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AIRCRAFT LOADS

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SUMMARY
The life of a weapon system is influenced to a high degree by the structural integrity of the airframe. Numerous programs to ensure this have been established within NATO´s Air Forces. Structural loads, leading to fatigue as well as corrosion, depending on the usage environment, are the major reason for degradation of structures. The many different classes of loads, the generation of loading conditions during the design phase, as defined in the weapons systems specification, consideration of static and fatigue loads for structural lay-out and validation concepts are presented.
The procedure of converting overall aircraft loads (“external loads”) into individual component loads is shown in principal .

0. BACKGROUND

The effectiveness of military force depends in part on the operational readiness of aircraft which itself is largely dependent on the condition of the airframe structure. This condition again is affected by a number of factors among those the physical loads in various forms together with the used life of the airframe are important. With increased and extented usage of airframes in all airforce inventories and the requirement for various role changes the subject of airframe loads assessment, -qualification and aircraft loads-monitoring becomes more important, not only for flight safety but also and with an increasing tendency for economic reasons.
A general understanding of the various types of airframe loads, their generation and application during the design process, the transfer processes from "external loads" into "structural loads", loads qualification during ground and flight testing is therefore of equal importance to the process of usage monitoring and derivation of usage factors from the different fatigue tests or the set-up of structural inspection programs.
When life of aircrafts are discussed, often the flight hours or number of flights are still considered the governing factor, sometimes adapted with factors on "damage hours" or "usage", while from a structural engineering viewpoint the operational stress spectrum and therefore the life on the different aircraft components are not only a matter of flight hours and spectrum ratio but also driven by modification status, structural weight status and role equipment.
This paper describes loads- analysis and verification activities during the major phases of the life of an airframe, where structural loads and their influences on the airframe condition are vital to the structural integrity and the economic usage of the weapon system:

* The structural loads during design and Qualification of A/C structures
* Loads monitoring during usage
* Impacts due to aircraft modification and role changes.

Trends with respect to the increased usage of theoretical modelling are also discussed.

1. STRUCTURAL LOADS DURING THE DESIGN AND QUALIFICATION OF AIRCRAFT STRUCTURES

Loads are accompanying an aircraft’s life from “the cradle to the grave”. Although the overall type and magnitude of major load sets remain the same, there is no “fixed” loadset that is be applied to one aircraft model throughout the life and often identical airframes serving different roles within a fleet over time will be subjected to very different loads.
To include as much as possible (or specified) of these loading scenarios in the early process of designing a new type of aircraft is the responsibility of the loads engineering department, while ensuring that these loads can be safely endured throughout the specified life is the task of the design and stress engineers. “New” loadsets, developed later during usage of the aircraft are common tasks and handled similar as the “initial design loads” by the design authority with the constriction, that now the airframe is already build and deployed and the focus is on minimising changes though structural modifications to qualify the structure for its new environment either through analysis and / or test.
In short, every major change in the aircraft’s role, payloads or usage in principle influences the loads acting on the airframe or at least some components. Fig. 1-1 gives an idea how loads are initially generated and how they are used throughout the design-, qualification- and usage process.

Paper presented at the RTO AVT Lecture Series on “Aging Aircraft Fleets: Structural and Other Subsystem Aspects”, held in Sofia, Bulgaria, 13-16 November 2000, and published in RTO EN-015.

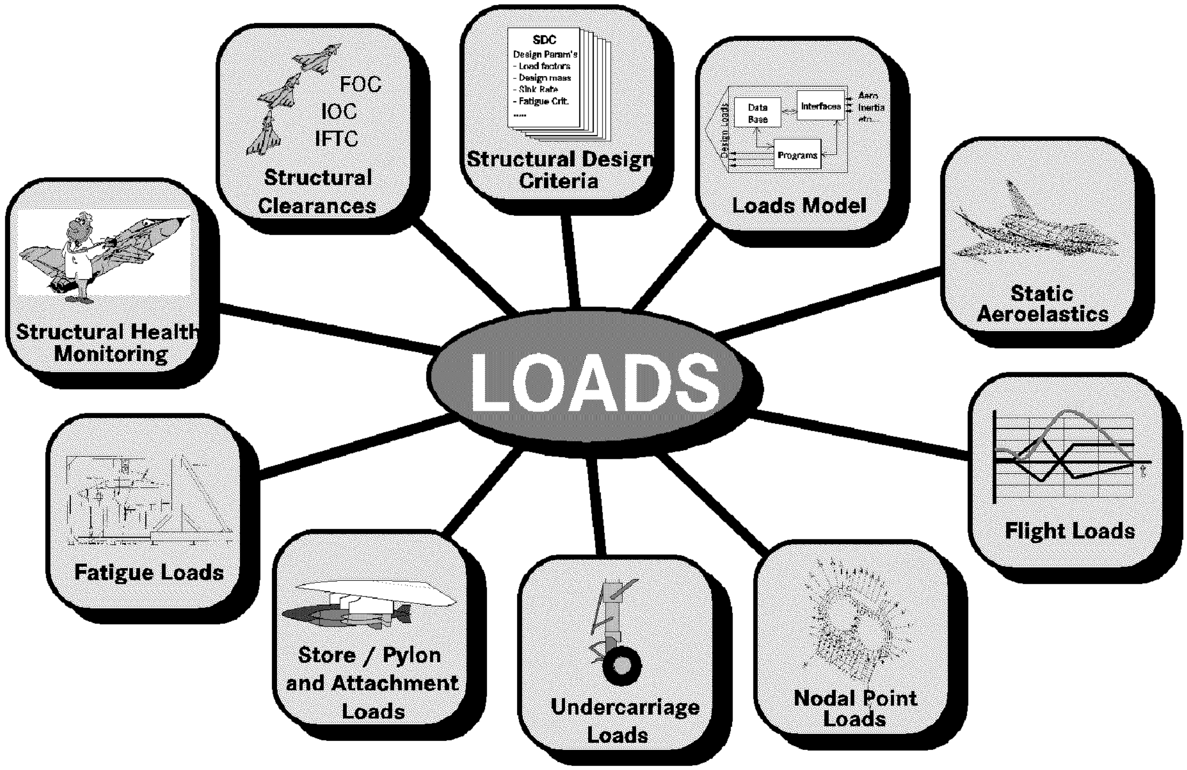


Fig. 1-1 Loads Main Tasks

1.1 Loads and Fatigue

The determination of loads together with the qualification for static strength and fatigue by calculation and test for all important structural components is a main prerequisite for successful design and safe operation of any aircraft.

Whereas for transport aircraft with their rather limited range of operational manoeuvres and high number of flight hours / cycles fatigue is the main design driver for the airframe, fighter aircraft are predominantly designed to (static) limit load cases for the "corners" of the envisaged flight envelope, which in general cover a lot of strength required for fatigue of their comparatively short life.

But this is only true as long as fighter life does not exceed the originally planned lifetime and the roles, missions etc. are compatible with the design criteria at the beginning.

Aging aircraft in both cases does not only mean that an aircraft is getting older in terms of flight hours and flight cycles, it also means that some of the reference data for the basic design criteria have changed during time, i.e.:

- airframe and equipment mass growth
- enhancement of systems performance, especially engine thrust
- new configurations (stores)
- update of flight control systems (FCS) (electronically or hardware changes like added slats or enlarged ailerons)
- mission profiles and additional/changed roles
- actual usage spectrum

Most of these changes have an immediate impact on aircraft load scenarios, others will not change load levels but may change underlying statistic, e.g. fatigue spectra. Assessment of external loads is therefore a basic task throughout the life of a fleet.

Admittedly in many cases there is no simple one to one relationship between "external" loads and local internal stresses, which after all are the basis for the assessment of "life consumption" or "remaining life" of structural components. But providing loads are known for a special structural interface or component, reliable conclusions can be drawn regarding local stresses relating to the manifold of load cases from experience, measurement and detailed FE analysis during design, qualification and test phases in many cases.

In addition the comparison of load spectra alone may already be suitable for drawing conclusions without recourse to detail stress calculations of specific locations for components with limited loadcase variations i.e. landing gears.

1.2 The Determination of Design Loads

Design loads, better "Initial Design Loads" are the first step in the loads history of an airframe that influences the detail design of a component (i.e. wing or fuselage structure) or, at a later stage in the design process, a part (i.e. wing spar cap or fuselage skin panel) in many details. Since not every load is determining these design tasks, establishment and identification of the "design loadcases" is important. The following is a summary on the methods how design loadcases are determined, with special attention to points where an immediate context with fatigue calculations exists.

Fig. 1.2-1 shows a typical "loads loop" which usually is repeated several times in the different phases of the aircraft design. First of all the Structural Design Criteria (SDC) are prepared as a basis for design, specifying the basic performance and flight parameters, then a Loads Model (LM) is built, based on the SDC's, the aerodynamic, flight mechanic and weight and balance data of the aircraft.

