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STRUCTURE DESIGN CONCEPTS FOR THE NEXT GENERATION SUPERSONIC TRANSPORT

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Abstract

Aerospatiale, British Aerospace and Daimler-Benz Aerospace Airbus are closely co-operating on studies aiming the development of a second generation Supersonic Commercial Transport (SCT). Realisation of such an aircraft will be very demanding from a technical point of view, as today's standard is not sufficient to guarantee total aircraft viability of a future SCT. However, significant progress in structure technologies, such as new materials combined with innovative design concepts, more effective manufacturing processes, and advanced analytical methods along with high performance computers indicate a large potential for improvement.

Results of studies performed so far indicate that technical goals are achievable. SCT material-usage will take advantage of recent advancement of metallic and composite technology. Compared with Concorde-standard, main components of a future SCT could be some 30% lighter. Though, in-depth structural justification is necessary to validate data and increase prediction-accuracy. Meanwhile, material, structures and related processing techniques need to be thoroughly tested and analysed to prove their long-term performance under SCT condition, reliability and economic performance. Minimizing development risks is the key to transform the SCT-project into an economically viable program.

1 Introduction

The challenge facing a manufacturer of a second generation supersonic transport is to produce an aircraft which is viable for the passenger, the operator and the manufacturer, while being environmentally acceptable [GRE]. To be successful in developing a future SCT, significant technology advances are necessary. Aerospatiale, British Aerospace and Daimler-Benz Aerospace have addressed this challenge and started in April 1994 a trilateral co-operation with following objectives:

- Close co-ordination to form a unified European Position on a second generation SCT,
- Close co-ordination to obtain political /financial support,
- Co-operation in technical and technological preparation of a SCT of the second generation.

The following paper is focusing on the structural aspects related to SCT-development presenting the results of the joint work performed so far by the three companies to establish a preliminary airframe structural design.

The next Chapter provides an overview of the way of working within this trilateral co-operation, i.e. the general process leading to major structural choices. Chapter 3 'Structures and Materials Challenge', deals with some essential aspects related to SCT-development. The purpose is to outline how different and challenging the structural design of a new generation supersonic transport will be compared to conventional subsonic aircraft, and meanwhile to highlight the need for technology-improvement compared to today's standard. Technology aspects will be then discussed in Chapter 4 .

Chapter 'Airframe Structure Concepts' is finally focusing on the design- and structural analysis-loops. Starting with the definition of an overall airframe architecture, also taking into account a possible material distribution and global Aircraft behaviour, the paper presents selected results from design trade-studies performed so far:

- MLG-Integration
- Wing-Box Structural Design
- Power-Plant Integration

2 Way of Working

Airbus Industries (AI) has played in the past a 'Referee Role', sharing the tasks to be performed by the AI-partners, also settling the key reference-points for the definition. The technical work

