DESIGN AND ANALYSIS OF A CFRP INTEGRALLY STIFFENED MAIN UNDERCARRIAGE DOOR

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ABSTRACT

The objective of the development for the monolithic CFRP-Main Landing Gear Door (MLGD) by German Ministry of Defence and DASA was to produce CFRP-MLGD's for longterm inservice testing on German AirForce (GAF) TORNADOS to build up expertise for the second generation CFRP-materials for future A/C-components. The CFRP-MLGD is a monolithic design wih an internal spar/stringer structure covered by inner and outer skin.
All structural elements are made of NARMCO 5245C/T800 prepreg-material. The combination of a hot-forming process with direct lay-up procedures and a one-shot curing process for the assembly of preformed elements demonstrate a reliable production process for complex shaped monolithic CFRP-structures. To fulfill the airworthiness requirements the test program considered static and dynamic loads at elevated temperatures and structural moisture equilibrium. The full-scale tests include controlled impact damages to demonstate an adequate damage tolerance behavior designed into the monolithic CFRP-structure. The paper covers the design approach, analysis procedure and airworthiness testing of the CFRP-MLGD, as well as first results from inservice experience at the GAF.

1.0 INTRODUCTION

The continous increase in composite structures for modern aircraft design, both civil and military aircraft, resulted in various development programs to evaluate design-, manufacturing-,test- and inservice-technologies for the industrie, the airworthiness authorities and the aircraft user. An important part of these programs is to exchange components of a limited number of aircrafts already in service with new high-performance materials and design concepts to study their behavior under normal operating conditions over a longer period.

This task was acomplished by design, manufacturing and certifcation of the CFRP - Main Landing Gear Door (MLGD, Ref. 1. The TORNADO, a multipurpose military A/C operational in several european countries and within the German Airforce and Navy was used in this program as a testbed.

The program was funded by the German Ministry of Defence and Deutsche Aerospace DASA. The structural testing was performed by IABG under a seperate contract.

Structural doors and covers as well as horizontal and vertical stabilizers have often been attractive components for technology programs because of their interchangebility, easy access and limited complexity.

The well known design conditions for the aircraft, possible adjustments in production technique due to a limited number of parts, a requirement for a non-restricted airworthiness certification and most important, the chance to gain experience with advanced structural materials and concepts within a normal A/C operating environment are some advantages.

The CFRP-MLGD-program introduced the first component with a fully monolithic design using advanced composite material to enter service into the GAF, Fig. 1.

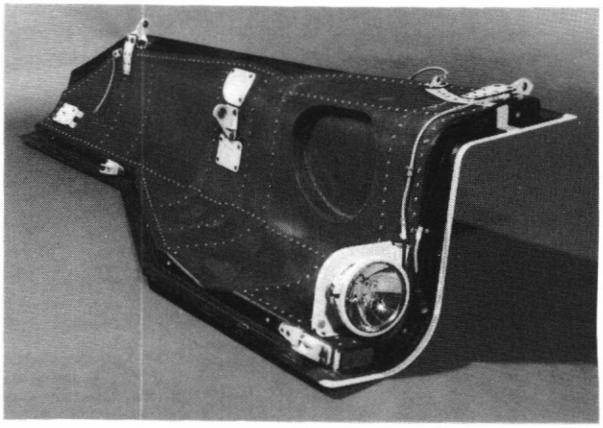

Fig. 1 Main Landing Gear Door

Its structural design-concept is also consequently realized on the new European Fighter Aircraft EF2000 for major components like fuselage, vertical stabilizer and wing structure.
The CFRP-MLGD-program allows the GAF and the industry to build up inservice experience with this type of monolithic structure to ease future introduction of other A/C were up to 35% of the structural weight is composite material.
Therefore the CFRP-MLGD-program does apply the design rules, production procedures and quality assurance requirements of the EF2000 program while at the same time complying to TORNADO airworthiness requirements to receive unrestricted clearance for the TORNADO flight- and operation--envelope.
To receive maximum experience from the program the development contract asked for a primary structure certification procedure, although the conventional MLGD is classified as secondary structure.

The production of 11 LeftHand-MLGD and their distribution to 3 different Airforce- and Navy-Squadrons ensures inservice experience from different environmental conditions, flight envelopes and typical ground handling conditions.

2.0 STRUCTURAL DESIGN

Unlike other aircrafts of this type the TORNADO features a single MLGD hinged at the lower outside fuselage section from FS X9107 to FS X11182. The overall length is about 2,1m (6,3ft), the width 0,6m (1,8ft) and the total weight approx. 21kg (47lbs), Fig.1.

The door is actuated by a single hydraulic actuator positioned approx. at the door center at FS X10030.