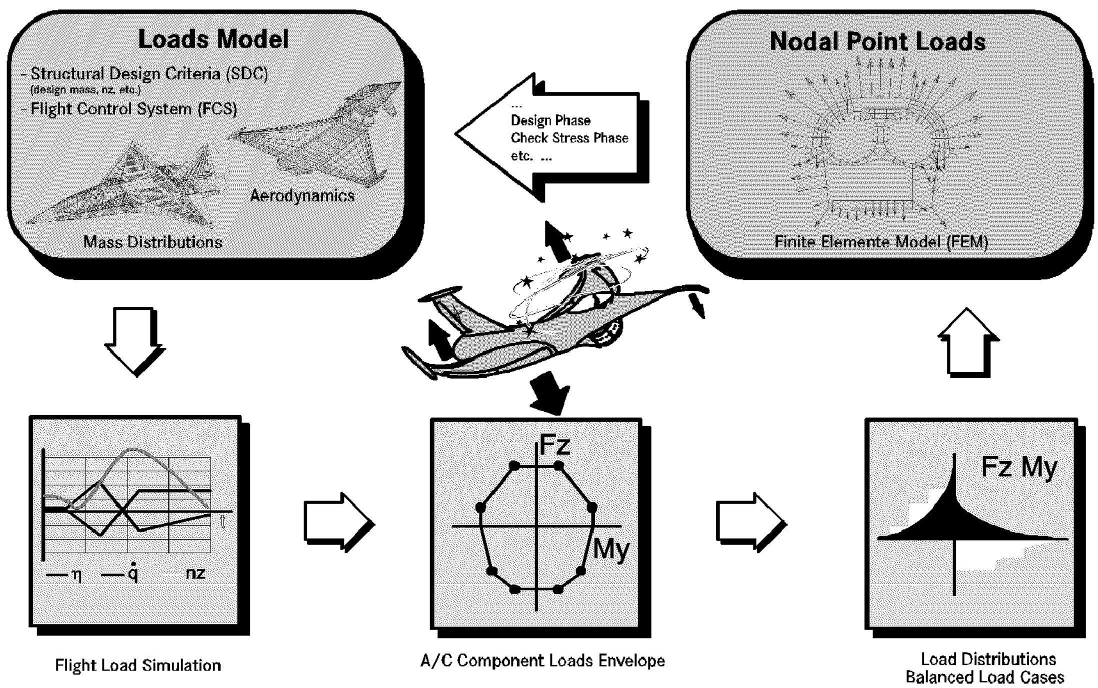


Fig. 1.2-1 Loads Loop

The loads module ensures that loadcases selected for design are analysed for an overall balanced aircraft (mass, inertia and aerodynamic forces) for all manoeuvres and the loads analysis is performed in a time history sequence, thus providing load information on structural interfaces for every timestep of the chosen manoeuvre. Results of the loads module is either continues external load distribution for any component (i.e. bending, torque and shear force distribution along fuselage stations for all loadcases or a) distribution of loads on the Finite Element (FE) grid nodal points for subsequent "global FE-Analysis".

Thus, starting with the SDC the load loop ends with the preparation of external loads for stress analysis of components.

Usually an improved or changed data basis results in an update of the LM and consequently in more accurate and more detailed design load cases. Typical improvements are a better aerodynamic data basis (i.e. via extensive windtunnel testing) or a refined FE-model because of an advanced design status. Modifications in the mass and balance status, control laws etc. may also result in substantial changes of the loads model, especially in advanced computer controlled flight vehicles.

The importance of the link between knowledge of external loads and structural stress distributions for the assessment of fatigue life cannot be underestimated. Whereas in the past the available computer resource was rather poor and strong software tools were scarce goods, leading to a strong selection of loadcases to be analysed in detail, today there are virtually no limits, from this side. Computers power do play an important part with respect to better and refined results in the assessment of loads, however the correct selection of the critical manoeuvres for the fatigue spectrum and their loads analysis still influences the fatigue performance of a structure during the design phase.

Most of today's ageing aircraft fleets of the NATO airforces were designed and flight tested by the end of the sixties or the beginning seventies, like the Tornado, Harrier, F-16, F-18, Mirage 2000 etc. An aircraft like the F-4 Phantom even dates back to the fifties and is still in service in some air forces of the alliance.

When comparing design environments of the a.m. models it should be pointed out that in the meantime the circumstances and requirements for aircraft design and analysis have changed in many ways, in detail:

- much better tools, soft- and hardware, and with that a very intensive investigation to calculate and control limit and fatigue loads (including a substantial increase in the number of component load monitoring stations)

	Tornado IDS	Future Europ.Fighter
Basic Loads Cases (BLC) Flight and Ground Handling Loads	33	105
Unit Loads Cases (ULC) Hammershock, Engine Thrust, Airbrake etc.	12	16
Combined Load Cases Superposition of scaled ULCs to BLCs	~ 100	590

- more accurate loads databases in terms of
  - advances in "Carefree Handling"- Flight Control Systems (FCS)
  - aircraft mass distributions predictions
  - aircraft aerodynamics calculated with mature CFD (Computational Fluid Dynamics) methods and verified earlier and more reliable in wind tunnel tests.
  - coupling of structural models and aerodynamic models for aeroelastic effects available
  - Finite Element modelling of the structure with interfaces to the Loads Model
- extensive flight testing, especially dedicated flight load surveys
- extensive structural ground tests

Basically this means that the static design of "old" aircraft usually is rather conservative and on the safe side.
With respect to fatigue the situation is often less satisfying, i.e. without powerful tools like a balanced Loads Model, one procedure was balancing loads over the aircraft artificially in those days, and design loadcases therefore were generated for parts of the structure like aft or forward fuselage or tailplane only, the effect of these loads on other areas of the structure remained unknown and components, not immediately under survey were not analysed for this loadcase, therefore the effect of changes to these loadcases later remained also unknown.

1.2.1 Structural Design Criteria (SDC)

Aircraft loads are determined according to requirements and regulations collected in a systems specification document called Structural Design Criteria, the major reference for loads and structural analysis engineers during the design phase.
Many of the SDC requirements come from the customer, others are prepared in co-operation between customer and original equipment manufacturer (OEM), usually the principal design contractor. The SDC are also subject to revisions during the design process.
Some of the more important items regarding loads and structures are:

Design masses are defined for different flight conditions to cover the whole mass and center of gravity (C.G.) range, i.e.:
- basic flight design mass
- landing design mass
- maximum take off mass

Total mass and mass distribution not only affect loads on wing as is sometimes believed but loads on most parts of the aircraft's structure. Design mass is one of the most important criteria for structural design. For example the basic flight design mass is coupled to the max/min allowed vertical load factor Nz, for increased masses through the rule: $Nz \cdot Weight = const.$ to avoid overloads or assessing the effects of over-g's.

V-n Diagrams define the regime of speeds in combination with max/min allowable load factor Nz including gust conditions, see Fig. 1.2.1-1. For low speed regimes the attainable limit Nz depends on the maximum lift and dynamic pressure for the wing whereas for higher speed Nz is limited by the structural strength of the aircraft. The v-n diagram is referenced to a specific mass and store configuration, i.e. clean wing and design mass.

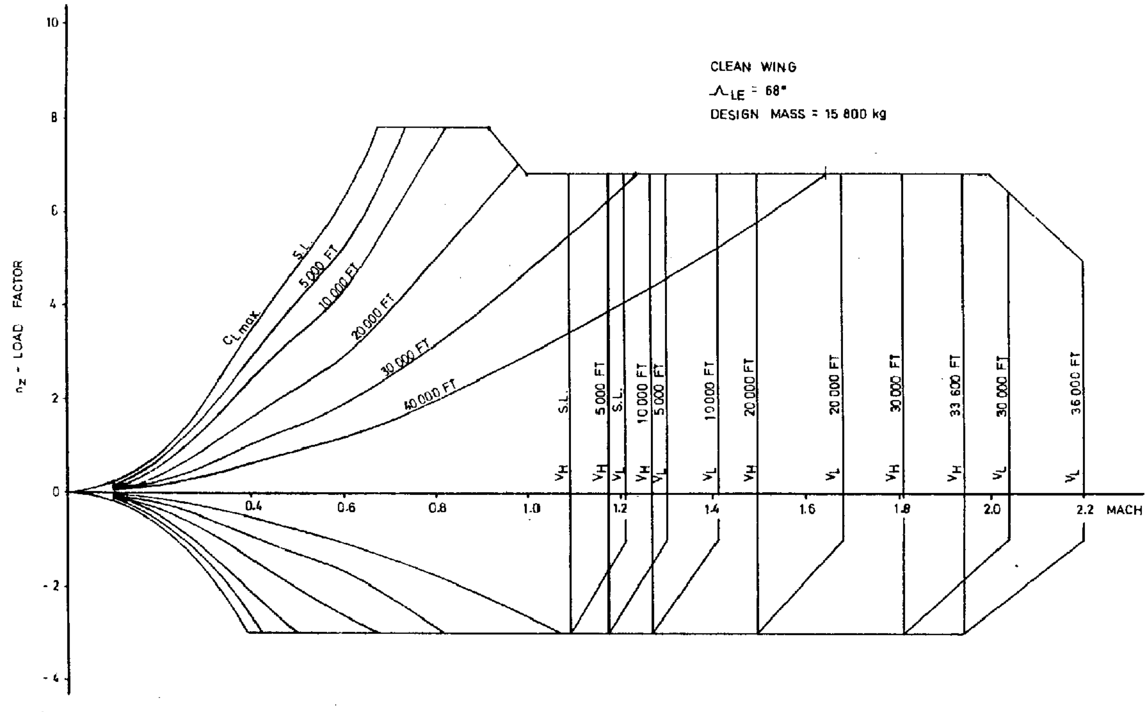


Fig. 1.2.1-1 Ma-n Diagram in Altitude

Flight Envelope(s) define the operating range with respect to Mach-Altitude regime, for which the aircraft is designed. Limits are determined by attainable Nz, temperature etc. Fig. 1.2.1-2 shows a typical flight envelope for the Tornado aircraft.