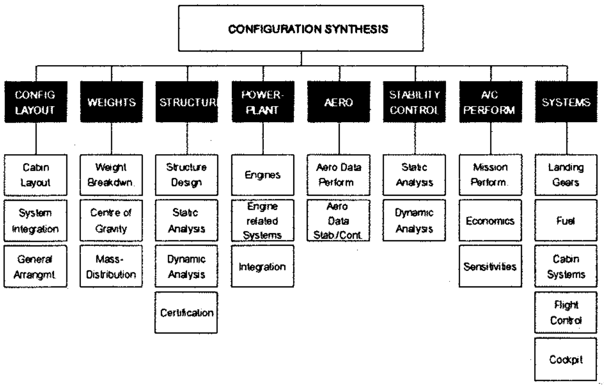

Figure 1 Trilateral Technical Working Groups

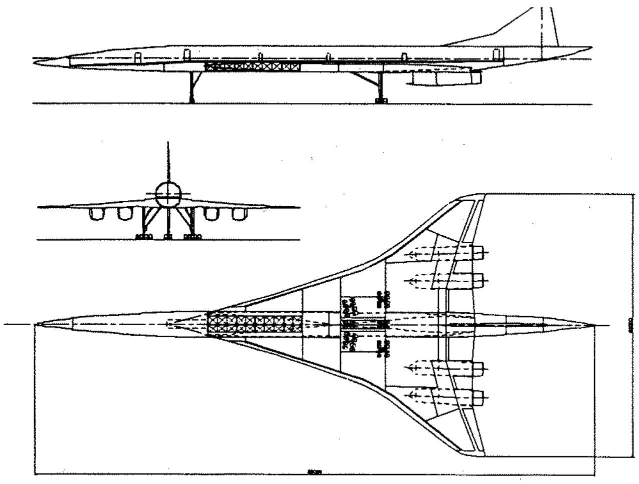

Figure 2 SCT General Arrangement

aiming the definition of the future Supersonic aeroplane is concurrently performed by the three companies: This approach involves a new way of working, taking into account the necessity for a multi-disciplinary approach [VRT]. The purpose of the new way of work is:

- to use resources distributed in the three companies in a more efficient manner,
- to avoid duplication of work
- to accelerate solution finding process.

The basic difference compared to the 'usual' approach is, that the work is not distributed within the different companies according to a pre-defined work-sharing, but within several cross-company teams (CCT), each one dealing with one major field related to aircraft development such as Structures, Aerodynamics or Stability and Control (Figure 1). Each one of the three companies is represented in each CCT.

CCT's are responsible for the tasks to be performed in their own domain; they have to find the best way to work (e.g. work independently, co-located teams, task-sharing) according to time-scales, resources and/or specific skills available in each company. An important task is also the assessment of the level of detail to be achieved, in order to guarantee the flexibility of design for future improvements.

3 Structures and Materials Challenge

Table 1 Main Aircraft Parameters

	SCT	Concorde	A340-200
Design Range	**9900 km**	6580 km	13'700 km
Passenger Load	**252**	100	263
MTOW	**340 t**	185 t	257 t
Overall Length	**89 m**	62.1 m	59.4 m
Fuselage Ø	**≅ 4 m**	2.9-3.3 m	5.64 m
Wing Area	**836 m²**	358 m²	362 m²

3.1 Design Driver's

Three main Aircraft design-parameters are strongly dependend on the airframe structural design and the related technology-level:

- Weight,
- Manufacturing Costs,
- In-Service (Maintenance) Costs.

In the past designer's have focused their efforts on reducing a/c weight and increasing structural efficiency. Currently, severe market and economic requirements are the main drivers behind subsonic aircraft design. Today's trend is to design for costs and analyse for weight, that means to reduce manufacturing- and maintenance-costs, whilst accepting slight weight penalties relative to the minimum weight solution [BRE,DAV].

Situation is more complex in designing SCT-structures, because the aircraft is both very demanding in terms of structural efficiency and highly cost-sensitive. The key to develop a viable productc, i.e. which will be profitable for both manufacturer and airliners, will be to find the optimum balance between structural performance and costs.

3.2 Basic Design Considerations

Analysis of aircraft project data and the general arrangement (Figure 2) highlight some essential aspects related to SCT-aircraft structural design:

- Structural weight hast an extremely high influence on MTOW (Figure 3). It is not only a question of converting weight into more fuel or payload. Weight saving affects overall aircraft design, allowing resizing of airframe and engines and mission-fuel decrease.
- Aircraft-size and -complexity significantly increase compared to conventional subsonic structures (see Table 1).
- SCT will be considerably more flexible compared to subsonic aircraft. Aeroelasticity will have an important influence on aerodynamic performance and structural efficiency.

