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ABSTRACT

The aim of this study was to investigate the potential of carbon fibre reinforced plastics (CFRP) materials for application in a suspension arm for a helicopter tail wheel. The development shows the feasibility of using carbon fabric and unidirectional (UD) carbon fibre reinforced epoxy resin for the arm and demonstrates relevant design procedures for determining the required laminate construction. A prototype CFRP arm was fabricated and tested to failure. The first prototype was not lighter than the aluminium original, but had significantly higher stiffness and strength properties showing that there is scope for weight saving in an optimised design.

1. INTRODUCTION

The paper describes the design and fabrication of a prototype carbon fibre reinforced plastic (CFRP) suspension arm for a helicopter tail wheel. The design study and prototype fabrication were carried out at the DLR Institute for Structures and Design in collaboration with Liebherr-Aero-Technik GmbH, who tested the prototype to determine the failure load. Current production helicopter suspension components are forged in aluminium alloy and optimised for weight and performance. The aim of this project was to investigate the potential of CFRP materials for the development of helicopter suspension components with the required stiffness and strength properties and with reduced weight.

In the last 20 years advanced composites with boron, glass or carbon fibres have been increasingly used in helicopters, see [1] for a historical review of composite helicopter components and [2], [3] for the current 'state of the art'. Because of their low weight and excellent fatigue properties composites are now established as rotor blade materials. More recently the trend towards streamlined aircraft and the ease with which composites can be formed into large integral shell structures, has led to the development of composites for cladding panels and fuselage structures. In future applications the trend is towards dual function structures, such as composite floor beams with structural and crash energy absorption functions, see [4], [5]. Helicopter suspension components come into the category of structures requiring structural stiffness and good low speed impact damping and absorption characteristics. Currently these components are in aluminium with spring and damping functions divided between the suspension arm and damper. They could be an appropriate application for composites in a suspension design concept which used materials properties such as low density, high strength, good damping and energy absorption properties in an integrated suspension structure.

The aim of the present study was to demonstrate the suitability of composites in a suspension component. The component selected was the tail wheel suspension arm which is highly loaded on landing and in ground manoeuvres, and which should be as light as possible because of its position relative to the helicopter centre of gravity. An important requirement here was that the composite component developed should have the same external dimensions and fixing points as an existing aluminium arm, so that it could be fitted to a helicopter or a test rig for evaluation. A consequence was that the CFRP arm developed is a hybrid component in which the original aluminium attachment fittings had to be integrated into a CFRP shell structure, with concomitant weight increase. It was thus not possible in this first prototype to achieve parts integration with the damper or dual function as crash energy absorber. However, the prototype development has served to demonstrate the feasibility of CFRP materials for helicopter suspension components. Future developments could then consider the development of suspension system concepts better adapted to exploit composite materials properties.

