, 10 & 11</u> Certification of a Large Aircraft

These VG's shows the generic process of conception, design, manufacture, certification and then production.

The Concept Phase can exist for many years, for example ideas for the A380 started in the mid 1980's and received its Type Certificate in December 2006. Eventually the market seems right and you have made a business case to the board of directors, so the product is launched (also known as Instruction to Proceed (ITP)). The A400M also started in the early 1980's and has just entered service (Sept 2013). It has had various project names over the years.

It is at this time that you apply for the Type Certificate and set the revision standard.

Typically it takes about 5 years from ITP to EIS (Entry Into Service).
At ITP the aircraft configuration will be defined and initial talks with suppliers (of metal billets and Landing Gears for example) will have taken place.
Then follows 24 months of detail design before the first metal is cut (or machined). Allow 6 months for further preparation of detail parts. 9 months for jig assembly of a major component (like the wing), transport to final assembly which will take about 9 months including any ground testing required (like checking the structural natural frequencies).
First flight followed by about 12 months of flight testing before CofA and EIS.

<u>Page 12</u> Types of Loading

Static Loading	The ONE big load that the Structure is Designed to withstand (equivalent to Limit Load)
Fatigue Loading	The repeated or cyclic loading that the structure should withstand for a given number of hours and/or flights.
Operating Loads	Anything that moves (like slats and flaps)
Rigid/Flexible Conditions	Most, if not all structures are flexible in that they distort/deform under load. However some structures are more flexible than others.

Flexibility affects loading in two ways (3 if we ignore it completely and take everything as rigid)

> Slowly applied loads like bending of the wing in manoeuvre cases which in turn affects the aerodynamic loading. To go from 1g to 2.5g can take 2 to 3 seconds.
>
> Rapidly applied loads like gusts or landing which give rise to dynamic effects (usually a function of the natural frequency of the aircraft or component). The time from 1g to maximum or peak load is 0.1 to 0.5 seconds depending on aircraft size.

Page 13 Wing Bending Frequencies

These rapidly applied loads depend on the natural frequencies of the aircraft. Using wing bending frequency as an example, this VG indicates what happens with aircraft size. These values do not necessarily correspond to the aircraft indicated but are shown for illustrative purposes only.

These values are typical and vary with aircraft weight and fuel load in the wing.
I have not tried it, but it would be interesting to plot frequency against span, wing area and aircraft weight.

Page 14 Wing Stiffness Data

The frequencies given come from an evaluation of the mass/stiffness effects on the wing.

This VG shows the spanwise variation of EI/GJ for a typical 150 seat aircraft.

Nearly every aircraft I have worked on in the design office has had an aeroelastic/flutter problem predicted - the bump in the GJ curve just inboard of the pylon was the result of adding material to stiffen the wing to improve flutter. Another way is to add mass at or near the wing tip.
In our quest for lower aircraft weights, airframes will become more flexible and we may have to use Active Flutter Control (and/or Active Control Technology) – this will be done by sensing some suitable parameter and then using the control surfaces to provide aerodynamic damping.

EI/GJ from the wing box FEM needs to be adjusted (increased) to allow for the Leading and Trailing edge structure. EI by 5 to 10% and GJ by 10 to 15%.

Page 15 Fuselage Stiffness Data

This VG shows the vertical Bending Stiffness EI for the fuselage of a typical 150 seat aircraft. There is also vertical Shear Stiffness data. Also, there is the corresponding lateral EI. The step between frames 51 and 57 is due to the lower hold door cut out.

Page 16 Factors of Safety

In practice, some margin must be allowed over and above the minimum airframe strength to cater for approximations and assumptions in design calculations, manufacturing tolerances, occasional overload due to some unforeseen circumstances, deterioration, wear and tear of the structure during its service life.

Modern design and calculation techniques are sophisticated and accurate. In any case, structural strength tests will usually be carried out to confirm the theoretical predications. There are moves a foot to do Virtual Testing using non-linear FEA (RAeS Conference in October 2006). Several years ago it was proposed to put seats in the holds below the normal floor level to increase passenger capacity. Some aircraft allow this during flight but NOT in the take-off and landing phases. In the assessment Airbus used non-linear FEA but it was calibrated against known results from drop testing. By the way, one case took about 24 hours CPU time to run.