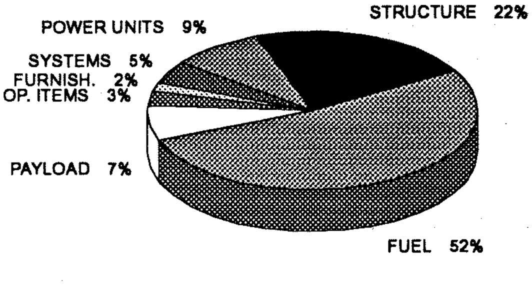

Figure 3 SCT-Weight Breakdown

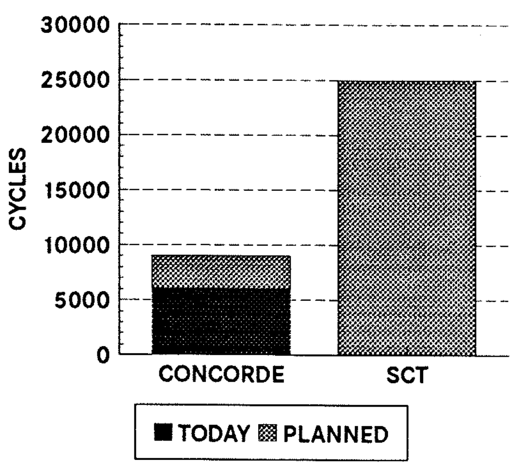

Figure 4 Design-Life Requirements

- Thin aerodynamic foils and slender fuselage are reducing available volume for MLG and other systems.
- Maintenance- and repair-procedures are expected to be much more demanding, due to the difficulty in providing the same degree of accessibility.

3.3 Operating Conditions

SCT-operating conditions, i.e. severe long-term thermal and environmental exposure, combined with static and fatigue-loading, require advanced materials and innovative design solutions to minimise the related weight-penalties. Durability and effectiveness of material and structures necessitate therefore careful investigation. Main requirements resulting from the SCT-operating conditions are summarised as follow:

- High Altitude Operations. Cabin Pressure differential is 25% higher compared to conventional subsonic aircraft.
- Design-Life:

  ⇒ 25'000 Cycles
  ⇒ 80'000-100'000 Hours
  ⇒ > 20 Years

  Each Concorde aircraft has presently accomplished between 4'000 and 6'800 cycles [DOY, SWA]. Current airframe life is defined as 6'700 cycles, which represent less than 30% of the economic design-cycles of the future SCT (Figure 4). Design-life requirements will also exacerbate certification of the aircraft, due to the difficulty in accelerating full-scale verification-tests under SCT-conditions.

- Temperature:

  ⇒ -50°-120 °C (M2.4: 160°) for the main structure.
  ⇒ Thermal cycling under moisture/radiation impact.
  ⇒ 60'000 Supersonic flight hours

  Thermomechanical effects are an additional concern, especially in areas showing high temperature gradient, e.g. wing-fuselage are, or by combination of materials with different coefficient of thermal expansion [USU]. Structural loading results from the superposition of mechanical and thermal stress. In addition, high temperature and changes in material properties over the service-life affect design allowables.

- High productivity/Utilisation:

  ⇒ Twice as many seat-miles per year are imperative compared to competing subsonic aircraft.
  ⇒ high dispatch reliability, along with an economic service-life of over 20 years.

4 Materials and Technologies

4.1 Structures and Materials within the ESRP

'Structures and Materials' is a major domain within the European Supersonic Research Programme [ESRP]. Main objective herein is the development, characterisation and validation of materials, design procedures, structural concepts and manufacturing technologies for application to economically viable SCT-structures. Metallic and non-metallic materials are basically conceivable for SCT applications, showing at the same time potential for structural weight reduction. Yet specific materials have to be developed to fulfil the challenges described in Chapter 3.

Aerospatiale, British Aerospace and Daimler-Benz Aerospace Airbus have started in 1995 a joint screening programme, encompassing Al-Alloys and composites materials. The objective is to characterise materials under SCT-conditions, to gain valuable data to establish models and laws to predict material behaviour and to develop accelerated procedures for material testing.

4.2 Aluminium

Aluminium has been widely used in commercial supersonic aircraft up to Mach 2.2 (Concorde, TU144). Basic trend for increasing Al- performance, is focusing on the development of new alloy-types along with more efficient manufacturing and joining techniques such as welding, brazing and extrusion. Compared to today's standard overall weight benefit up to 15% can be expected in the future. Material performance of aluminium, along with resistance to crack propagation and corrosion, fracture toughness, rapidly decrease between 100° and 200°C.

Advanced Al-alloys with improved temperature behaviour are under development. Major risks are related to the difficulties in estimating influence of material degradation on final weight. On the other hand a well-directed use of advanced Al-structures, e.g. welded or extruded panels made of new Al-alloys could perform a great contribution in reducing costs and certification concerns.