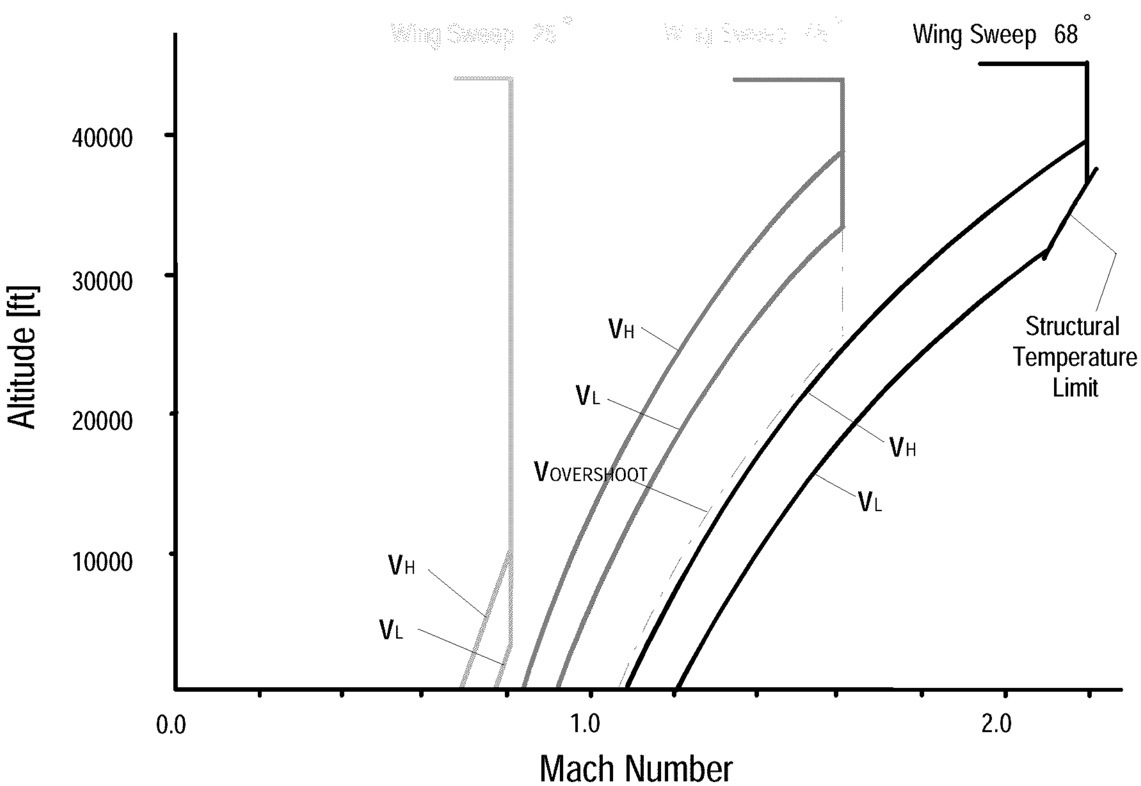


Fig. 1.2.1-2 Altitude – Mach Number Envelopes

For an fixed wing aircraft usually only one flight envelope diagram has to be defined, but the Tornado, like other swept wing designs, presents an additional complication as each (fixed) sweep position has to be considered as a different aircraft. This is clearly seen by the different flight envelopes for the shown sweep positions of the wing.
Fig. 1.2.1-3 indicates what part of the flight envelope is of importance for the investigation of loads and shows points in the Mach-Altitude range for which loads are calculated according to the scheme explained later. The points are selected to cover all essential effects due to high Nz, incidence, roll rate, gust, Mach effects etc. Traditionally the analysed manoeuvres could be found following the low pressure altitude and high mach number boundary, but non-linear aerodynamic effects of flexible structure and the modern flight control layouts are the reason for many "interior" points in the Mach-Altitude range ("points in the sky") of importance for today's loads analysis.

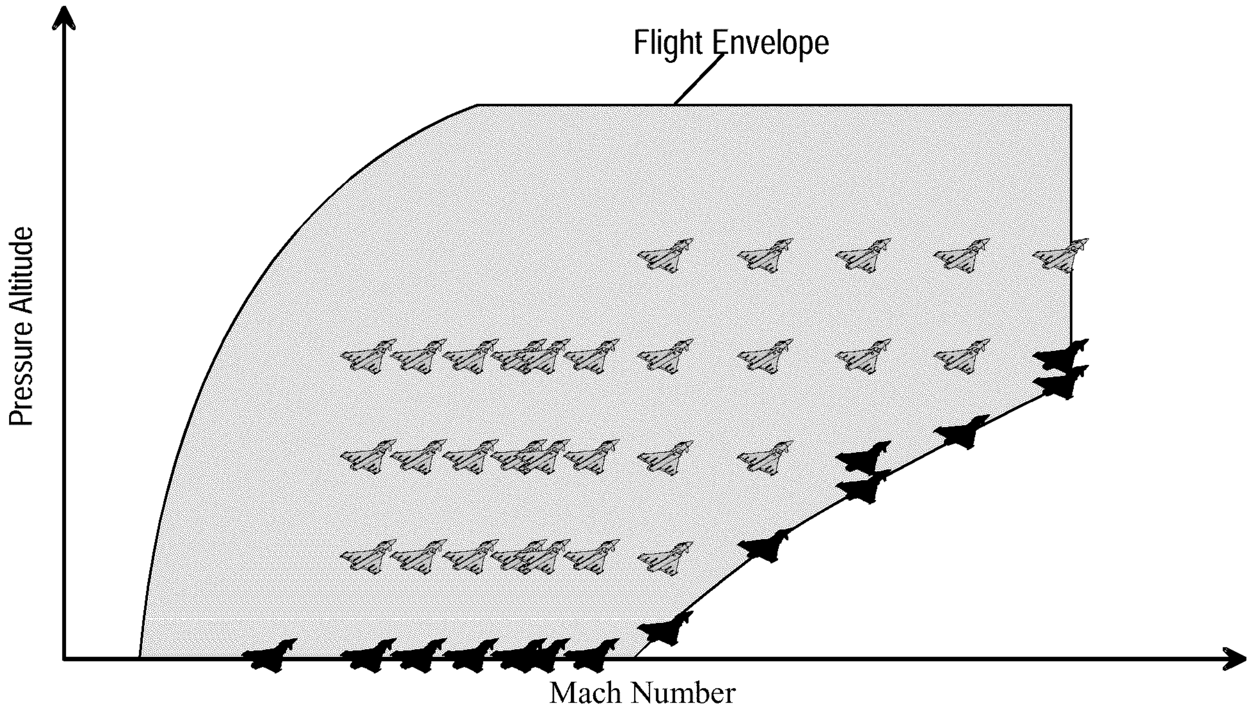


Fig. 1.2.1-3 Mach - Altitude Points of Loads Model (flex. Aerodynamics)

Environmental Conditions also define or influence tructural loads and include

- System pressures
- Cabin and fuselage bay pressures
- Temperatures and noise levels
- Local accelerations for qualification of equipment
- Vibration levels

Performance Requirements with respect to steady state manoeuvres, transition response, flight and ground handling qualities are to be fulfilled.

Example: Due to aeroelastic deformation under load the effectiveness of a control surface may be reduced substantially, for differential tail design's even roll reversal may occur. Therefore a typical specification would be the max. allowable degradation in control efficiency under such circumstances. This means that an optimisation of the flap structure, its control devices and the attached structure must be carried out to ensure a required roll rate for a given control input.

Configuration specification with respect to external stores, and control surface schedules like high lift devices , airbrakes etc. Store configuration definitions can have great impact on fatigue spectra due to either load alleviation or increments by inertia effects (stores on wing versus on fuselage). See also Chapter 1.3 for a discussion and example of component load changes due to store configurations.

Fatigue Load Spectra are defined based on expected usage and mission schedules for the aircraft and based on the customer weapon systems specification. Together with the applied scatterfactor it defines the loading scenario for qualification of the structural design through analysis and ground tests. A more detailed discussion of this point can be found in the second paper "LOADS MONITORING AND HUMS" of this Lecture Series.

1.2.2 Aircraft Loads

The characteristics of loads acting on aircraft are of different kind. Although non-exhaustive, the following grouping shall give an idea of the "classes" of loads to be considered in parallel during design:

Quasi-static loads**:**

Flight Loads:
- Symmetric manoeuvres
- Asymmetric manoeuvres
- Deep and flat spin
- Gust loads

Ground Handling:
- Take off
- Landing
- Repaired runway
- Taxiing (asymmetric braking, turning etc.)
- Towing, Pivoting etc.

Local and Internal Loads:
- Max./min. aerodynamic pressures (outer surfaces)
- Local accelerations
- System pressures
- Bay pressures (pressurised areas)
- Hydrostatic pressures (fuel tanks)
- Intake duct pressures (steady state)
- Engine thrust

Dynamic Loads**:**

- Buffet (Outer wing, vertical fin buffet etc.)
- Dynamic Gust
- Vibrations
- Acoustic Noise
- Limit cycle oscillation
- Shimmy (Undercarriage)
- Engine hammershock conditions (Duct)

Fatigue Loads**:**

Fatigue load cases are derived from the a.m. quasi-static and dynamic load conditions if the frequency of the respective load cycle is sufficiently high during the assumed usage. Fatigue loads are always a combination of loads from the a.m. list, especially flight loads combined with local and internal loads or acoustic noise. Other loads, occurring only during failure situations are excluded from the fatigue load sets (i.e. engine hammershock will certainly not be a fatigue case), Dynamic buffet, although difficult to predict, needs to be included die to its high cycle characteristic and therefore high damage potential.

Flight measured buffet on a vertical fin is shown in Fig. 1.2.2-1 for a symmetric, no side slip pitch-up manoeuvre to 50° AOA, indicating bending moments Mx and torque Mz at the fin root with R=-1, picking up around 35° AOA and increasing to the max angle of attack flown during this manoeuvre.