Furthermore, provided the aircraft is always flown within the limitations laid down in the flight manual, overload situations are most unlikely: the main possibility being the result of encountering extreme weather conditions. This latter possibility should also be minimal having regard to modern weather forecasting techniques but they do get it wrong.

Structural deterioration during the service life of the aircraft is most likely to occur as result of crack growth due to fatigue and also maybe corrosion. However, regular inspection and maintenance of the structure should reduce this possibility to a minimum. Also don't forget that airport vehicles do occasionally run into aircraft.

During the construction of the airframe, regular acceptance tests are performed on samples of every batch of material supplied. Any batch in which sample tests fail to reach the minimum standard will be rejected. Similarly, rigorous inspection is carried out for every component and major assembly to ensure that sub-standard workmanship is eliminated.

Based on the above, it could be argued that large factors of safety are unnecessary.

In addition, it is clearly important to keep the weight of the airframe to an absolute minimum. Usually, any weight increase results in a corresponding reduction in payload and/or range therefore loss in efficiency of the aircraft. Taking account of the above, the following minimum safety factors are used in practice:

It is usual to define two main factors of safety for aircraft design which are applied to **Limit Load.** Limit Load is the load level defined by CS's and is sometimes known as the Unfactored Load. It is the largest load likely to occur 'once' during the life of the aircraft.
It is debatable whether 'once' in the life of the aircraft is referring to an individual aircraft or to the fleet. (usually in probability terms taken as 10^5 or 10^6 hours)

1. The Ultimate Factor of Safety (UF) is defined in terms of the Design Ultimate Load, such that: Design Ultimate Load = UF x Limit Load.

   The value usually adopted for the UF is 1.5, although this may be increased to 2.0 in some circumstances (Note that some failure/crash cases can have an UF as low as 1.0). The structure is required to be able to withstand the Design Ultimate Load without collapsing. Damage and permanent deformation short of total failure is usually acceptable during an ultimate test.

2. The Proof Factor of Safety (PF) is defined in terms of the Design Proof Load such that: Design Proof Load = PF x Limit Load.

   The structure is required to be able to withstand the Design Proof Load without suffering any damage or permanent deformation, i.e. it must remain airworthy following application of the proof load.

   For non-military aircraft, a PF = 1.0 is usually required but can go as high as 1.5 in some cases.

Note that UF/PF = 1.5. This corresponds, approximately, to the ratio of ultimate stress/proof stress for many aluminium alloys used in aircraft construction.

Proof stress is the stress which when applied to a tensile test piece and then removed shall not have caused a permanent extension greater than the specified percentage, e.g. 0.1%, 0.2% etc of the gauge length. These proof stresses are obtained from the stress-strain curve. If the straight line of proportionality is continued beyond limit of proportionality and another straight line drawn parallel to it and at a distance specified by the percentage strain from it, the point where this line cuts the stress-strain curve is the specified proof stress.

Ultimate stress is the maximum nominal tensile stress developed in a material and is determined by relating the maximum load shown before fracture to the original cross-sectional area of the test piece.

The UF generally ensures that the aircraft limit (proof) load case will not cause structure stresses in excess of the material proof stress and thus no plastic or permanent deformation will occur in aircraft service.

For military aircraft, the PF is usually slightly greater e.g. 1.125. This is to allow for the fact that military aircraft are more likely to be pushed outside their particular flight envelope during offensive or defensive manoeuvres.

In practice, it is virtually impossible to design to an exact strength and most elements of the structure will be somewhat over-strength.

This reserve or over-strength, for either the ultimate or proof cases, whichever is the most critical, is defined in terms of "Reserve Factor of Safety" (RF), where:

RF = Structure actual strength / Required strength (measured by test)

RF = Material ultimate (or proof) stress / Calculated ultimate (or proof) stress in the structure (by calculation)

Clearly this factor must always be greater than unity.

It should be appreciated that, even though design is generally based on the ultimate load case, it is always necessary to confirm that the proof reserve factor is at least = 1.

It should be noted that USA practice is to talk about Margin of Safety which equals (RF – 1.0) and hence should not be negative.

Page 17 & 18 Environmental Conditions

These 2 VG's show the general Environmental Conditions from CS-Definitions and those of an actual aircraft.

For actual equipment, there will be the need to include 'g' levels and other things.