4.3 Titanium

Titanium is very attractive for its outstanding mechanical properties, but improvements are required for some material characteristics and to reduce manufacturing costs. Many efforts have been undertaken for better manufacturability; look for instance at the SPF/DB process. Utilisation of Titanium in conventional aircraft is limited to about 4%. In a future SCT, Ti-weight part could consistently increase. Possible applications are in strength designed areas, such as complex 3D-loaded parts and highly loaded components within composite structures.

4.4 Organic Composites

Fibre reinforced composites and particularly carbon fibre reinforced plastics (CFRP) have been used for years in primary structures of Airbus aircraft, replacing more and more Aluminium. State of the art in commercial aircraft production is the use of high tenacity (HT) carbon fibres with.epoxy-resins. Presently about 15% of the aircraft structures are made of composites, with an average weight reduction of about 20% compared to aluminium. The proportion of composite structural weight in the SCT could dramatically increase to meet stringent weight requirements. Various development programs have demonstrated the technical feasibility of both wing- and fuselage composites-structures. Drawback of composite technology, is that low design-values and manufacturing constraints do not fully allow the advantage of the outstanding material properties to be used. More economic processes such as RTM and pultrusion are under development, targeting the reduction of hand procedures and higher reliability in product manufacture. Thermoplastic technology has not found yet a large application, because of the costly raw materials and the problems related to the high process-temperatures.

Today's opinion is, that Intermediate Modulus Carbon fibre represent a good compromise between performance and costs. As far as the matrix-system is concerned, high temperature toughened Epoxy-resins, Bismaleinimides (BMI), cyanates and thermoplastics (PEEK) have been selected for screening tests on durability and environmental resistance.

According to generic requirements, possible area of application have been identified for the different material families (Figure 5).

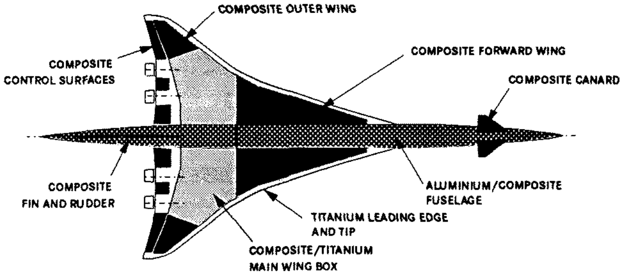

Figure 5 Possible Material Usage

5 Airframe Structure Concepts

5.1 Aircraft Structural Architecture

A preliminary airframe structural architecture is shown in Figure 6. Related structural concepts for aerodynamic foils and fuselage have been established following 'design philosophy' presented in Table 2.

Load-carrying structures can basically be designed in monolithic or sandwich constructional form. Sandwich structures are very promising for their elevated weight-reduction potential. Disadvantages are the critical moisture ingestion, the poor damage tolerance and the substantial problems in designing joining, fittings, inspection-holes and other particular regions.

Design criteria need particular attention: Tension failure mode takes full advantage of the outstanding properties of advanced materials. Unfortunately, according to studies published by NASA, large portions of the SCT-aircraft are low loaded area, governed by stiffness, stability and minimum gauge design criteria [NASA]. Panels-size, -layout and material-choice must therefore be optimised, to achieve a well-balanced load-level in the different structural elements, thus minimise weight.