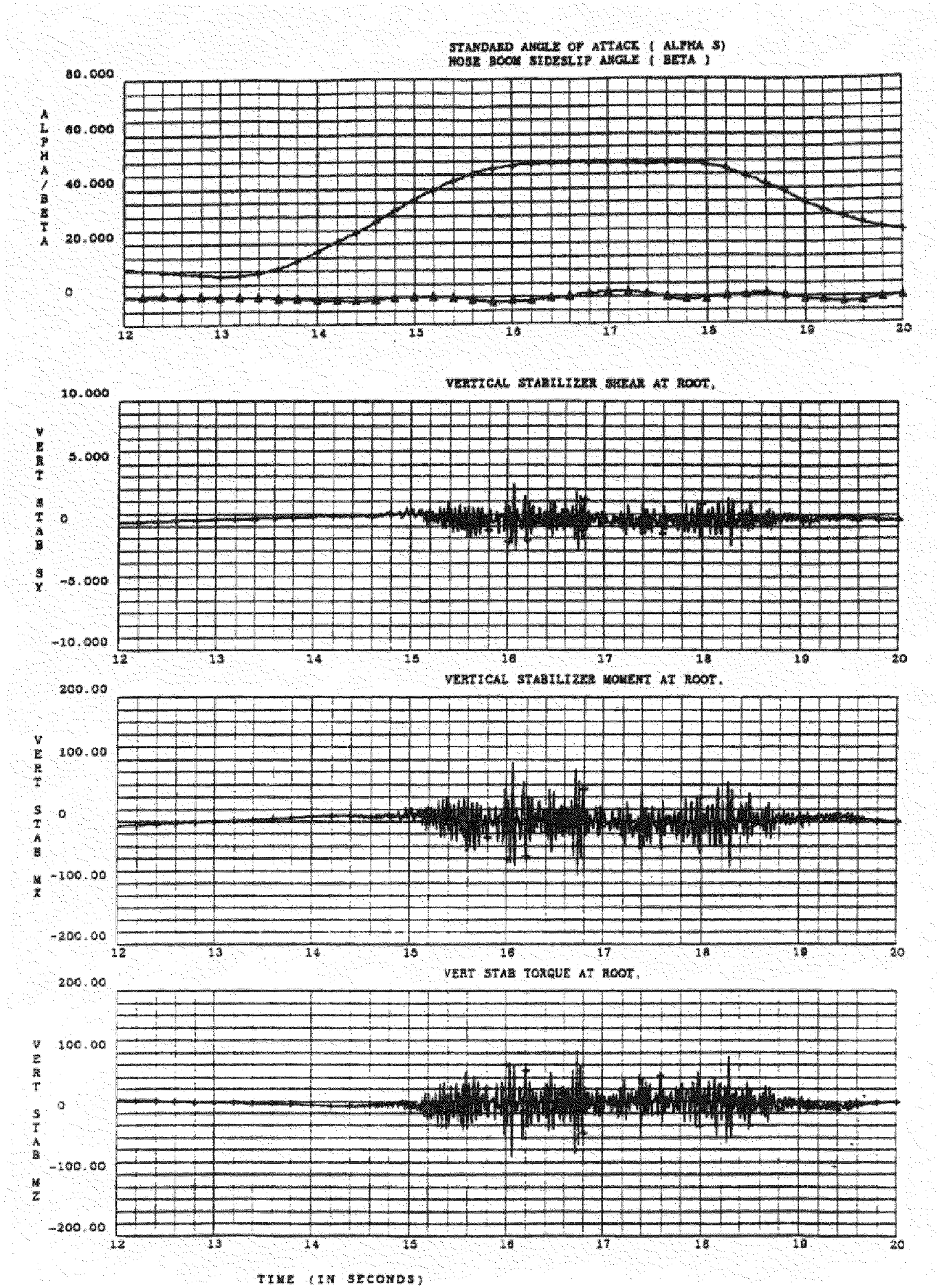


Fig. 1.2.2-1 Fin Buffet at High Angle-of-Attack (Flight Test Results)

The above static, dynamic and fatigue loads have to be combined with the corresponding structural temperatures, for the worst environmental conditions (i.e. cold / hot day) and also moisture conditions if material properties like for composites are effected.

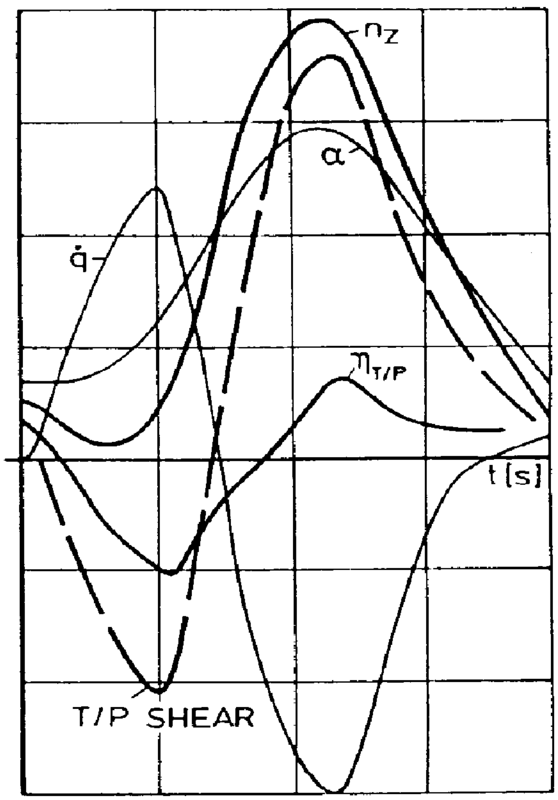
1.2.3 Flight Parameter Envelopes

Loads are not a function of Nz alone but depend on many other flight parameters, the most important are:

Incidence or angle of attack (AOA)
- Sideslip (for design the significant factor is • ·Q, the product of sideslip and dynamic pressure)
- Control surface deflection angles (aileron, rudder, tailplane etc.)
- Lateral load factor Ny
- Vertical load factor Nz
- Roll rate / Roll acceleration
- Pitch acceleration
- Yaw acceleration

Usually less important for load derivation:
- Longitudinal load factor Nx
- Pitch rate
- Yaw rate

Adequate combinations of those parameters - as occurring during real flight manoeuvres - can yield high loads on different parts of the aircraft structure, even for rather moderate vertical load factors. In order to illustrate this context, Fig. 1.2.3-1 shows flight parameters during a typical MIL-Std. pitch manoeuvre versus time and indicates the delay between command input (tailplane deflection angle), change in AoA for the aircraft and the increase in loadfactor and the force on the tailplane (=T/P SHEAR), the value for the loads envelope for this component.



nz	vertical load factor
α	angle-of-attack
q̇	pitch acceleration
η T/P	tailplane deflection angle
T/P SHEAR	tailplane vertical shear force

Fig. 1.2.3-1 MIL-SPEC Pitch Manoeuvre

Therefore it is the engineers skill to find all the critical combinations for the different aircraft configurations and the possible manoeuvres within the whole flight regime. Regulations like Mil-Spec for fighter aircraft or FAR for other A/C provide a good guide to determine the critical combinations of flight parameters for design, at least in the case of stable aircraft and conventional FCS. Very often it is desirable to determine flight parameter values from response calculations, using an aircraft response and loads simulation program.

However, in the early and intermediate stages of modern fighter aircraft design a reliable model of an FCS usually is unavailable, therefore agreement between specialists of different disciplines (aerodynamics, flight mechanics, loads etc.) on flight parameter limits in the form of envelopes is the adequate way ahead. Fig. 1.2.3-2 shows typical envelopes as used in the early design phases with the envelope corners design critical regions for different aircraft components.

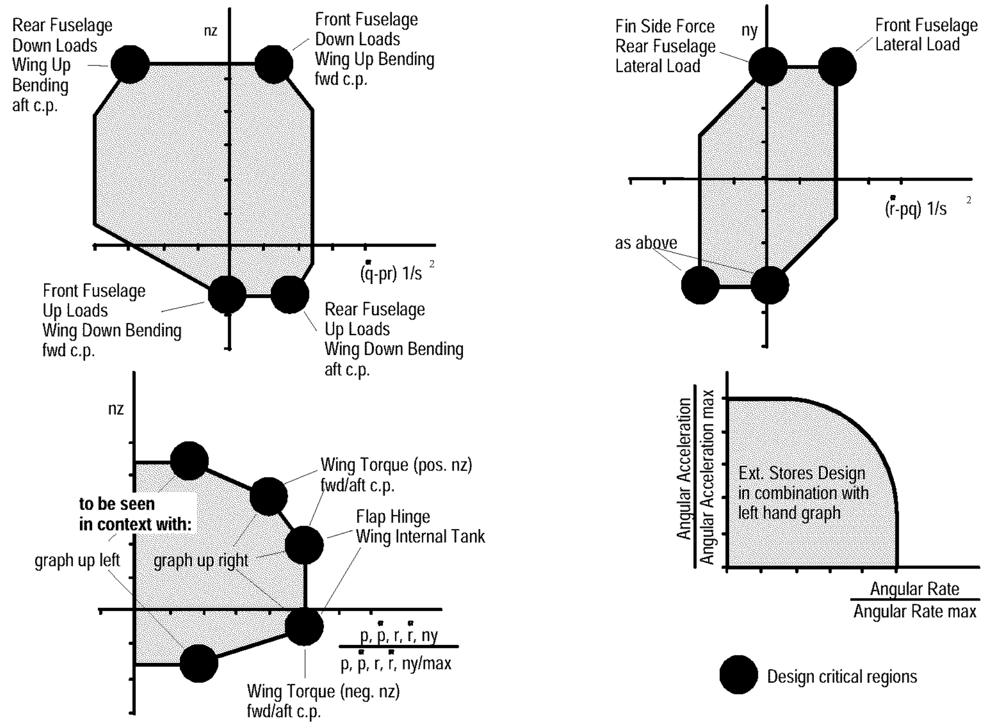


Fig. 1.2.3-2 Flight Parameter Envelopes for Structural Design

1.2.4 The Loads Model

The Loads Model is the central tool for running the "loads-business". It presents a model (on computer) of the total aircraft, integrating the physics of motion, the aerodynamic dataset, structural design criteria etc. and has interfaces to other disciplines, in detail:

A collection of all input data relevant for the calculation of (static) loads like
- Wind Tunnel and flight test aerodynamic data
- FEM-grid including stiffness matrix
- structural, systems and role equipment masses and mass distributions
- FCS program module (for simulation of flight load specific manoeuvres and landing cases)
- Aerodynamic surface grid

provides a computer program to determine loads and load-specific data like:
- Pressure distributions as a function of Mach number, incidence, control deflections on all surfaces
- Calculation of aeroelastic effects from the coupling of structural flexibility and loads (aerodynamic and inertia)
- Aerodynamic derivatives for total aircraft (used to simulate A/C motion) and aircraft component aerodynamics, harmonised with respect to flight test and wind tunnel data
- Manoeuvre response simulation and interface loads (at component monitor stations), calculation for preparation of component loads envelopes
- Landing gear model and landing simulations (flexible aircraft) with structural loads calculations
- Generation of external loads distributions along structure components axis
- Distribution of design loads on nodal points of the subsequent FEM for stress analysis

and makes available a data base of
- Flexible aerodynamics (components and total aircraft) for the complete Mach/Altitude regime
- Manoeuvre response and -load cases
- Nodal point distributions for design load cases

One of the focal points realised by the Loads Model is the fact, that all (design) load cases are calculated as balanced load cases, i.e. all conditions with respect to aerodynamics, mass distribution and flight manoeuvre match and provide the correct loads for each structure item for any load case. In other words, the sum of net[1)] forces and net moments at all monitoring sections of the structure must be zero:

$\Sigma_{x,y,z}$ F(x,y,z) ≡ 0 and $\Sigma_{x,y,z}$ M(x,y,z) ≡ 0

As mentioned above, such a complete Loads Model was not available for aircraft's developed in the '60 and '70.

1.2.5 Aircraft Component Loads and -Design Cases

Loads may be calculated in 3 degrees of refinement:

- Interface or component loads
- Load distribution*s*, e.g. bending moment along wing span, usually one dimensional
- Nodal point loads for Finite Element Analysis

The latter two are suitable to stress analysis and sizing of parts and are usually only applied to design load cases. Component loads, however, are used to find the design load cases, which usually are different for individual structure locations. Therefore the A/C structure is divided in components, with the boundaries representing main constructive items like interfaces, bulkheads, system attachments etc.
An example can be seen in Fig. 1.2.5-1, showing the aircraft components

- Wing
- Wing spoiler
- Front fuselage transport joint
- Fwd front fuselage
- Radom
- Rear fuselage transport joint
- Taileron
- Fin
- Rudder
- Airbrake

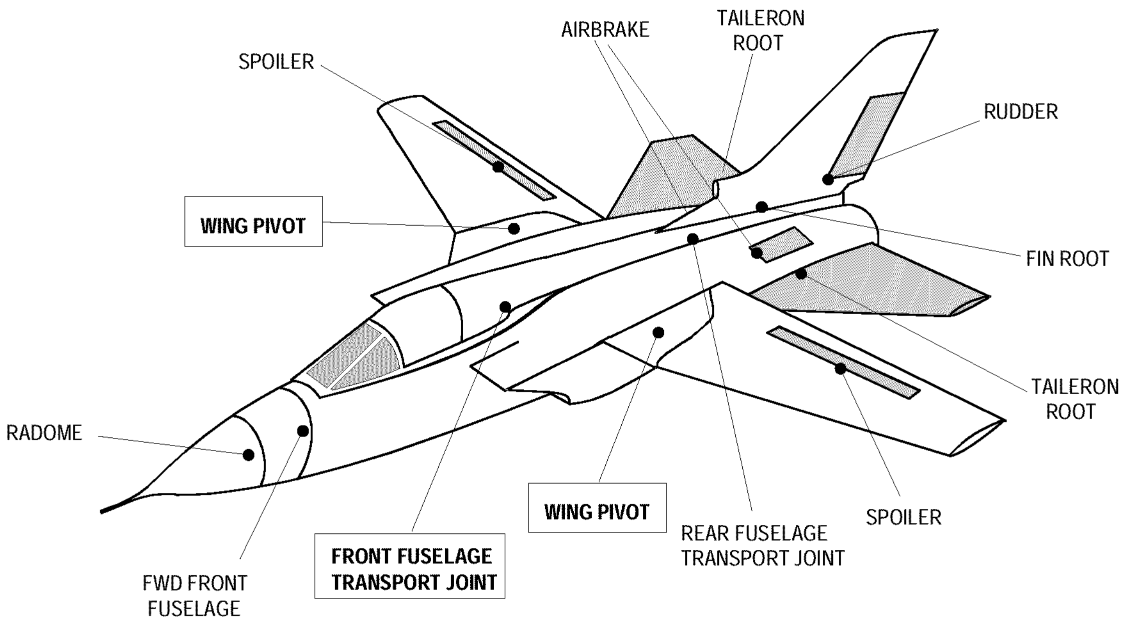


Fig. 1.2.5-1 Load Monitoring Stations

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1) net forces / loads = aerodynamic load + inertia load

The respective load monitoring stations are also shown in the figure, where probably the maximum loads are acting. For these stations the forces and moments are calculated for the whole variety of possibly critical manoeuvres (flight/landing conditions, aircraft configuration and mass etc. as parameters) resulting in at least one loads envelope for each monitor station.
Fig. 1.2.5-2 illustrates the concept of load envelopes for the front fuselage and the wing root. Indicated at the corner points of the envelope are the essential conditions, which lead to the design loadcases.

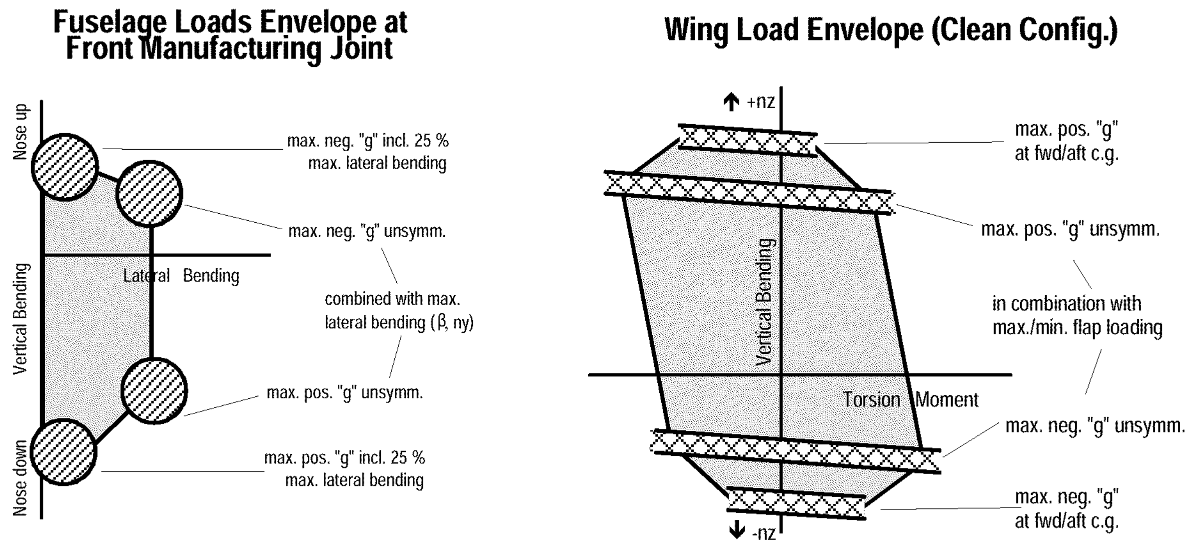


Fig. 1.2.5-2 Major Aircraft Component Loads Envelopes

As a first and in many cases correct approximation the design cases can be selected from the corner points of the different loads envelopes.
Usually there is a rather unique relation between corner points of a loads envelope and the flight parameters involved. Therefore considering modifications in the aircraft's role or changes in equipment, mass or performance it is often straightforward to draw conclusions with respect to component load changes and therefore to stress/fatigue implications. This aspect is discussed in chapter 2.