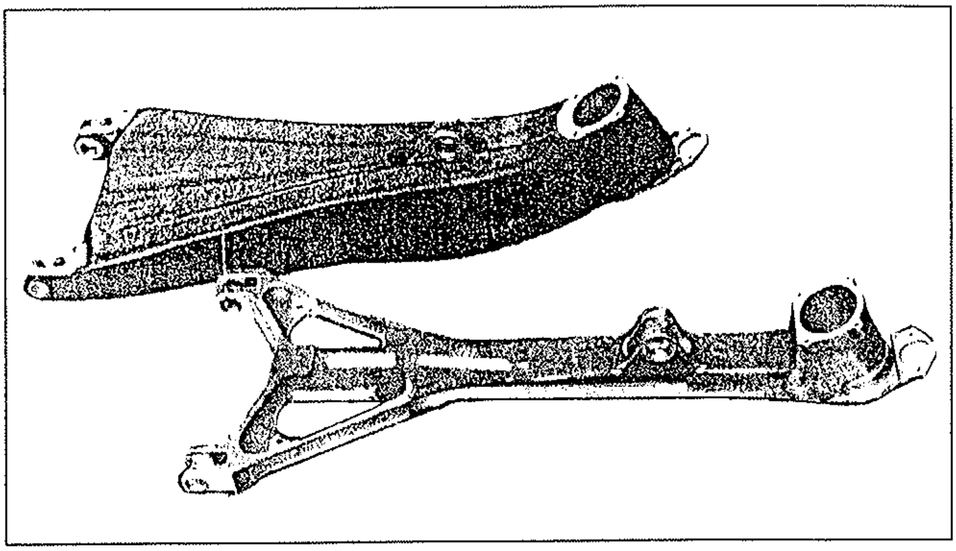


Fig. 1 The CFRP and aluminium suspension arms

Fig. 1 shows the original aluminium component together with the prototype CFRP component. The suspension arm is a highly loaded component on landing, when it is subjected to combined bending and torsion loads. In order to achieve the required stiffness in the CFRP component it is necessary to change the component geometry from the aluminium beam structure to a shell construction as shown in Fig. 1. The CFRP prototype consists of an outer torsion shell, with UD reinforcement at the corners to take the bending moments and a forked central web to take transverse loads. The six main shell subcomponents were hand laminated in the first prototype and the arm was assembled by adhesive bonding onto machined aluminium end fittings. The latter consist of fittings for the end pivots, the central damper attachment point and the fork box for the wheel axle. These fittings matched exactly those of the aluminium component so that the CFRP arm could be fitted to an existing helicopter suspension for testing. The chosen construction is discussed in Section 2 and is suitable for a series production using autoclave technology.

Section 3 describes the design analyses carried out on the CFRP suspension arm to first determine a suitable laminate construction for the CFRP shells, and then to assess the stiffness and strength of the component under the design loads. Because there are both bending and torsion loads in the structure, with no dominant uniaxial load system, the arm requires reinforcing fibres in several directions. Thus for ease of manufacture CFRP fabric reinforcements were chosen. A balanced fabric with fibre directions at ±45° to the beam axis was used to provide the torsional stiffness and strength, together with a UD fabric in the beam axial direction for the bending properties. A preliminary analysis based on a 2- and 3-celled box beam construction at various sections along the arm length was used to determine the maximum loads on the cell walls and hence suitable fabric lay-ups and thicknesses.

This was followed by a detailed finite element analysis (FEA) of the CFRP structure using a new integrated laminate analysis /FEA software. The analysis determined maximum deflections in the structure together with strength reserve factors for the composite laminates based on a first ply failure condition. The results showed that under a hard landing flexural load case the suspension arm has adequate stiffness properties, and for most of the structure more than adequate strength properties. Detailed study of the strength reserve factors shows in which parts of the structure there is scope for reduction in the number of fabric plies in a future optimisation of the CFRP component.

A prototype CFRP arm with integrated aluminium inserts was fabricated by hand lay-up and adhesive bonding as described in Section 4. Bending tests carried out on the CFRP arm and an aluminium prototype to measure the ultimate failure loads are also discussed. The CFRP arm remained undamaged at the design ultimate load. Further loading led to a final brittle fracture at a load about 50% higher. This first prototype has thus demonstrated the feasibility of using CFRP materials for helicopter suspension components and has provided valuable experience for an improved CFRP prototype.

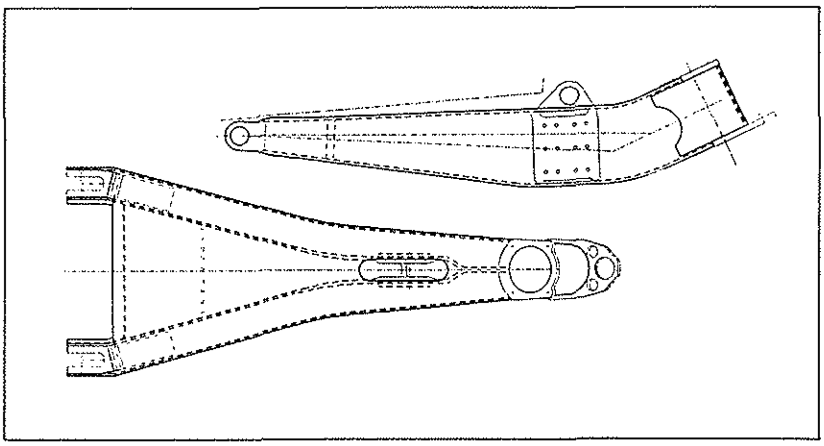
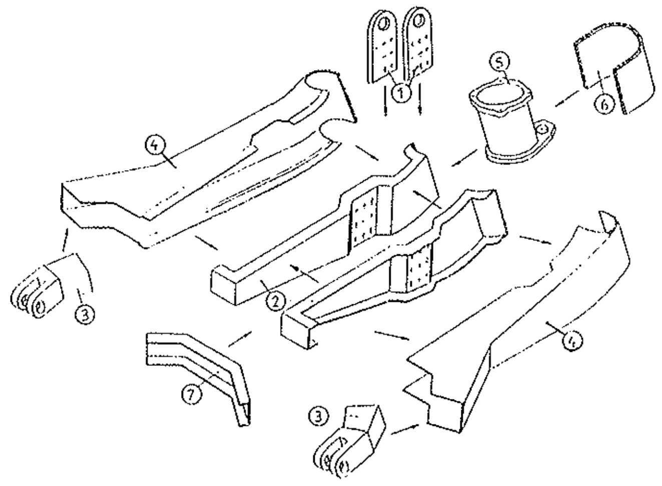