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Page 19 & 20 Probability and Failure Categories

These 2 VG's show how a probability of an event can influence how one approaches design and how failures are categorised.

Page 21 Typical Design Loading Conditions(1)

Aircraft Structural Design Loads

We have already had a brief look at loading conditions and are now going to expand it.

The regulations cover a whole range of flight and ground conditions or cases applicable to the complete aircraft – (usually known as overall aircraft loads) – and those applicable to an individual item – (usually known as component loads). Quite often the results of the overall aircraft calculations are required as a starting point for component loads (for example:- C_{LL} for slat loads).

The regulations are more and more asking for a rational analysis (involving time responses) and hence going away from the simple conditions. I support this way forward but it does make things difficult in explaining some of the principles involved and also doing simple checks before the whole structure is defined. You do need to have some simple checks in place.

Overall Aircraft Conditions – Flight Cases

Vertical Manoeuvres
- trimmed steady symmetric manoeuvres at a range of 'g' levels, For CS 25 this is 2.5g down to –1g(inverted flight)
- pitching manoeuvres resulting from a sinusoidal input from the pitch control (usually the elevators)

Vertical Gusts – very simply (can be up or down)
- discrete gust – best described as like hitting a curb
- continuous turbulence (or Power Spectral Analysis) – best described like riding over cobblestones

Lateral Manoeuvres
- pilot induced rudder action causing the aircraft to yaw (and maybe roll) and then generating loads due to sideslip

Lateral Gusts – as for Vertical Gusts (also 'Round the Clock' gusts from any direction)

Engine Failure
- Engine Thrust decay resulting in aircraft response in Yaw/Roll/Pitch with Pilot corrective action included.

Rolling Manoeuvres
- pilot induced using the roll control, usually ailerons and/or Spoilers

Pilot Forces are defined in CS and don't be surprised at the magnitude - e.g. pedal force for Rudder manoeuvres is 300lb (1334N),
[I am not large but have applied 250lb.]

Page 22 Typical Design Loading Conditions(2)

Overall Aircraft Conditions – Ground Cases (including Landing Gear)

Dynamic Conditions

- *These are the result of a fully flexible dynamic response calculation*
- Landing cases at Limit Drop Velocity 10 ft/sec. Landing cases are covered for Tail-up, Tail-down and level (all wheel contact). Critical conditions are peak vertical load (Zmax), maximum drag load (Spin up) and maximum forward load (Spring back).
- Take-off/Taxi. The given runway profile is taken from San Francisco 28R during the 1960's. It has probably been re-surfaced several times since but is still used as a reference runway and is given in CS-25. OR from specified arbitrary profiles – Def Stan 00-970 has defined profiles as does Russia (4 profiles labelled A,B,C and D which we have to assess – from a fatigue point of view D was very damaging (if I remember rightly)
- Braking. Response to Braking System inputs can excite the aircraft – remember that oleos are in fact springs

Rigid or Book Cases

- Rigid Aircraft Overall Loads associated with Landing Gear inputs
- Take-off bump of 1.7g including engine thrust to give a 'wheelie' effect (for an aircraft like the A320) See AMC to CS-25.491
- Turning 0.5g applied laterally at the aircraft CG [largest measured value that I know of on a civil aircraft is 0.3g]
- Pivoting about one leg - can put large loads on the other legs of an aircraft like A380
- Landing with drift or sideload – some drag load also included
- Braking – based on a maximum coefficient of friction of 0.8 (rubber to concrete). [Note that Formula 1 Grand Prix cars use a much softer or stickier rubber and generate mu of 2 or 3.]
- Towing – regulations ask for a towing load of 15% MTOW which is then applied for all aircraft weights.
- Jacking – a landing gear to change a wheel or the aircraft for maintenance
- Crash/Ditching – wheels-up landings assume drop velocity of 5ft/sec. Ditching is a premeditated alighting on water, running off the runway or landing short do not count as ditching.
  I only know of 3 occurrences for large civil aircraft – DC9 (1970 in the Caribbean following loss of fuel), Nimrod (1995 In the North Sea following an engine fire) and A320 (Jan 2009 in the Hudson River' New York following a bird strike).