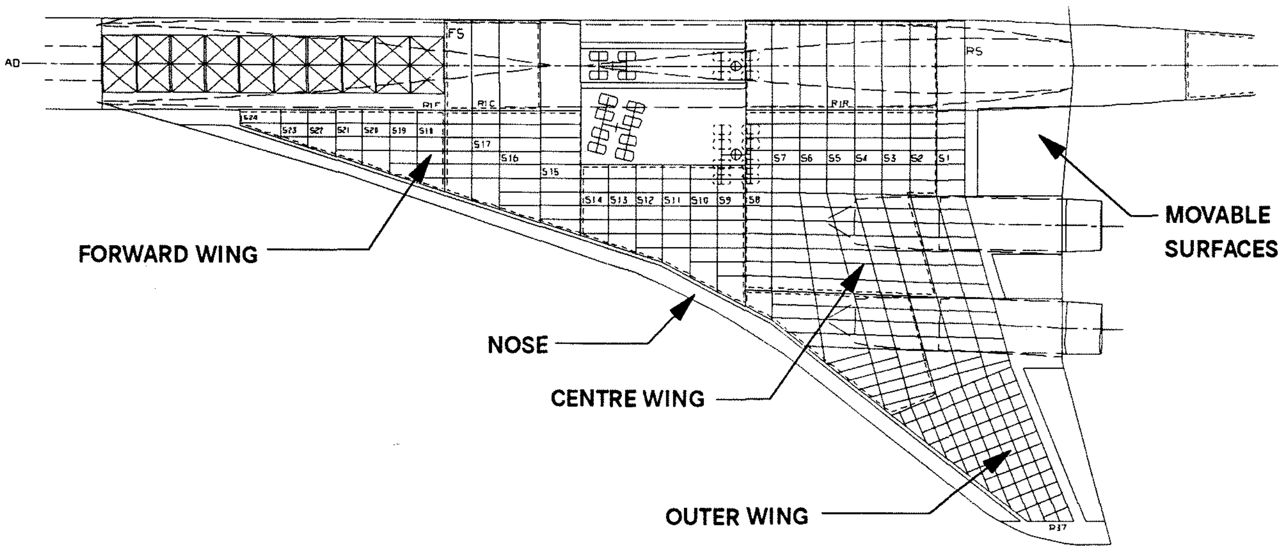

Figure 6 SCT Wing Structural Architecture

Table 2 Design Philosophy

Material	Extensive use of composite materials for better structural efficiency. Aluminium where cost and certification concerns are predominant. Titanium for highly loaded parts.
Concepts	Mainly monolithic design. Load-carrying panels of different types Damage Tolerant (fail-safe) design.
Joints	Discrete, Quasi continuos, continuous joints between main sections according to specific design criteria
Production Aspects	Structure split will take into account maximum-size for transportability Cost effective manufacturing of subcomponents Adequate access for assembly and Inspection

5.1.1 Wing

Wing geometry is characterised by a very large surface and a thin thickness to chord ratio. Structural layout presents five regions according to different design criteria.

The very extended wing/fuselage interface (over 40 m) presents a variety of interesting design aspects:

- Thermo-mechanical effects, resulting from different temperatures in fuselage and wing,
- large concentrated forces caused by wing loads, MLG and engines,
- beneficial influence of the wing structure on the fuselage longitudinal stiffness,
- fuselage underfloor and centre wing are occupied by large systems (MLG, fuel tanks and luggage-stowage),
- weight penalties associated with the extended cut-outs and the long load-path necessary for load-transfer

Centre Wing

To ensure a well balanced load-transfer, a carry-through box consisting of six to eight Ti-heavy-spars, -ribs and upper and lower Ti- or CFRP-wing skin run across the fuselage in front and aft of the main landing gear compartment. Spars, ribs and fuselage frames act together to minimise deflections induced by wing-bending and react and redistribute the high load resulting from the main landing gear and engines. The combination of titanium and composites is well proven under corroding environment. The Coefficient of Thermal Expansion (CTE) mismatch between CFRP and Ti is not affecting structural design in this area for a Mach 2.0 configuration. Blade-stiffened upper and lower panels are favoured for manufacturing/cost reasons. Main wing design is seeking an orthogonally arrangement of spars and ribs with square or quasi-square skin panels.

Outer Wing

The Outer- is a full-composite structures. This flutter critical part requires a stiffness design with closely spaced ribs and spars. Latest are running parallel to the rear wing-contour.

Forward Wing

Forward wing is a low loaded area. Composite-sandwich with different cores represent here an interesting alternative to conventional panels to increase mechanical stability.

Thermo-mechanical loads and fuel-tank requirements are major design criteria in designing the forward wing attachment to the pressurised fuselage. A continuous attachment would require a long cruciform beam to tie the wing-skin to the fuselage-skin. Alternatively only wing spars could be directly connected to the fuselage frames at each station or possibly every two or three stations.

Wing-Nose -Tip and Movable Surfaces

Wing-nose and -tip are SPF/DB-titanium sandwich with extruded Ti-leading edge.