The advantage of this design is a simple mechanismen for operating the door, using one actuator,two hinges and two locking positions only; but the geometry of the part is rather complex to follow the fuselage loft in this area and since the complete door stays open during flight, areodynamic doorloads are significant. Additionally, interface lines that must match the fuselage loft are extremly long for a single, line-replaceble item. Since trimming and geometric rework is very limited due to the contour, close tolerance tooling and manufacturing procedures are important.

GFRP fabric skin material bonded to a full-depth Aluminium honeycomb core and Aluminium attachments, bolted through the structure was selected for the original component, a composite design typical for the early 1970th.

2.1 General Design Considerations

The new design considered the experience gathered from previous development programs with monolithic structures made from unidirectional prepreg tapes, using a concept were stiffners are cocured to the skin thus avoiding bolted joints between skin and substructure on the aerodynamic surface, a "Integrally Stiffened Design", Fig.2.

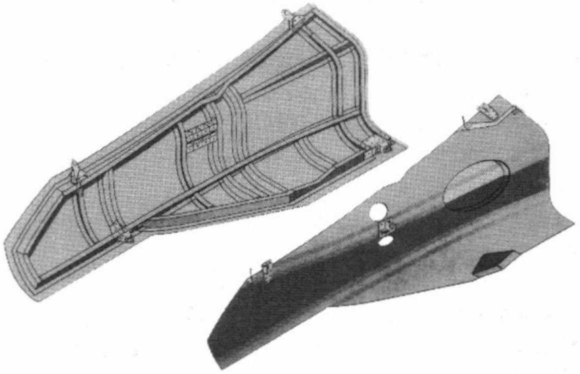

Fig. 2 Integrally Stiffened Design of the MLGD

The structural concept started with a spar/stringer reinforced outer skin where all attachments were bolted on and the complete structure was accessible when the MLGD was open.

Structural analysis soon indicated that this "Open Design" would not fulfill the stiffness requirements unter operation loads and that increased torsioal stiffness was mandatory, therefore the second "inner" skin provided a "Closed Box Design" with much better structural behavior and less weight but also more complex manufacturing and less accessible inspection- and repair- areas, once assembled.

The final design showed four J-stringers running in flight direction, and nine spars almost perpendicular to them, acting as the inner structure with the outer skin cocured and the inner skin bolted to the stringer/spar flanges, Fig.3.

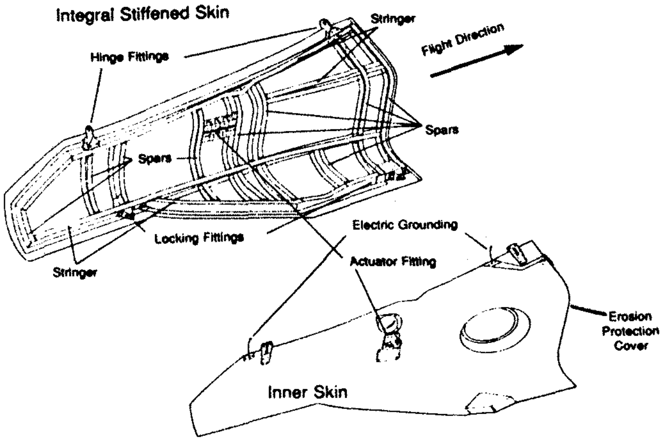

Fig. 3 Structural Reinforcement Concept

Stringer No.I and III running the full length of the door and together with the skins act as a primary bending beam along the hingeline while stringer No.IV supports the lower contour and the forward locking device.
The spars are placed to support contour and overall torsional stiffness, define skin panels and distribute local loads from attachment fittings, Fig.3.
They feature the same basic J-type design as the stringers, but the extreme radii in some areas required adjusted web layups and segmentation, Fig.4.

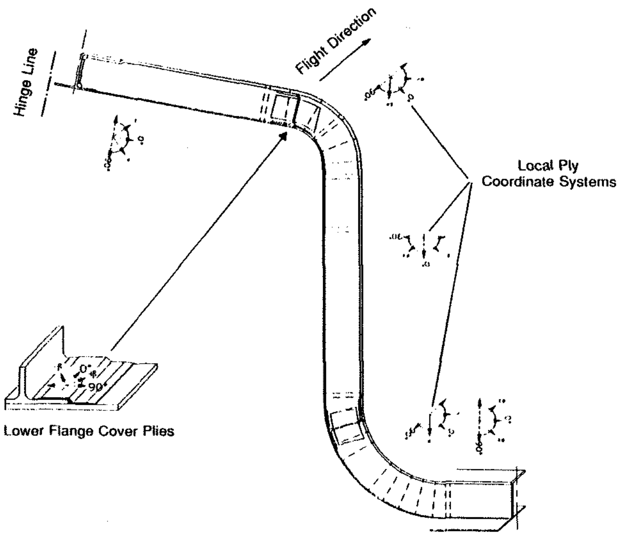

Fig. 4 Typical Spar Layup and Ply-Segmentation

The inner skin provides access holes close to the actuator attachment bracket and a MLG-wheel cutout between the spars No.2 and 4.
For a replaceble part all interfaces to the A/C-structur like hinge-positions, actuator attachments and locking devices had to remain unchanged and the door sealing area had to consider original loft data in order to avoid steps between fuselage skin panels and MLGD-skin, which are always prone to erosion damage during low level, high speed flights.