Page 23 Typical Design Loading Conditions(3)

'Minor' Components or Local Loading

The term 'minor' component refers to local loading cases or loading on small items. It can often take longer to derive the loads on these 'minor' components than it does to calculate overall aircraft loads. [I could probably make a reasonable initial estimate of wing root BM in about a couple of hours – slat loads to a similar standard would take a couple of days.] Also data can come from other disciplines (like systems).

Slats/Flaps - extended, retracted and operating cases have to be considered (slats are Leading Edge devices as are Kruger Flaps)
Control Surfaces - like Ailerons, Spoilers, Airbrakes, Rudder and Elevators (remember that spoilers and airbrakes can be the same surface, hence multi-functional)
Landing Gear Doors
Retraction Jacks and Actuators - for Landing Gear and Control Surfaces
Wheels/Tyres/Brakes
Floor Loading - Running Load (kg/m)
Distributed Load (kg/m^2)
Local Heel Loads or Crate Cornering
Cabin Pressure - for civil airliner typically 600mb and negative of 70mb
Fuel Pressures - Flight/Refuelling/Crash but note that the fuel people need to know what the structure is capable of withstanding in order to design the fuel system.
Duct Failure - De-icing or Air Conditioning Duct failure giving rise to increased pressures and/or temperatures.
Bird Strike - usually tested rather than predicted – a 4 lb bird is used for windscreens and most surfaces (usually leading edges) except the tailplane where the FAA ask for 8 lb bird. [The only place I know of finding a 4 lb bird is the supermarket shelf.] The tests by the way normally use chickens killed immediately before the test. [Some one did a test a few years ago using a frozen bird!!]
Jam Cases - moving surfaces can jam and then the maximum effort of the power source has to be reacted through the jam.
Thermal Effect - can come from Solar/Kinetic/De-icing/Duct burst
Failure Conditions - these can be detected or undetected – the regulations allow the use of an ultimate factor which varies with the probability of the failure which can be mechanical or electrical (including computers).

It is perhaps worth noting that AvP-970 (a predecessor of Def Stan 970) has lots of useful methods of tackling the calculations required – it was pre-computers. BCAR also has some information.

<u>Page 24, 25 & 26</u> Design Speeds

Design Speeds
P24 - Typical Values for an airliner, P25 & 26 - Self explanatory

Note that $C_{L\,max}$ reduces with Mach No and W reduces with altitude.

The Design Speeds (V_A, V_C and V_D) that we are talking about here are the values used for Structural Design. The Flight Manual could probable have different values indicated by V_{NO} and V_{NE}.
A maximum altitude is also specified.

There are similar Design Speeds for slats and flap extended conditions.

Other speed criteria that one should be aware of are:-

V_{MO} (Maximum Operating Speed) not greater than V_C

V_{NE} (Never Exceed Speed) not greater than V_{DF} Demonstrated Flight Speed.

V_{DF} not less than $0.9V_D$

Page 27 Relationship between CAS, EAS and TAS

This diagram shows the relationship between
Calibrated Air Speed (CAS)
Equivalent Air Speed (EAS)
True Air Speed (TAS)

There is also Indicated Air Speed (IAS) which is the value shown on the airspeed indicator. With no positioning errors, IAS is the same as CAS. I have seen some figures for light aircraft that show a difference of 6kts. (EAA and CAFE)

Page 28 Typical Flap & Slat Design Speeds

The maximum altitude for Flap and Slats extended is usually taken as 20000ft, this then covers the highest airports in the world. Names not known but we are looking at something like 15000ft for the smaller airliners (say A320), airports suitable for say something like an A330 will at a lower altitude.

Page 29 V-n Diagram

This diagram shows the V – n Diagram or Envelope for typical short range airliner at 20000 ft. There is V-n diagram for every altitude.
It is made up of a Manoeuvre Envelope and a Gust Envelope

Manoeuvre Diagram

For this aircraft, n_{max} is 2.5g and n_{min} is –1.0g

The stall line comes from

$$L = nW = C_{L\,max} \times \tfrac{1}{2}\rho_0 V^2 S$$

and by using a negative value of C_{Lmax}, the negative stall line can be derived.

-1.0g is inverted flight, 2.5g is achieved by a pull out from a dive or a banked turn.
Bank angle is related to g by $n = 1/\cos\varphi$ (φ is the bank angle).

Gust Diagram

Before constructing the Gust Diagram, it is necessary to understand how the aircraft responds to a gust, which we will look at later.