Movable surfaces consist of composites sandwich with honeycomb-core.

5.1.2 Fuselage

The fuselage has a very high degree of slenderness with a nearly constant cylindrical cross-section and an unpressurized nose and tail cone. Structural approach is conventional consisting of a monocoque structure with T-, Z-stiffened skin. Window-panels and other main cut-outs are reinforced with titanium frames. Orbital shear junctions could be used to join Fuselage sections.

Material selection for the fuselage will consider following aspects:

- Weight reduction potential of composites is limited by specific design criteria, airworthiness requirements and constraints resulting from complexity of detail design.
- Certification of a full-composite fuselage.
- Lack of experience in conventional aircraft.

5.2 Global Aircraft Behaviour

5.2.1 Problem Description

The overall geometry of the proposed aircraft creates significant structural design problems as the aerodynamic performance is achieved using a large thin wing and a long slender fuselage. Two engines are mounted aft on each wing and the large undercarriage bay also complicate the wing structure. Furthermore the temperature differential between the wing skin inside and outside the fuselage may induce significant thermal stresses.

To summarise, the design of the wing is influenced by the following structural features or loads:

- Aerodynamic loading
- Size and position of the MLG-bay
- Wing-fuselage attachment
- Discrete load inputs at engine nacelles
- Discrete load inputs at undercarriage and control surface attachments
- Thermal stresses due to the different temperature distribution in the wing and fuselage

The aircraft has a long slender parallel fuselage which is subjected to greater cabin pressure than a subsonic aircraft due to the higher operating altitude.

5.2.2 Approach

To assess the overall aircraft behaviour in terms of strength and stiffness, it is necessary to construct a global finite element model of the structure and analyse with suitable load cases. The finite element model provides the ability to:

- Optimise the design for minimum weight - one of the main design parameters.
- Determine the global deflections of wing and fuselage.
- Determine the major load paths in the structure
- Assess the effect of varying the material properties of major components such as skins or spars.

For tri-lateral co-operation to work effectively it was necessary to jointly agree an overall structural layout. For finite element modelling and preliminary sizing purposes the proposed aircraft structure was divided between the partners. To assist the exchange of data between the partners and to avoid duplication of work it was agreed to use a common analysis code (MSC/NASTRAN) and CAD-System (CV CADDS5).

To enable a meaningful analysis to be performed and to achieve consistency a set of typical load cases are required covering the whole aircraft. Ideally both ground and flight static cases should be considered:

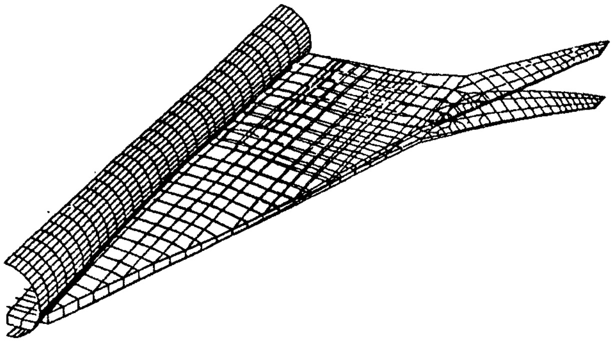

Figure 7 Deflected Shape of Wing Centre Fuselage

- Flight Cases using aerodynamic data for a limited number of Mach numbers M=0.5, 0.9, 2.2
  - ⇒ Pitch manoeuvres +2.5g and -1g at MTOW and MLW
  - ⇒ Rolling manoeuvre, critical for wing/fuselage joint
  - ⇒ Yawing manoeuvre and engine failure, critical for fin and lateral fuselage design
  - ⇒ Gust, both vertical and lateral
- Ground Cases
  - ⇒ Dynamic landing, critical for forward fuselage
  - ⇒ Turn, braked roll, towing pushing case
- Additional cases
  - ⇒ Cabin pressure case
  - ⇒ Thermal climb, cruise and descent data applied to appropriate flight cases.

Figure 7 shows a deflected wing plot from an analysis performed during earlier studies, which gives an indication of the large wing deflection (Weight=327904 kg, Alpha=3.92°, M=0.953, N=1.0g with inertia relief). Similar large deflections were found for the rear fuselage.