To illustrate the practical sequence of steps to be carried out in order to calculate a flight load at a certain structural component a typical procedure could be as follows, see also Fig. 1.2-1:

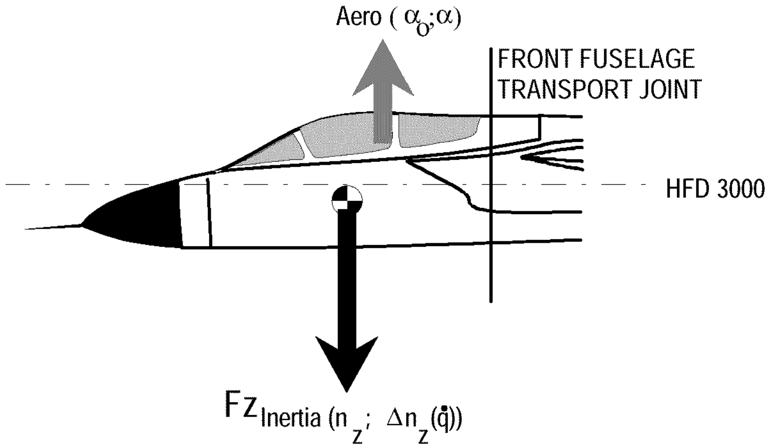
1 Define mass and c.g.
2 Define point in Mach-Altitude range
3 Define sort of manoeuvre (symmetric, roll man., combined man. etc.)
4 Simulate manoeuvre and calculate response parameters
5 Calculate external net loads (forces & moments) on component from aerodynamic pressures, inertia forces etc.
6 Convert external load distribution to nodal point loads on FE grid
7 Analyse structure and determine local stresses (e.g. NASTRAN)

1.3 Impact of Changes (Mass, Role, etc.) on Component Loads

Forces acting on an A/C caused by various effects:

Load	Dependant on (list not Complete)
Aerodynamic loads	Incidence, sideslip, control angles, Mach, Altitude etc.
Inertia loads	Nx, Ny, Nz, angular ratesand accelerations etc.
Engine thrust	Mach, Alt. Combat thrust, idle etc.
Internal loads e.g. cabin pressure	Specs, local accelerations
Actuator forces for Control surfaces	Hinge moment = f (Mach, Alt.)
Hydrostatic pressure	Local accelerations

The different kind of forces and moments contribute to the loads on the monitor stations in a different manner. The front fuselage up bending is clearly dominated by inertia loads, therefore an increase in the front fuselage mass will result in a higher front fuselage load, see Fig. 1.3-1



Max. down bending design loads

	Air	Inertia	Net	
Vertical Shear Force	100	-310	-210	%
Vertical Bending Moment	**100**	**-480**	**-380**	**%**

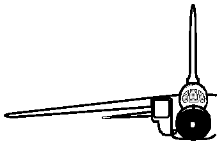
Conclusion: **An increasing Front Fuselage mass will lead to higher Front Fuselage loading.**

Fig. 1.3.-1 Front Fuselage Transport Joint Critical Load Conditions

This is not an fictitious case, Tornado front fuselage mass has increased over the years and so the current critical load is definitely higher (max 15 %) than calculated during design.

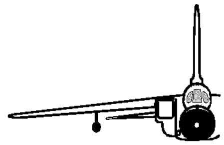
In a similar manner it can be seen that the rear fuselage monitor station is dominated by inertia loads for the vertical bending, but aerodynamic loading (mainly from the horizontal tail) increases the total load, in contrast to the front fuselage case.
Torque, which is neglectable for the front fuselage design, plays an important part for the rear fuselage and is almost entirely dominated by aerodynamic forces from the taileron (differential tail) and the fin (sideslip and rudder, horizontal gust), which may result in high loads during rapid roll manoeuvres.

Looking at the wing, it is clear that the wing bending is dominated by aerodynamic forces - the wing has mainly to carry the aircrafts weight - but substantial relief come from inertia forces as shown in Fig. 1.3-2.



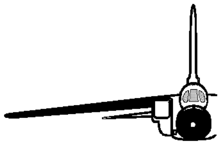
Clean Wing - dry (Design Condition)

	Air	Inertia	Net	
Normal Force	*100*	*-15*	*85*	%
Torsion	*100*	*-13*	*87*	%
Bending	***100***	***-13***	***87***	**%**



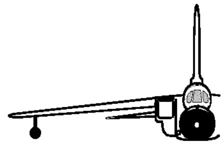
Clean Wing - dry + i/b store (350 kg)

	Air	Inertia	Net	
Normal Force	*100*	*-22*	*78*	%
Torsion	*100*	*-17*	*83*	%
Bending	***100***	***-17***	***83***	**%**



Clean Wing - wet

	Air	Inertia	Net	
Normal Force	*100*	*-24*	*76*	%
Torsion	*100*	*-19*	*81*	%
Bending	***100***	***-19***	***81***	**%**



Clean Wing - dry + o/b store (350 kg)

	Air	Inertia	Net	
Normal Force	*100*	*-22*	*78*	%
Torsion	*100*	*-23*	*77*	%
Bending	***100***	*-24*	***76***	**%**

Conclusion: **Adding mass to the wing (e.g. carriage of stores) leads to reduced wing loads.**

Fig. 1.3.-2 Influence of Wing Loading Contitions on Wing Loads

As indicated, for the Tornado the wing root bending moment is 11% less carrying outboard stores than for the clean wing without stores.
If the assumption for fatigue design includes the majority of missions, flown **with stores** on the outboard wing station, this does not correspond to reality and although the overall aircraft mass might be lower, a severe reduction in lifetime can be the result. This example highlight's, how changes in the usage and configuration affect lifetime and how this can be assessed by rather simple considerations.

The following case of the Tornado undercarriage also shows impact of how design loads were calculated and how usage assumed during design may be completely different from real life usage later:
When it became apparent that the number of starts and landings for a certain squadron was much higher than projected the conclusion was that the nominal lifetime of the squadron's aircraft was exhausted, at least with respect to the landing gear and the support structure. The question arose, whether lifetime could be prolonged and an investigation came to the following conclusions:

- Design of the landing gear was based on the assumption of dry runway conditions. Dry runway landing yields higher loads because of an high friction coefficient. But in reality dry runway landings occurred much less than expected, lifetime could be extended.
- At the same time takeoff and landing mass had increased relative to the design landing weight, causing a lifetime reduction.
- Assumptions during design that approximately 50% of all landings would be 3-point landings were completely unrealistic for this squadron. As only about 10% of all landings were identified to be 3-point landings, the nose landing gear could be expected to have a far longer lifetime than projected.
- Overall methods (e.g. MIL) often result in safe but unrealistic loads. A detailed analysis of landing simulations led to more accurate loads and therefore to a far better assessment of landing gear lifetime.

Considering all the a.m. points together sufficient life for projected usage of airframes for this squadron could be guaranteed.

1.4 Qualification of Loads, Static and Dynamic Tests

Static and dynamic loads critical for the structure are checked not only during the early stages of aircraft operational flight test but previously through ground tests as required by the certification procedures for the individual aircraft type.

The major milestones for ground testing are the ground resonance Test (GRT) to check dynamic structural response and confirm flutter margins established analytically to prevent flutter during initial flight tests, the "Major Airframe Static Test" (MAST) and the "Major Airframe Fatigue Test" (MAFT) for critical loadcases identified during structural analysis. The loads for both tests coincide with the loadset used during the development phase, a requirement critical for validation of analytical results.

One possibility to prove the correctness of loads itself can be done by wind tunnel measurements (pressure plotting wind tunnel model or component balances) and/or modern flight load survey. Flight load survey provides information from exact in-flight pressure measurements which, together with wind tunnel data, is fed back to the aerodynamic model of the aircraft and leads to an update of the Loads Model, including other reference data (masses etc.). Then critical load cases are recalculated and thereby confirm/update design load calculations. A typical layout of pressure measurement locations for flight test is shown on Fig. 1.4-1.

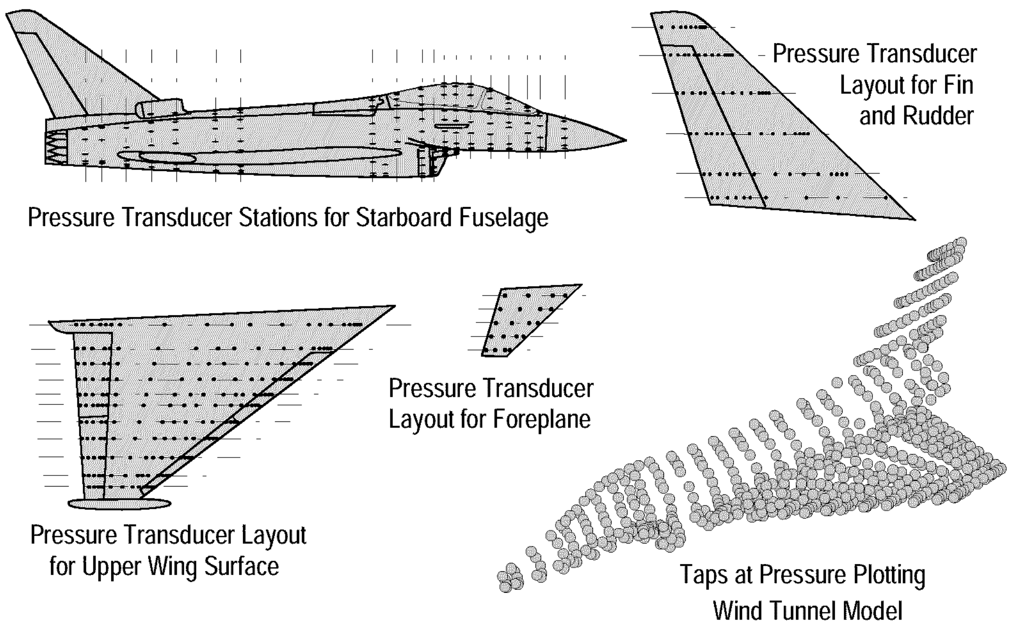


Fig. 1.4- 1 Prototype Pressure Plotting for Flight Load Survey

A further procedure to gather flight loads data is by measuring net loads with calibrated strain gauges on test aircraft's.

2. AIRCRAFT ANALYSIS USING STATIC LOADS AND FATIGUE LOADS SPECTRA

2.1 Static load conditions and fatigue spectrum generation

Safety of flight for any aircraft rely on the recognition that the structure must withstand maximum static loads as well as repeated loads in addition to a certain amount of manufacturing defects and in-service damage throughout the service life without detrimental degradation of the structure leading to catastrophic failure of components. The two major tools for achieving this are the engineering analysis in accordance with the Structural Design Requirements (SDR) and fleet inspection programs.

The SDR documented in the aircraft weapon systems specification are the background for the set of loadcases to be addressed during the sizing of the different aircraft components.