The Gust values have been calculated at MTOW, note that lower aircraft weights can give higher values (probably up to about 3.3 g for this aircraft)

There are also versions of these diagrams for slats and flap extended conditions.

Page 30 Design Weight Terminology

Maximum Taxi Weight (MTW) [also known as Maximum Ramp Weight (MRW)]

The maximum taxi weight shall be the maximum weight of the aircraft for maneuvering on the ground.

Maximum Take-Off Weight (MTOW)

The maximum take-off weight shall be the maximum permissible weight of the aircraft when the brakes are released for take-off, or at the start of the take-off roll.

Maximum Landing Weight (MLW)

The maximum landing weight shall be the maximum weight at which the aircraft meets the appropriate landing certification regulations. It will include adequate fuel reserves.
MLW is typically MZFW plus the worst fuel reserves (usually an arbitrary value)

Maximum Zero Fuel Weight (MZFW)

The maximum zero fuel weight shall be the maximum permissible weight of the aircraft less all usable fuel. This is equivalent to OWE plus maximum Payload.

Operating Weight Empty (OWE)

The operating weight empty shall be the manufacturers weight empty plus the operator's items. The operator's items shall be the flight and cabin crew and their baggage, unusable fuel, engine oil, emergency equipment, toilet chemicals and fluids, galley structure, catering equipment, seats, documents etc. This definition does vary from manufacturer to manufacturer.

Manufacturers Weight Empty (MWE)

The manufacturer's weight empty shall be the weight of the structure, power plant, furnishings, systems and other items of equipment that are considered an integral part of the aircraft. It is essentially a 'dry' weight, including only those fluids contained in closed systems (e.g. hydraulic fluid).

The definition of MWE and OWE can vary from one manufacturer to another.

Note that MTOW and MLW are used for determining the performance of the aircraft.

Minimum flight weight can be taken as OWE plus a fuel load of about 2.5% of OWE. The absolute minimum is probably MWE plus a fuel load of about 2.5% of MWE.

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For light aircraft often the All-up Weight (AUW) which is equivalent to MTOW, is used for most if not all loads calculations.

Page 31 Payload-Fuel Loading

So far we have looked at the speed and altitude conditions to be considered. The regulations also specify that a complete range of payload and fuel combinations are considered for the full Centre of Gravity (CG) range.

The diagram shows possible combinations of payload and fuel. For instance, at maximum payload we can only load approximately 9 tonnes of fuel to achieve MTOW. Similarly with maximum fuel, approximately 14 tonnes of payload can be carried. There are also regulations for minimum values of payload and fuel (explain VG)

Note that the weight values for passengers and baggage might not be current.

Page 32 Weight – CG Diagram

CG diagram or rather Mass~Moment diagram, What determines the limits?

Forward limit usually set by elevator power required to raise the nose at rotation during take-off, also if too far forward can give rise to large nose landing gear loads which in turn means a heavier aircraft. The cut-back at high aircraft weights is for this reason thereby avoiding unrealistic design loads.
Forward limit is also set by trim on approach which determines tailplane size.

Aft limit set by stability or manoeuvre criteria for flight conditions. On the ground, controlling the aircraft (steering) sets the limit by maintaining a load on the nose landing gear which is of the order of 2% of aircraft weight. This is determined taking into account the fact that on aircraft with engines mounted below the wing (and hence below the CG, the thrust from the engines gives a 'wheelie' effect. Statically, the nose gear reaction is about 6% of aircraft weight at aft CG rising to about twice this at forward CG. Under braking this can rise to about 20%.

This diagram also shows what can happen when an increase in aircraft weight is requested by a customer. The wing load is kept constant as the CG moves aft and the aircraft weight grows.

Page 33 Mission Comparison

This shows a comparison of the aircraft weights (or masses) for the Design Mission (164 passengers for 1500 nm), the fatigue mission (120 pax for 500 nm) and the Design weights for certification.

Note that for fatigue conditions, a 1% increase in load you can have a 5% decrease in life, this is for a metal structure.

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Page 34 & 35 Typical Fatigue Mission

Page 36 Design Speeds – includes Fatigue Mission

I have added the typical Fatigue Mission flight profile to the Design Speed picture.
Certainly in the USA there are air traffic control speed limits below 10000ft (V=250ktsCAS), this is to try to reduce the speed differential between light general aviation and the heavier (and normally faster) commercial aircraft.