5.3 Results from Performed Trade Studies

5.3.1 Main Wing Box Structural Design

To design the main wing box structure with an acceptable stiffness will require a multi spar and rib construction. Regarding the materials to be used for the different structural elements, e.g. spars, ribs and skin-panels, reference configuration is based on a hybrid wing-box consisting of CFRP blade stiffened panels with a Titanium sub-structure. Alternatively, a welded Titanium structure could represent a viable solution if:

- Ti-price would decrease
- Welding technology would reach the high level of performance required.

Welded Titanium Structure

A major benefit of a welded wing box compared to a conventional design is that, this construction would dispense thousands of bolt-holes, resulting in reduced crack-initiation, sealing concerns and also saving costs for drilling and assembling (Figure 8).

Wing box skin is constructed with panels welded from a patch work of titanium sheets. Welded joints need then to be

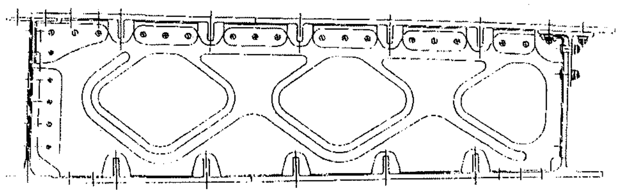

Figure 8 Welded Titanium Wing Box

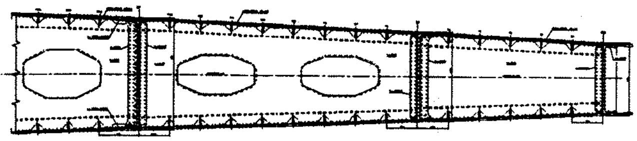

Figure 9 Hybrid Centre Wing-Box Cross-Section

machined to suppress notches resulting from the electron beam or laser usage. Following specific design rules, it is possible to replace bolted assemblies by butt-welded joints and to eliminate most overlaps. Fittings-attachments and spar-webs can also be integrated to the skin panels.

Hybrid Wing-Box

System wing-box reflects the arrangement shown in Figure 6. Upper and lower CFRP-skin-panels are one-shot-bonding parts with precured blade stiffeners. Titanium spars are U-shaped milled or forged elements with integral stiffeners, which are used for the spar-to-rib joint on one side of the rib. On the opposite side the spar-to-rib joint is designed with L-shaped connecting angles. Ribs are exact in contour and splitted from spar to spar. They are designed as L-shaped sheet-metal, L- or I-shaped milling parts (Figure 9).

Assembly of the different sub-components is done by conventional riveting (Hi-looks resp. blind rivets where accessibility is not given). The degree of a later applicable automation depends on production numbers and rates.

5.3.2 Main Landing Gear

Design and integration of main landing gear is very complex, embracing the main fields related to aircraft development. Specific problems are:

- MLG with increased size and complexity to fulfil SCT-requirements.
- Stowage concerns, due to the reduced volume in fuselage and wing.
- Structural penalties are expected, due to big MLG-bay compartment.
- Belly-fairing leads to aerodynamic penalties.

Main task is to integrate MLG minimising drag-penalties and structural disturbances. Investigations have been carried-on in concert with specialists from systems, aerodynamics and configuration. A large number of different alternatives have been set-up and implemented in the actual configuration by help of 3D-simulations (Figure 10).