2.2 Design Details

Using the prepreg material in unidirectional tape form allowed the design engineer to adjust the layup and thickness in every section and made the drastic contour changes, starting as a Z-contour up front and ending up as a semicircle with constant loft changes in between, Fig.5, possible.

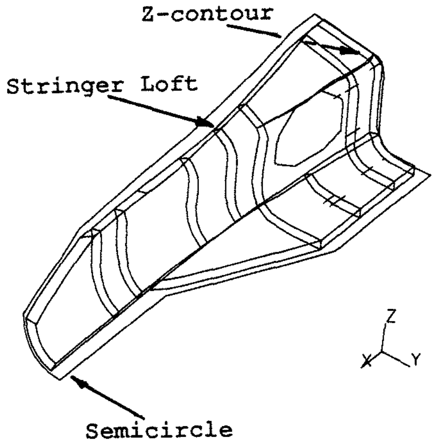

Fig. 5 A/C-Loft in the MLGD-Area

It also ensured laminate layups in accordance with the stiffness and strength requirements without applying material in directions not necessary, common when using fabric material.

A good example is the J-type stiffner, shown in Fig. 6, where the flanges are carrying most of the bending load and are therefore reinforced by 0-Degr.Plies, while the web consists of +/-45-Degr.-Plies only to carry shearloads.

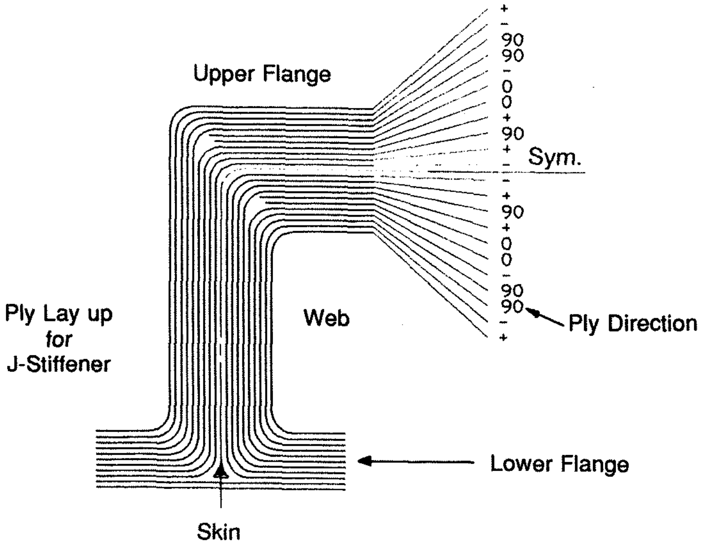

Fig. 6 Typical Layup of the J-Stiffner

For erosion and lightning strike protection the leading edge is reinforced by an Aluminium protection strip over its entire length and is electrically connected to the A/C fuselage. In addition the complete outer surface is covered by a copper mesh cured onto the first skin ply during production, Fig.3. Working with 3-Dim. design models like CATIA was essential for design-, manufacturing- and structural analysis engineers to transfer the geometric data from the design database to their manufacturing- and analysis-models and to determine local geometric effects.

2.3 Material

The complete composite structure consisted of NARMCO 5245C/T800 prepreg material, a bismaleimide modified epoxy with an intermediate modulus fibre, approx. 60% nominal fibre content and 0.125mm/per ply-thickness. The thermoset material is used in a unidirectional prepreg form, cured at 175°C (350°F), postcured at 190°C (375°C). The material is qualified for primary structure within the EF2000-Program.

Engineering material properties are shown in Fig. 7.

Property		RT	100°C/WET	
Tension Modulus	0	162000	162000	MPa
Compr. Modulus	0	145000	145000	MPa
Tension Strength	0	2700	2300	MPa
Compr. Strength	0	1650	1400	MPa
Tension Strain	0	1,67	1,42	%
Compr. Strain	0	1,14	0,97	%
Tension Modulus	90	9200	8000	MPa
Compr. Modulus	90	9500	9000	MPa
Tension Strength	90	55	45	MPa
Compr. Strength	90	225	165	MPa
Shear Modulus	45	5000	2600	MPa
Shear Strength	45	135	95	MPa
Interlaminar Shear Strength	0	100	80	MPa

Fig. 7 Engineering Material Properties

Application of identical incoming inspection procedures, material handling specification and Non Destructive Inspection (NDI) requirements as for the EF2000-Program was a main objective of the program to demonstrate consistancy of manufacturing techniques for production.