Page 37 Typical Operating Ranges

This VG shows how aircraft with a design range of greater than 1500nm can spend at lot of its time flying sector distances much less. This is the result of data recorded on ONE day.

Page 38 Life Cycle Comparison

Note that 60000 hours can be 60000 flights of 1 hour or 20000 flights of 3 hours or anything in between.

Page 39 Aircraft Reference Axes

The aircraft is modelled as a series of 'sticks' or 'branches'. These sticks are properly known as reference axes and the loads are presented or referred to these axes.
Each branch or component can have its own local datum but they are linked to the overall aircraft datum or origin which is usually the nose.

Page 40 Wing Strip Geometry

Each branch is then divided into strips on which acts the mass and aerodynamic effects. For flexibility effects, these strips are joined by springs representing the stiffness characteristics. Where point loads or heavy masses are attached, we make use of 'zero' width strips. This then gives a before and after situation at the load point.

Page 41 Wing Bending Moment

The loads are presented along the reference axes as Shear Force, Bending Moment and Torque. We actually calculate 3 forces, 3 moments, inertia factors (at least vertical g) and local lift coefficient for EACH strip. This VG shows wing BM, Note that the loads are along or relative to the reference axis BUT the spanwise dimension is taken normal to line of flight or aircraft centre line.

The effect of GLA (Gust Load Alleviation) is to reduce the wing BM by about 12% for this aircraft. Target was to have the same BM as the manoeuvre case.

Structural Airworthiness

Note that it is important to label diagrams correctly - applicable ultimate factor and whether the loads are limit or ultimate. This graph gives LIMIT load (which is not stated), Ultimate Factor is 1.5.

Note the steps at Y=3.9m and Y=5.75m where the Landing Gear and Pylon loads come in.

The curves start or stop at the wing root, however for overall balance checks you do need to know the value at aircraft centre line (and in line of flight).

Page 42 Fuselage Bending Moment

Page 43 Wing Vertical Inertia Factor

Page 44 Fuselage Vertical Inertia Factor

This VG shows the maximum 'g' levels for manoeuvre, gust and dynamic landing. It also shows the 'g' level associated with the maximum Bending Moment for the landing case.

Page 45 Tailplane Vertical Inertia Factor

Page 46 Fuselage Lateral Inertia Factor

Page 47 Typical Time History

This VG illustrates the phasing of selected loading quantities – actually for a station on the wing – explain timing of SF/BM/g

Page 48 Engine/Pylon/Wing Attachments

This VG shows some of the critical cases for the engine/pylon/wing attachments.

The inertia values are limit and are applied at the engine CG.

Note the 1.25 factor on the wing side of the attachments to ensure that the wing is stronger than the pylon. As the aircraft develops and actual RF's are known, the factor may reduce, the minimum I would recommend is 1.10. (It would appear that EASA and FAA are asking for a 1.25 factor, probably as a consequence of some B747 problems).

The surprising fact of this VG is that the vertical gust produces the largest lateral load.

Page 49 Pendulum/Nodding Effects

The engine is a large mass on a relatively flexible beam. As the wing bends upwards, the engine will swing outwards but as the wing bends downwards, the engine will swing inwards. This motion excites the engine in a lateral sense thereby causing the high lateral loads. The engine acts like a pendulum.

In landing conditions there is a nodding effect

Structural Airworthiness

Page 50, 51, 52 & 53 MLA & GLA

This shows how Manoeuvre Load Alleviation (MLA) and Gust Load Alleviation (GLA) can influence wing loads.

For MLA the wing will probably be working close to Clmax. Also the aircraft has to still pull 2.5g and although the ailerons/spoilers reduce lift on the outer wing, the incidence will be increased to regain the lost lift. Result is that SF is little changed due to re-trimming the aircraft and BM reduced.

GLA affects both SF, BM and T, BUT beware of other cases becoming critical (see page 53).

With 'fly by wire' (FBW) or EFCS (Electronic Flight Control Systems), failure conditions of the computers and control system have to be considered, including oscillatory conditions.

Page 54 Typical Dimensioning Cases

So far we have looked at the general description of all the cases that are assessed.

What is shown here is where these cases are critical for the overall aircraft.