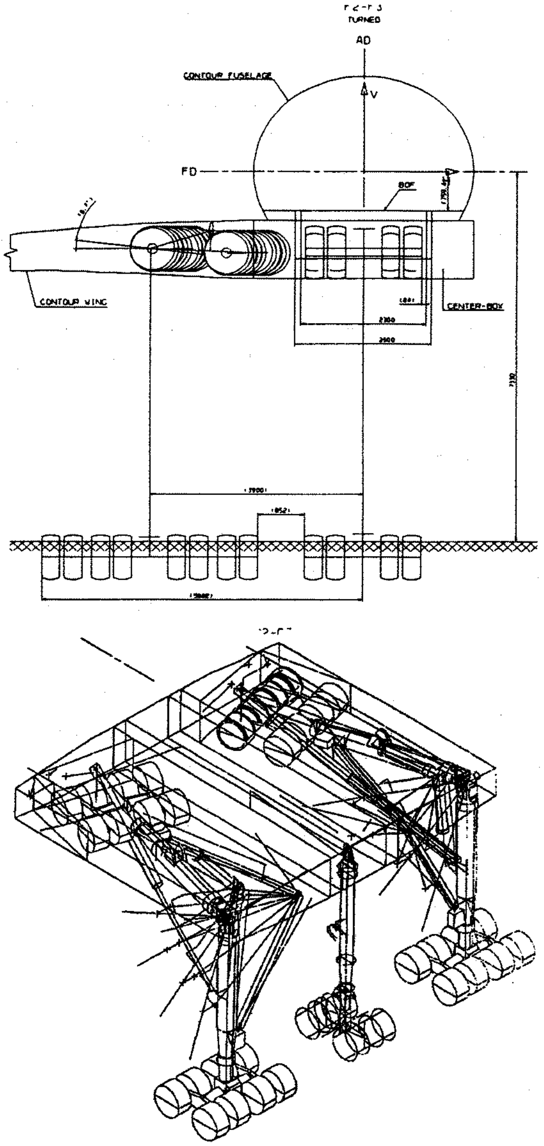

Figure 10 MLG-Arrangements

5.3.3 Powerplant-Integration

Integration of the SCT-powerplant- is a further challenge for the designer, involving a multi-disciplinary approach. Structure design only represents one aspect of the entire exercise.

Main target is to define minimum space-envelope to integrate engines and related equipment, considering that our envelope will have to meet the aerodynamic requirements, i.e. minimum drag for maximum effectiveness during supersonic flight. As we have seen in Chapter 'Global Aircraft Behaviour' wing flexibility will induce an unusual capacity of the nacelle boundary to match the lower skin of the wing, thus minimising clearances. Furthermore MLG-length will have to take into account supplementary provision, and may need an extra clearance for the engine.

The structural attachment may require supplementary structures to „hang“ the engines, according to the engine concept selected. The Airbus pylon-attachment, i.e. static determined attachment to the pylon, may be converted in a new way of distributing the loads, with non independent Air-Intake, Engine and Nozzle.

The uncontained rotor burst requirements will lead the designers to investigate new fields of structural design applied to powerplant-integration.

Current studies are focusing on two engine Types:

- Mid tandem Fan,
- Ejector-mixer nozzle engine.

For a mid tandem fan engine, the challenge will be to achieve the most effective nacelle aerodynamic design, as air-intake-, engine- and nozzle-contour are not the same, resulting in a blended nacelle-surface. Equipment's will be located as close as possible to the engine, taking into account minimum ventilation flow required and system segregation criteria.

For an ejector-mixer nozzle engine, the external contour of the air-intake is similar to the nozzle-contour. The current nozzle is a 2D-design. In this case it is logical to suit the external shape to minimise the blended area. Equipment's could be distributed to the four corners. On the other hand the length available for the installation will be shorter.

6 Conclusion

To meet overall objectives, SCT-airframe design requires both structural weight reduction and lower costs. Critical development-issues regard the severe operational and design-life requirements along with the time necessary for technology selection and validation.

Preliminary results indicate that technical goals are achievable. SCT material-usage will take advantage of recent advancement of metallic and composite technology. Compared with Concorde-standard, main components of a future SCT could be some 30% lighter. Investigations have shown a further potential for weight reduction, employing more aggressive structural concepts.

In-depth structural justifications are necessary, to validate data and increase prediction-accuracy. Meanwhile, material, structures and the related processing techniques need to be thoroughly tested and analysed to prove their long-term performance under SCT condition, reliability and economic performance. Minimizing development risks is the key to transform the SCT-project into an economical ly viable program.

Cost prediction is a complex issue, due to the difficulty in providing reliable data at this early stage of investigation. However, indications are that SCT-structures could be produced at acceptable cost-level..

Due to the high carry-over opportunities a Mach 2 aircraft could take advantage of the cost efficiency attained in subsonic aircraft production, having on the other hand a beneficial influence in future development of conventional aircraft.

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