The improved material data and a more sophisticated design and analysis procedure lead to an overall component weight reduction for the CFRP-MLGD of 25%.

3.0 ANALYSIS PROCEDURE

3.1 Global Modelling

Strucural analysis of the MLGD was performed using a detailed Finite Element Model (FEM) in NASTRAN, that was generated on the geometric database from the design group.
Transfer of the CATIA model into the NASTRAN Data Deck used the IDEAS PREPROCESSOR software to generate all necessary input information like grid-geometry, element type and properties and material data, Fig. 8.

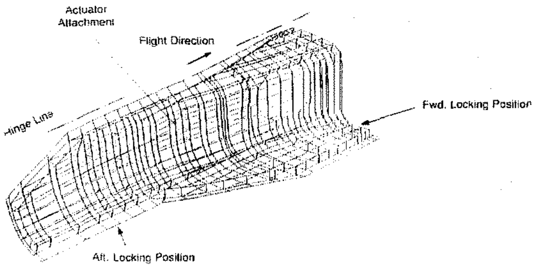

Fig. 8 FEM-Model for Structural Analysis

Both skins and the shear webs of spars and stringers were idealized using 2-dimensional elements (SHELL) with orthotropic material properties, bending elements (BAR) for stiffner flanges and RIGID ELEMENTS for the attachment fittings with their own local coordinate systems. This technique allowed the analysis of loadcases in both "opened" and "closed door"-position during a single FE-run. Global and Local deformation, reaction loads, skin element strains and stresses for each element were derived from the FE-run and postprocessed using the IDEAS POSTPROCESSOR.

3.2 External Loads

From the TORNADO A/C-flight envelope the critical loadcases were selected and analysed with regard of aerodynamic pressure loads, system operation loads and system malfunction cases. All loadcases were identical to the original MLGD component.

In general 3 different categories of loadsets were evaluated:

- Door closed, normal flight/maneuver envelope
- Door operating, restricted speed envelope
- Door open and holding, restricted speed envelope

Fig. 9 shows MLGD hingemoments for various door positions.

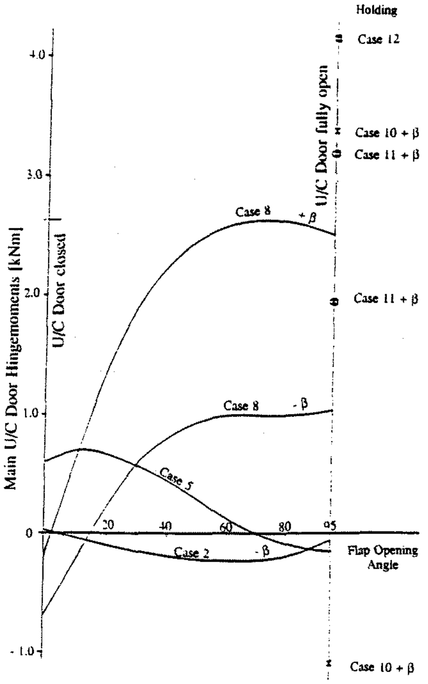

Fig. 9 MLGD-Hingemoments

Also considered were 3 design conditions with jamming of door locking mechanismen and the actuator trying to open the door. These loadcases were considered as normal static conditions without time limitation. A summary of the critical Design Loadcases are listed in Fig 10.

Loadcase No.	Door Position	Actuator Load	Locking Pos.		v	
			X9263	X10556		
1	0°	21465N	-	-	M 1.2	Operating
2	0°	-28430N	X	0	250kts	Failure
3	0°	-28430N	0	X	250kts	Failure
4	0°	-28430N	X	X	250kts	Failure
5	95°	22000N	-	-	280kts	Operating

X: Locking Device Blocked
0: Locking Device Open

Fig. 10 MLDG-Design Loadcases

3.3 Design Criteria

Design Criteria followed the requirements for structural CFRP-components made from NARMCO 5245C/T800 for the EF2000 program and adjustments incorporated for the TORNADO A/C-system.
The most important criteria are:

- Complete structure designed using statistical "B-Values". Safety factor j=1,5 for limit load (all LC)
- Design for max. operational temperature 100°C (212°F)/humidity saturated at 85%/70°C(185°F), all LC
- Design of unnotched areas against max. Strain Criteria in fibre direction at UDL:
  $\varepsilon=+5500\mu$ tension
  $-\varepsilon=-4200\mu$ compression
- Orthotropic laminate design with equal No. of plies in +/-45°,direction, using a nominal 0/+-45/90 degree layup.
- Min. of 3 ply-directions in any major laminate loading direction.
- Max. of 4 plies stacked together in the same direction
- Design of bolted joints using elastic stress concentration theorie for loaded holes in laminates and single ply failure analysis, no laminate failure allowed at ultimate load.
- Buckling of skin laminates allowed at limit load for thicknesses < 3 mm (0.118 in).
- No buckling of laminates for thicknesses >3mm at ultimate load.