In order to reach this stage it is possible that up to 2000 different combinations of M/V/H/W have been considered. In the case of Time Responses and counting each time interval as a 'case' then we look at something like 2 to 3 million cases (this was when I last checked, it is now probably more). By means of sorting and selecting routines, the stress office will probably assess something in the order of 100 cases for the wing.

Take each component in turn and explain – don't forget to include WHU and sliding cases for the nacelle.

Page 55 Wing Box Design Cases

The dominant cases on the upper skin tend to be the gust and manoeuvre cases giving high compression stresses in the skin due to upward bending. Minimum material thickness tends to be the criteria for outer wing skins due to the much lower stress levels, the minimum thickness that can be machined being about 1.5mm. The inner wing skin may require thickening up to increase stiffness to avoid any aeroelastic/flutter problems.

The lower skin is also dominated by upward bending but because this induces tension stresses in the skins it tends to be fatigue cases that are critical.

Landing Gear cases may also be critical in the inner wing near their attachments.

The critical cases for the spars are often gust and manoeuvre conditions. The inner front spar requires special attention (as do other fuel tank boundaries) to meet the 9g crash case with a full tank of fuel, this can generate up to 90psi or 6bars for the A320. Regulations now ask for 4.5g.

Fuel density can vary between 743 to 851 kg/m3. The nominal or typical value is 785 kg/m3 and this value should be used

The inner rear spar tends to be critical for ground cases like braked roll or turning.

The ribs are normally designed by brazier effects, inertia forces and local inputs from flaps/slats/spoilers/ailerons/jacking points etc. The local inputs also affect the spars.

When sorting for critical spar cases care must be taken because spar shear flows are a combination of shear and torque.

Page 56 Shear/Torque Combinations

The vertical shear produces an upload on both spars but when this is combined with torque, the spar shear flow is reduced on one spar and increased on the other.

One way to ensure that the critical case has been chosen is to generate phase plane plots (also known as 'potato plots').

As can be seen, neither the maximum shear or maximum torque give the worst combination but it is this condition just below the maximums which tends to give the critical spar cases.

Also applicable to minimum conditions as well.

Page 57 Wing Construction

At this stage it is perhaps worth saying something about the structure and materials.

Aircraft Basic Structures

The aircraft structure is divided into two sections: primary structure and secondary structure.

Primary structural members contain: Spars, Skin, stringers and Ribs for the wing
and Skin, stringers, floor and pressure bulkheads for the fuselage.

Secondary structural members contain: Leading edge and Trailing edge for the wing
and Fairings and Transparencies (windows)for the fuselage.

Looking at the wing in more detail.

Spar (typical material 7010 Aluminium)

The spar acts like a cantilevered beam, fixed at the wing root. It reacts wing shear in the spar web, compressive loading in the top flange (due to wing bending) and tension loading in the bottom flange (due to wing bending) for a flight case with upward bending. There can be large local inputs to the spar (from the undercarriage, flaps, slats and engine). Small aircraft may only have one spar (gliders), larger ones have two spars (A320), and very big aircraft may have three spars (A340 and A380). The spar will commonly act as fuel tank boundary and hence have to be able to withstand pressurisation loading.

<u>Skin Stringer (typical material, 2024 lower cover, 7075 top cover Aluminium)</u>

The skin stringer structural element is designed as an end load carrying member. In the top skin, the primary loading is compression so buckling and instability are the design considerations. In the lower skin, the primary loading is tension hence fatigue and detail design to remove any stress concentrations are the main considerations. The lower cover will also have access holes to allow maintenance and inspection. The skins form a tank boundary and are subjected to fuel pressurisation loads as well as the external aerodynamic pressures.. The skins, together with the spars form a closed box to react the applied torque.

<u>Rib (typical material 7010 Aluminium)</u>

As a wing develops lift it bends, this bending causes the top and bottom skins to move closer together. The function of the ribs is to keep them apart. This subjects ribs to a compressive load known as Brazier loading. The ribs also act to break up the length of the spanwise skin panels. Local input loads (from the undercarriage, engine, flap, etc.) can be distributed into the wingbox by the ribs.