In general these loadsets can be divided into the following groups:

* Limit loadcases
  (relevant for fatigue design requirements)
* Ultimate loadcases
  (relevant for static strength requirements)
* Special loadcases
  (i.e. birdstrike, crash, weapon release, buffet, etc.)

The defined set of missions for the aircraft configuration is the base for the generation of static and fatigue loadcases, which the structure should withstand throughout its intended service usage under defined environmental conditions, demonstrated through engineering analysis in the development phase and proofed via full scale testing (static ultimate and fatigue) later. Typical static loads criteria for a "care free handling"-flight control system equipped aircraft are shown in Fig. 2.1-1.

STATIC LOADS DESIGN CRITERIA

- **Two Load Levels:** **Design Limit Load (DLL) = Max. Operational Load in Service**
  Design Ultimate Load (DLL) = Failure Load of Structural Components
- **Ultimate Load:** **1.4 x Limit Load**
  for all Loadcases controlled by FCS
- **Ultimate Load:** **1.5 x Limit Load**
  for all loadcases not controlled by FCS
  e.g. undercarriage cases, actuator loads, store attachments etc.
- **Requirements:** **No structural failure at DUL**
  No permanent deformation at DLL
  Buckling of panels must remain elastic at DLL
  No buckling at DUL for items where structural integrity is affected by stability
  No buckling up to 110% DLL for items where operational function is affected by stability

Fig. 2.1- 1 Static Loads Design Criteria for Airframes

The results of the calculations are documented in "Static Strength Reports" for each part and form the input during the flight envelope expansion phase from the structural side, the so-called "Strength Envelope".
Durability or fatigue criteria are extracted from the planned/defined mission profile and combined with the overall life requirements in term of flight hours (FH) and/or flights within a defined timeframe of service years. If several aircraft roles are defined in the specification, overall life is split into Flights/Mission, appropriate representation of fatigue critical conditions within the fatigue spectrum is essential.
Manoeuvre loads are covered by an "overall g-spectrum" for the prime aircraft missions, i.e. Air-to-Air or Air-to-Ground as "Points in the Sky" for a given Mach/Altitude level and A/C-Weight/Store-configuration. Excedance curves are then generated as shown in Fig. 2.1-2 for combat aircraft.

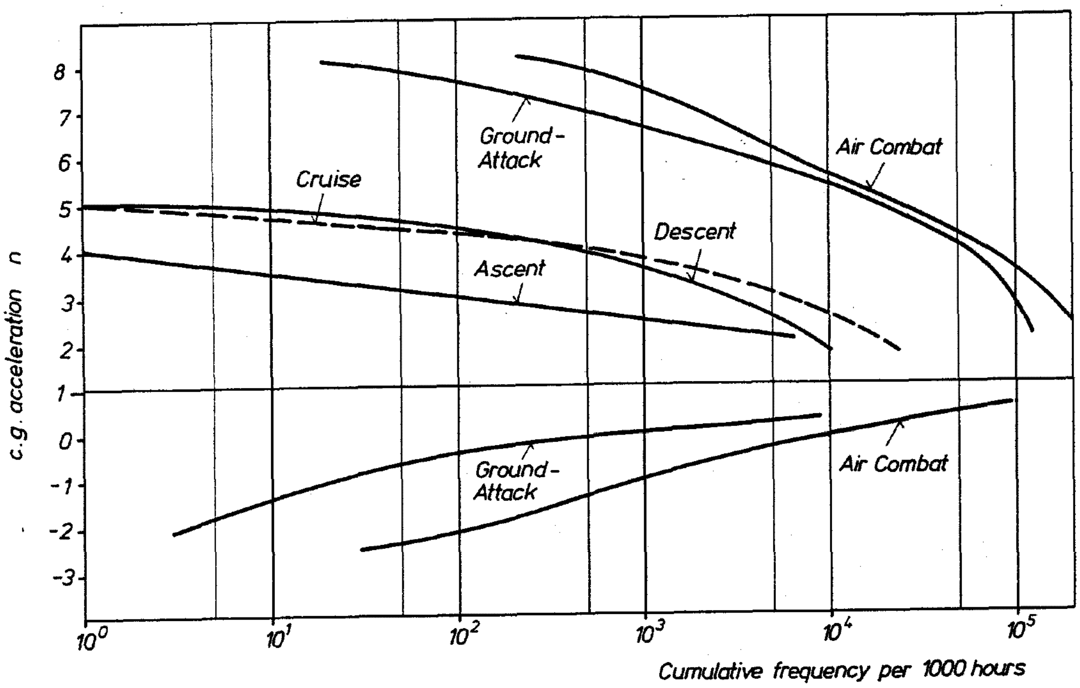


Fig. 2.1- 2 Typical Excedance Curves for Combat Aircraft

Special load spectra are needed for components like control surfaces, airbrakes, engine mounts, stores or landing gear.
For transport A/C cabin pressure cycles are an important factor for fuselage durability together with gust spectra.
The various loading spectra form the basis for the fatigue or fracture mechanics analysis depending on the design concept - *Safe Life* or *Damage Tolerance*- adopted.

2.2 Conversion of "external loads" into structural airframe loads

For the static and dynamic analysis of airframe structures a mathematical model of the aircraft is build using the Finite Element Analysis (FEA) -technique, representing the geometry and structural stiffness of the major items and providing the bases for generation of "internal" structural forces in components like bulkheads, longerons, skins, spars and ribs etc. as well as other important information like maximum deformation of parts under loads. The detailing of these FE-models depend on the different phases within the iterative process and has improved dramatically with computer performance and modern Pre- and Post-processing capabilities in recent years. "Global" coarse mesh models are used to analyse load paths in the overall structure of aircraft or large components. "Local" models in general are more detailed and they do simulate the special stiffness distribution like thickness changes, cut-outs etc. Structural trade-off studies with this techniques in all phases of airframe development are standard procedures for some years, computer based optimisation of major elements like skin thicknesses are used today in early design stages. A decrease of computer cost and processing time, and in parallel the improvement of model generation, linking the design software (i.e. CATIA) with the loads model output of FEA-nodal forces and the finite element solver through pre-processors, will continue this trend towards more detailed models, better (and more) pre/post-processing information but also increased number of loadcases and refined component loads as discussed in chapter 1.2.
Fig. 2.2-1 shows a typical "coarse mesh"-finite element model of a wing structure with wing box and flaps, where 40-50 "design loadcases" were identified from the loads database of 500 load conditions and used for subsequent strength analysis.

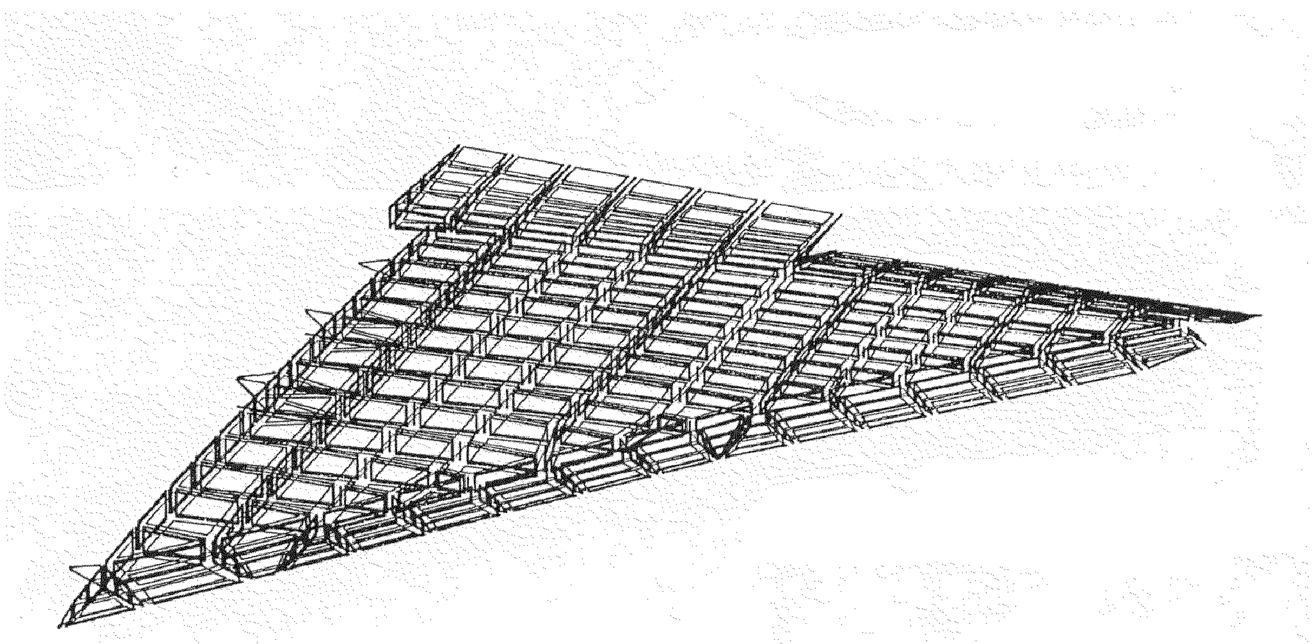


Fig. 2.2-1 Coarse Mesh FE-Model of Wing Structure

Fig. 2.2-2 shows a similar model of a center fuselage for a fighter aircraft, cut at Y0-station for symetrie.