3.4 Analysis Results

Analysis of the FEM runs provided the database for component stress layouts and stability analysis of inner and outer skin panels. The general procedure for the analysis is shown in a flow chart form, Fig.11.

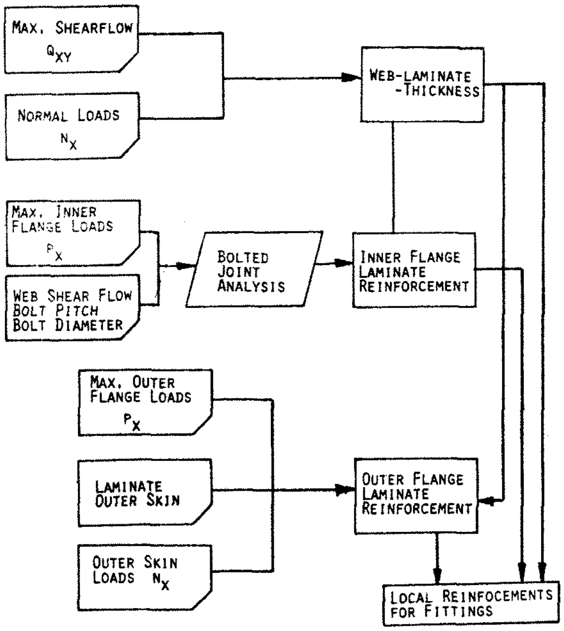

Fig. 11 Flow Chart for Analysis Procedure

Since laminats for individual areas of a component have to match with other areas (i.e. plies of the flange laminate of a spar or stringer are also found in the web), changes in layup and thickness and therefore strength can be achieved only when considering the design, strength and manufacturing requirements of the neighbour-area at the same time too. In practice, when changing the stringer flange laminates due to the bolted joints with the inner skin, the web laminate and even the lower flange of the stringer changes too, requiring additional strength checks afterwards.
This is one major difference compared to metal design concepts, where these parts are made from isotropic material and the local thickness is the only design variable.
Due to the component size and its single actuation concept the deformation in the closed and opened positions are a major design driver for stiffness, requiring a redesign during the early predesign phase when switching from an open stiffened-skin to a stiffer closed-box design concept.

Maximum elastic deformation in a closed position are shown in Fig. 12 and for the most critical loadcase in the opened position in Fig.13.

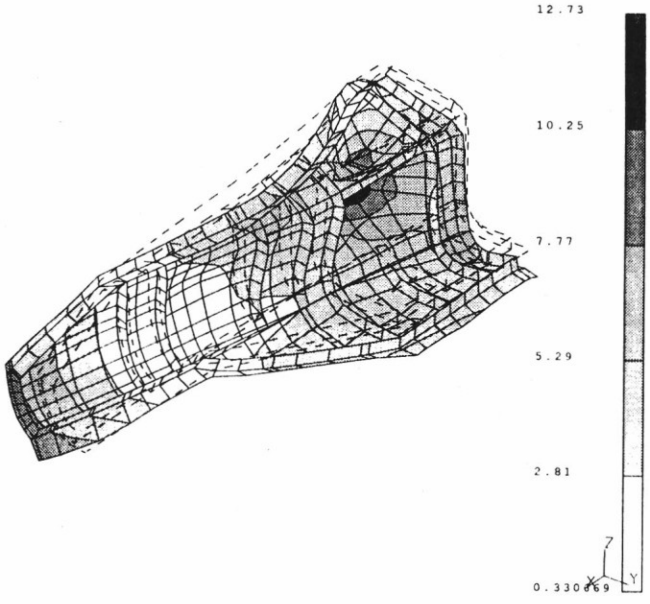

Fig. 12 Elastic Deformation, Closed Position

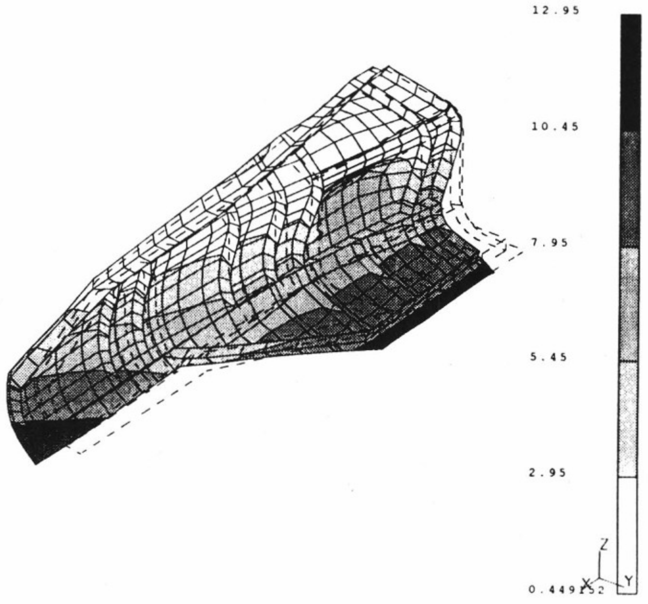

Fig. 13 Elastic Deformation, Opened Position

Contour plots are used for the visualisation of the skin loading in typical loadcases, as shown in Fig. 14.