<u>Leading Edge</u>

The leading edge on small aircraft can be very significant in terms of their structural capability but on larger aircraft their main function is aerodynamic. On large aircraft (like Airbus) the Leading Edge is divided into Fixed and Moving with the mechanisms for deploying/retracting the slats in the fixed portion. There is a trend towards composites for the fixed portion, however the moving portion has to withstand birdstrike and at this moment in time, metal is probably better. The failure of the systems in the Fixed leading edge can lead to high pressures and high temperatures (influences choice of materials)

<u>Trailing Edge</u>

Generally the trailing edge is not structurally significant on light aircraft. On large aircraft (like Airbus) it is divided into Fixed and Moving and there are several structurally significant elements within the trailing edge – the false rear spar and the gear rib. On Airbus aircraft there is a large carbon fibre composite content within the trailing edge. Items contained within the trailing edge include the attachments for the aileron, spoilers, flaps, and the main undercarriage. All the associated mechanisms for controlling the trailing edge devices are also squeezed into the small space behind the rear spar.

Space is always an issue and design for ease of maintenance is not easy.

<u>Page 58</u> Typical Landing Gear

Critical cases are those that give the maximum fore/aft, side and vertical loads (plus moment cases for torque links and steering).

For the MLG these are

- Braked Roll (max. drag load)
- Spring Back (max. forward load)
- Turn Case (max.side load)
- Pivot Case (max. moment for torque links)

Note that a 60/40 distribution is used between tyre/wheels (see CS23.511), CS25.511 has a more rational analysis.

Page 59 Sign Conventions

Sign Conventions Yes, they need to be mentioned. What ever you use, it is best to declare (specify) what it is. AND think what is happening physically.

Sign conventions are important. Some examples of what has happened to me.

C_L (for the wing) +ve up
C_Z (for the elevon) +ve down
We assumed that both were +ve up without checking.
It did cause some problems until we realised what was happening.

Wing root loads, at the time Filton Stress Office usually said Shear +ve up, Bending Moment +ve tip up and Torque +ve nose up. Our French colleagues used Torque +ve nose down. This caused some difficulties at the root interface when resolving from swept to normal axes.

In one of the Loads Manuals, a table was produced that gave the sign conventions of each of the companies that made up Airbus, and even different groups within each company had different conventions.

At one time, different groups did separate parts of the calculation, for example trimmed flight was done by aero, the gust response by dynamics, a third group combined them, and a fourth group might be the end user.
Different sign conventions, one group doing the calculations for the port side while another did the starboard side. Yes we did have some problems.

In Aircraft axes,	Wing axes (rotates 90°)
X fore/aft	X root/tip
Y sideways	Y fore/aft
Z up/down	Z up/down

You can also have lots of other rotations to align the local component.

Page 60, 61, 62 & 63 Longitudinal Equilibrium

Longitudinal Flight Balance

Page 64, 65, 66, 67, 68, 69 & 70 Gust Loads

Gust Load Evaluation.

A little more explanation about Gust Velocities (in particular the discrete type) indicating some of the changes that have taken place over the last 30 years or so. The gust shape or profile is known as '1-cos'. The gradient distance (distance to maximum gust velocity) was originally set at 12.5 chords (geometric not aerodynamic). The maximum gust velocity (U_{de})

was evaluated and published in NACA 1206 (NACA being the predecessor of NASA) . The author being Kermit Pratt. In my early days in the aircraft industry it was often known as the 'sharp-edged' gust formula or Pratt formula. In the UK, it was permitted to vary the gradient distance, usually in association with a reduced gust velocity (90% U_{de}).

The Orange Paper (introduced at Change 14 to JAR 25 and now hence part of CS-25) allows the gust velocity to be related to the time an aircraft will spend in each altitude band - it was initially known as 'altitude weighted'. The Orange Paper (U_{ref}) tends to give wing bending moments (1g + Δgust) about 15% lower than U_{de} - both assuming flexible aircraft and the '1-cos' gust shape.

Note: on Page 67 $\delta CL/\delta\alpha = 7.219$ includes the effect of the tailplane and hence is a complete aircraft value.

In the latest change to CS-25, U_{ref} now goes to 60000ft

.

CS-25 asks for rational analysis, while CS-23 asks for sharp-edge gust with appropriate gust speeds.

Page 70 shows an example of how one can find a worst case.

Remember that you are ENGINEERS first and Computer Operators Second

Thank you for listening and I wish you well in your future careers.

And remember you never stop learning