Fig. 2 Detailed geometry of the CFRP arm

2. DESIGN CONCEPT

Fig. 2 shows the CFRP suspension arm in more detail. The component has a length of 950 mm and pivots about a horizontal axis at two bushes (on the left end in Fig. 2), where it is attached to the helicopter tail structure. At the right end is a cylindrical bearing for the tail wheel assembly. At a position of 350 mm from the right end is the mounting bracket for a telescopic shock absorber. During a hard landing at 6 m/s the main impact energy is taken by the shock absorber and the design requirements for the suspension arm are based on static stiffness and strength requirements at a maximum equivalent short term static loading. Long term static or dynamic fatigue loading are not considered to be significant. Additional factors which influence the choice of matrix resin and the protective surface coating for the CFRP arm are the temperature range under load - 30°C to 45°C, resistance to water and aviation fuels, damage tolerance under stone impact and lightning strike protection.



SUBCOMPONENTS

CFRP :

2. Central shear webs
4. Flanged torsion shells
6. Wheel bearing cap
7. End closure

Aluminium :

1. Attachments for shock absorber
3. End bushes
5. Wheel pivot bearing

Fig. 3 Sketch of the CFRP arm construction concept

The design concept for the CFRP arm is shown in Fig. 3. The solid or thick walled beam structure used in the forged aluminium arm of Fig. 1 is most unsuitable for fabrication in composite materials which are better suited to thin walled shell structures. Compared with metals, composites generally have high strength and dynamic fatigue properties, but relatively low stiffnesses except in the fibre directions. Thus designs are often stiffness limited as discussed in [6] and structural stiffness is achieved by component shape. In the present case this is achieved by replacing the aluminium beam by a shell structure with the maximum cross-section allowed by the positioning of neighbouring components. Considerable attention must also be given to the various subcomponents of the shell structure, in particular how they are to be fabricated, what tooling is required, and how they can be assembled into the final component.

Depending on the wheel position on landing and when being towed, the arm may be loaded by axial, transverse and torsion loads. The design concept for the CFRP arm is a closed shell structure which, corresponding to the loads, has three main components: a torsion shell with fibres at ±45° to the arm axis; unidirectional (UD) fibre reinforced flanges to take bending moments and longitudinal loads; central shear webs with ±45° fibres and some quasi-isotropic fibre reinforcement for the transverse loads. Composite laminate thicknesses and ply lay-ups were determined from the preliminary design calculations described in Section 3.1. Further important considerations in composite structures are the methods of attachment to the aircraft structure and the problems of load introduction into thin walled shell components. The solution adopted in the prototype development here was to use machined aluminium inserts which were bonded into the CFRP shell at the main attachment points.