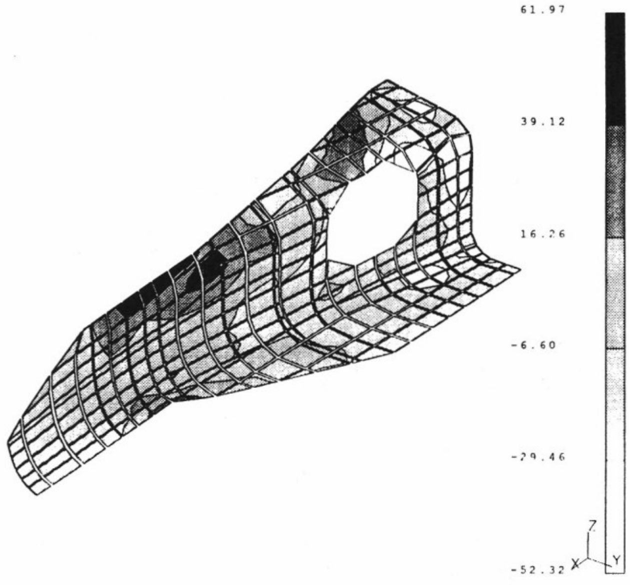

Fig. 14 Inner Skin Load

These plots are then used to run the local strain-limited analysis for the local layups and the panel buckling analysis, taking the curvature of the laminate into account.
The basis layup for the skin is then reinforced to provide local bearing strength for the bolted joints to the inner structure and the attachment-fittings.

Typical shear load distribution for the inner stucture is shown in Fig. 15 for Spar No. 2 as an envelope plot, designing the web, inner cap and lower flange are then reinforced with primarily 0-degree plies.

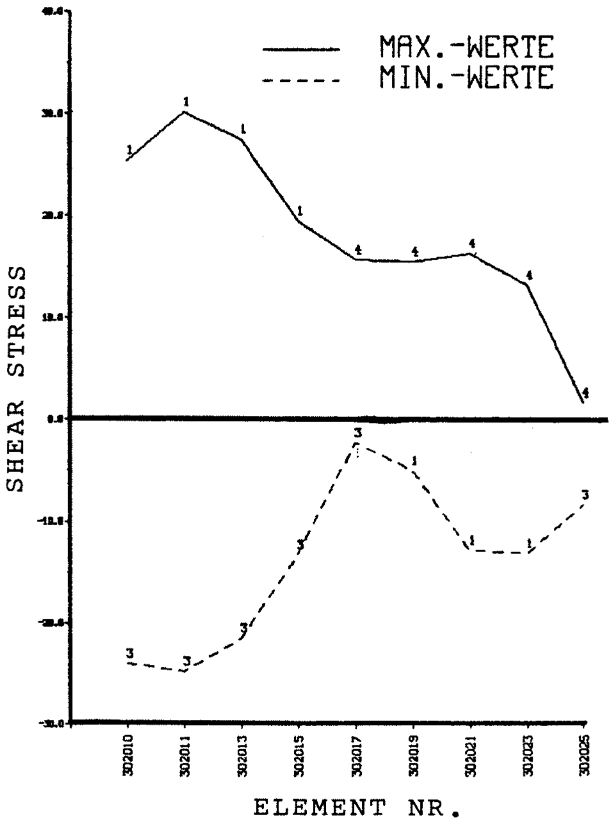

Fig. 15 Shear Load of Spar No. 2

Load introduction brackets for hinges and actuator are analysed using conventional techniques for envelope loadcases, usually dominated by the failure cases, Fig.11.

4.0 Certification Approach

The certification approach for this long-term experimental program was tailored to the program needs in two major aspects:

- The test phase was carried out on service A/C in different squadrons
- The approach was identical to the requirements for a primary composite structure

The general goal was to receive unrestricted operational clearance for the complete A/C service life with respect to:

- Function and loads
- Environmental conditions
- Erosion and corrosion behavior
- Inspection and damage tolerance
- Repair

A qualifiation program was established to cover the strength requirements for three component conditions:

- Component manufactured i.a.w. QA-specs, no damage
- Component with artifical impact damage
- Component with artifical damage and repair

and the following spectra:

- Static condition j=1.0 all loadcases
  j=1,5 most critical loadcase
- Fatigue loading 4000 Flight Hours (Scatter factor 4)
- Residual strength loadcase j=1,2

for all component conditions.