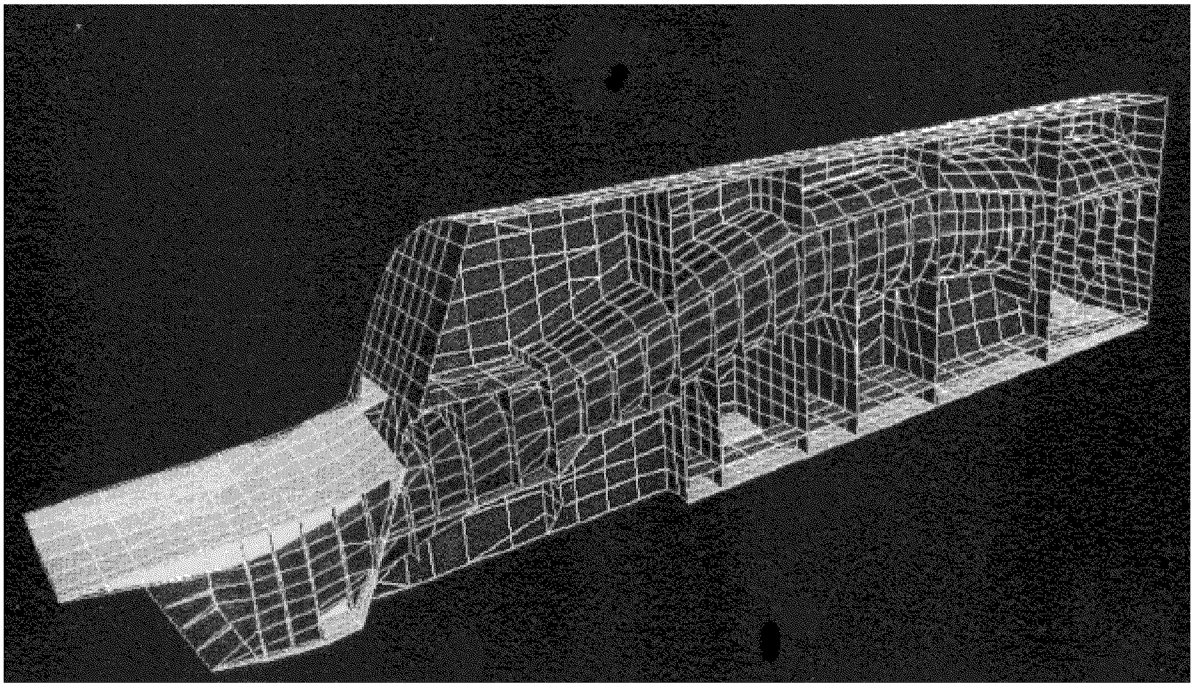


Fig. 2.2-2 FE-Half-Model of Center Fuselage Structure

The general trend in international programs towards development and production-workshare is mirrored in the global finite element model as well as through superelement techniques requiring detailed data transfer checks and- protocol requirements. The Eurofighter global model shown in Fig. 2.2-3 was generated by 5 European aircraft companies on different computer hardware and operating systems, therefore model compatibility and -quality checks were essential during the so-called "Check Stress Full A/C- Finite Element Model Static and Dynamic Assembly". The overall model size is about 35000 elements and more than 580 loadcases after superposition. After the unified analysis the results were transferred back to each company for further processing and structural analysis.

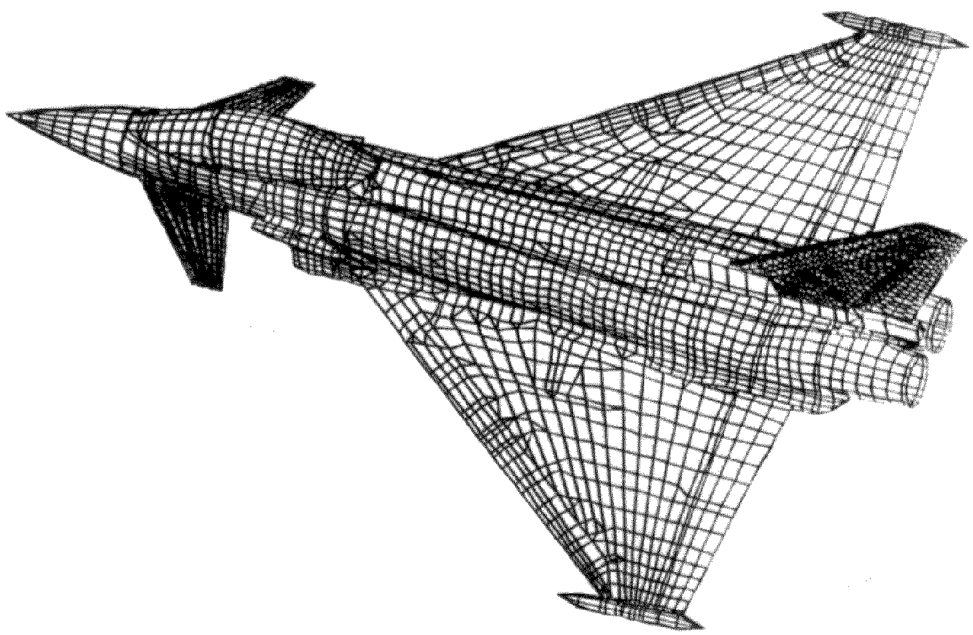


Fig. 2.2-3 EF2000 Global Model for Unified Analysis

To further detail the loads in components and individual parts for actual sizing of the structural members, a "cut-out" of the global model with the exact bondary conditions applied to the “edges” of the component of interest from the results of the global model is possible and often used for detail investigations like effects of local cut-outs, reinforcements, stability checks, etc.
Fig. 2.2-4A and 2.2-4B shows an example of this technique for a center fuselage bulkhead.

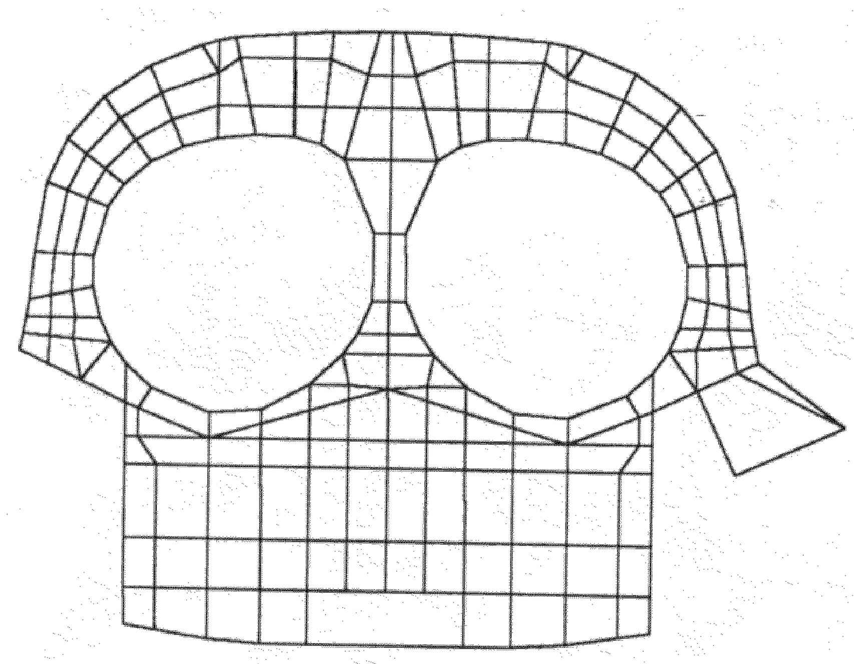


Fig. 2.2-4A   Coarse Mesh FE-Model of Cemter Fuselage Frame

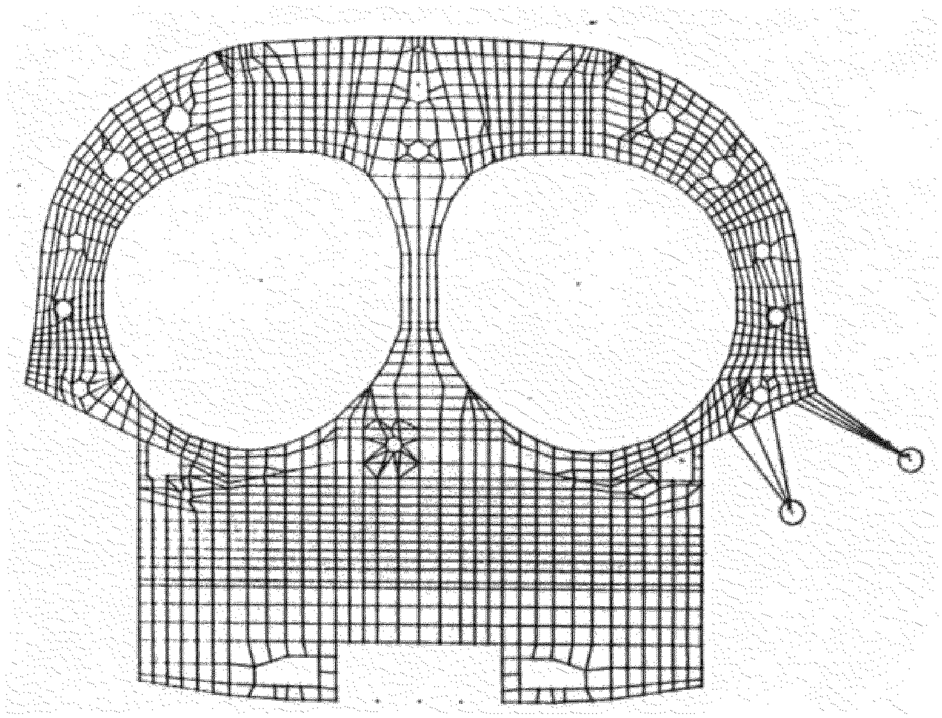


Fig. 2.2-4B   Fine Mesh FE-Model for Detail Analysis

The results of these detailed model technique provide the background for strength analysis of static ultimate loads as well as fatigue loadcases in accordance with the allowable for the materials used and the geometric effects in the design.