The functional requirements were validated using the original production master-gauge and check-installations on service A/C including gear-retraction cycles and original gap-requirements.

Installation for the CFRP-component must be possible using the original specification.

5.0 Structural Test Program

The full-scale testprogram was performed at the IABG-testcenter, Ref. 2, and included the following phases:

I. Static test at 100°C(212°F)/WET with impact damage
   - all design loadcases to limit load (j=1,0)
   - most critical Loadcase to ult. Load (j=1,5)
   - most critical Loadcase to failure

   The "WET"-condition for the component was defined as saturation of the laminate at 85% relative humidity and 85°C (185°F) temperature.

II. Fatigue test of a representative spectrum equivalent to 4000 flight hours with a scatter factor of 4.
   This spectrum included load cycles in the opened and closed position, thermal load cycles and vibration loads,Fig. 16.

vibration loads,Fig. 16.

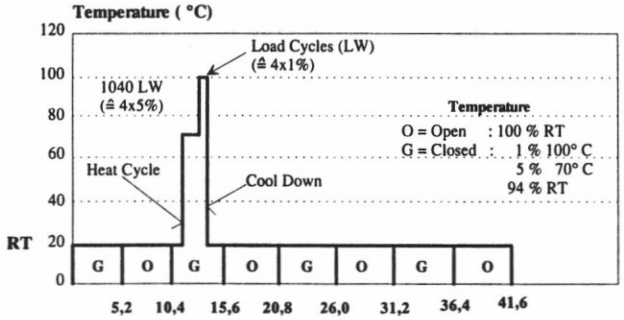

Fig. 16 Thermal and Mechanical Load Cycling

The test-rig allowed application of loads in both, opened and closed position with the original A/C-hingeline simulated by dummy fittings and original bolts, Fig.17.

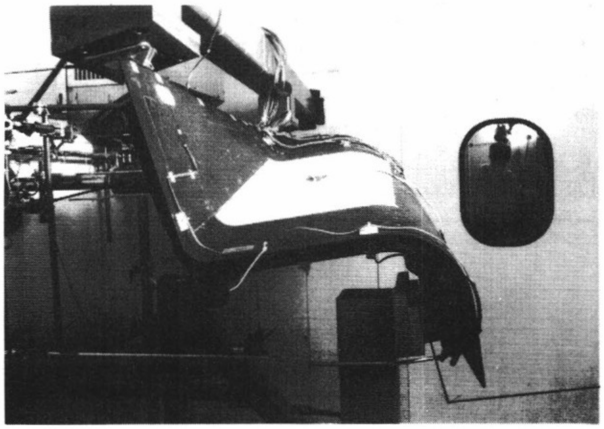

Fig. 17 Test Rig Setup

Test temperatur of 100°C(212°F) was applied by two 15KW heaters, additional heated humidifiers were used to balance redrying effects of the moisture saturated components during test duration. Loading device was a single 60 KN (11Klbs) hydraulic actuator with dynamic tension/compression capability.

The total loadcycles for a complete service life included 5200 cycles each in the

- closed position with actuator static tension load
- opened postion with vibration loading
- opened position with max. aerodyn. loading

The different spectra were blocked and superpositioned with temperature cycles:

Opened Pos.: All loads at Room Temperature
Closed Pos.: 94% at Room Tempeature
5% at 70°C (158°F)
1% at 100°C /212°F)

The test chronology for the 3 testarticles is described in Fig. 18.

Test-Item Nr.	Loadcase	j	Fatigue-Cycles	Residual Strenght	Impact	Repair
1,100°C WET	1-5 2	1,0 2,0	None	-	Yes	None
2,100°C WET	1-5	1,0	20800			
	1-5 2	1,5 2,0		Yes	Yes	None
3,100°C WET	1-5	1,0	20800			
	1-5 2	1,5 2,1		Yes	Yes	Yes

Fig. 18 Chronology of Testarticles

The most important results are:

- All components showed excellent linearity of strain gage readings, Fig. 19 and deflection meters, Fig. 20 up to a load level of approx. j=1.8, where local damage caused redistribution of loads.
- Failure of all testarticles were between j=2,07 and j=2,11 at the same location with no effect of fatigue loads or artificial damage repairs and no damage growth during fatigue cycling.
- These results proved consistancy of the manufacturing quality and qualiity assurance methods for production processes too.
- Laminate strains measured during the tests reached 88% of the allowable data at ultimate load.

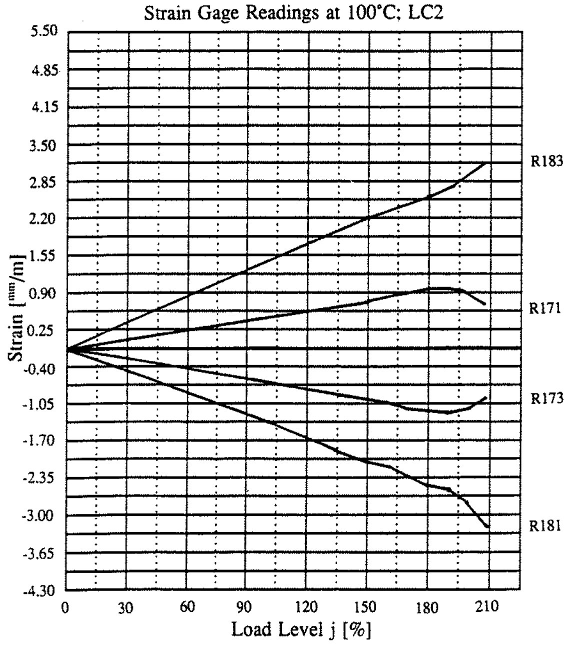

Fig. 19 Strain Gage Readings of Testarticle No. 1

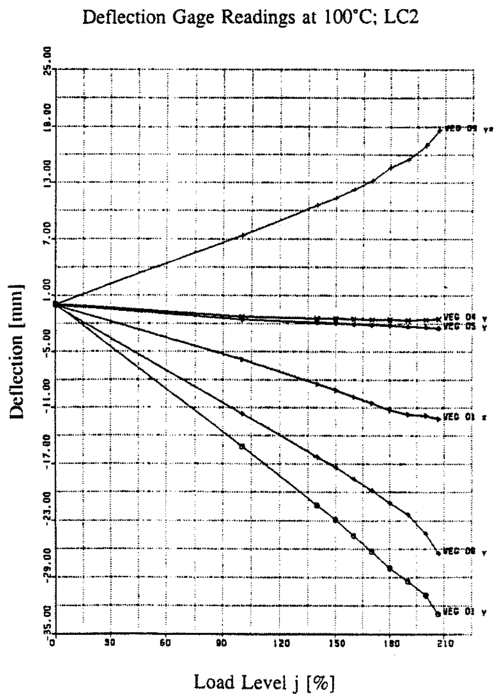

Fig. 20 Deflection Gage Readings of Testarticle

6.0 Inservice Testing Program

The general background for the inservice test program was to gather experience with advanced CFRP-material during aircraft operation in a service environment.

Service life for the 11 test components is scheduled for 15-25 years and max. 4000 Flight Hours in three different squadrons. The original components remain in the squadrons inventory as a spare part to allow rapid retrofit if necessary.

In order to increase the database on the longterm behaviour of damages and repairs, 3 components are operated with artificial damage introduced, and 3 others have artificial impact damages that have been repaired.

The initial artificial damage was recorded using identical NDI-methods and equipment used later on the aircraft to establish any damage growth.

The quality standard was defined by NDI checks for every testitem prior to 1. Flight and documented in the parts historic records. This included also any manufacturing concessions issued during production.

Beside normal pre- and postflight checks a detailed inspection plan was established together with the A/C-user on flight hour bases with the following inspection levels:

Level I (300 FH), On Aircraft:

- Check for max. operating temperature
- Check for moisture pickup using travellers
- Extended visual inspection
- Ultrasonic inspection of defined areas

Level II (A/C-Depot-Inspection), Part removed:

- Detailed visual and NDI-inspections performed on industrie level.

Level III (End of service life):

- Plans for global striffness and residual strength checks using full-scale test setup from certification phase

- Destructive inspection of special areas.

Level I and II results are documented together with any actions or repairs within the historic files of each component, to allow tracking of usage spectra or environmental influences.

The first component entered service in Oct. 1990 and has since logged 550 flight hours. Other components followed later in 1993 and have accumulated approx. 50 FH each.
During the actual service life no annormalities with respect to the advanced CFRP-material have occured.
The first Level I - Inspection of the test item - was performed at the squadron without indication of inservice damages, Ref. 3.

7.0 Summary

The CFRP-Main Landing Gear Door program for TORNADO focussed on inservice experience for advanced composite material during normal aircraft operation in different squadrons.
Design and analysis efforts together with new manufacturing and tooling techniques have resulted in an overall weight reduction of 25% compared to the standard part.
Certification of the testitems for an unrestricted envelope was achieved by successful static and dynamic full-scale tests under worst case environmental conditions.
Typical damage due to low-energy impacts and required repairs have also been incorporated in the certification process and made the introduction of artifically damaged and repaired components into service possible.
A detailed inspection program, supported by the A/C user and the industry was established to evaluate the structural behavior of the components throughout the service life.

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