In order to fabricate the prototype arm in composite materials it is necessary to devise a design concept which takes account of the available fabrication technology. The preferred method adopted in the first prototype was to fabricate the shell components by contact moulding. It is thus necessary to split the shell into a number of subcomponents as shown schematically in Fig. 3. The torsion shells (4) with UD fibre flanges, the webs (2) and the end caps (6), (7) are fabricated in CFRP by contact moulding in one-sided tools. The CFRP shells were fabricated from epoxy resin reinforced by two types of carbon fibre fabric, a balanced twill fabric and a fabric with 90% UD fibres, as described in more detail in [7]. The remaining subcomponents are the attachments which were machined in Al, these are the bushes (3), the wheel mounting (5) and the brackets for the shock absorber mounting (1). These Al fittings serve two purposes: they are identical to the fixing points on the Al arm so that the CFRP prototype can be tested in service conditions; and they serve as load introduction elements for the CFRP structure. Assembly took place by adhesive bonding on a steel fixing jig.

This design concept was appropriate for the fabrication of a prototype arm by the impregnation of carbon fibre fabrics with epoxy resin and hand lamination. It is also suitable for a small series production using autoclave technology with carbon fibre/epoxy resin prepregs, which would give more consistent laminate thicknesses and fibre volume fractions through better control of the pressure and temperature cycle in the autoclave. As an alternative the CFRP shells could be fabricated in carbon fibre reinforced thermoplastic prepregs with PEI or PEEK resins by thermoforming or hot stamping in a press, which would speed up production considerably. Closed shell structures such as this are also suitable for filament winding in carbon/epoxy rovings or tape using a lost core method. In this case an appropriate concept could be to first fabricate the shear webs by contact moulding and bond them to the aluminium fittings, then overwind the outer shell over a soluble or fusible core. Such technology would be appropriate for a large scale series production.

3. DESIGN ANALYSIS

3.1 Preliminary Design Studies

Design with composites is an iterative process and before a detailed FEA of the structure can be carried out, it is necessary to first select ply materials, fibre orientations and laminate thicknesses. This was achieved from a simplified analysis based on box-beam elements in the arm cross-section..From the design loads on the arm maximum values of axial load, transverse load, bending moment and torsion moment at 100 mm intervals along the arm were determined. At these positions the arm cross-section has a either a two-cell form (between wheel mount and damper bracket), or a three-cell form as shown schematically in Fig. 4 (between damper bracket and pivot). Simplified design formulae (see [6], [8]) were then used within a spreadsheet program to compute properties such as bending strengths, torsion strengths and shear strengths for the two-cell and three-cell sections as functions of cell geometry, wall thickness and materials properties. The spreadsheet was used in conjunction with LAMICALC [9], a PC laminate analysis software, for the calculation of the shell wall laminate properties.

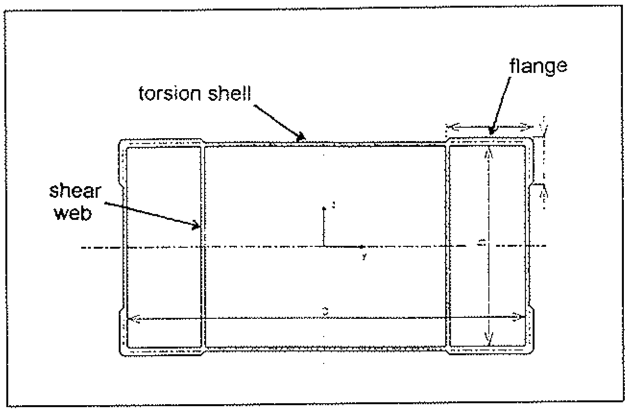


Fig. 4 Three-cell cross section for preliminary design

In order to meet the section loading, each part of the section was designed with a specific function. Thus the outer shell is a torsion shell, with fabric reinforcement at 45° to the axial direction. The flanges at the corners of the two-cell and three-cell sections (Fig. 4) consist of UD fabric aligned axially to take the axial and bending loads. The shear webs consist also of 45° fabric for the transverse shear loads. The spreadsheet program was then used iteratively with LAMICALC to determine laminate thicknesses and the proportion of balanced and UD fabric for each part of the section required to avoid section failure under the main load conditions. Additional simplified calculations were carried out [7] to determine the thickness of the U-shell at the wheel mounting; to check that the webs and upper shell surface can withstand buckling, and to analyse load transfers from the metal inserts to the CFRP shell through rivets and adhesive joints.

From these analyses followed a set of laminate constructions for the various parts of the structure, which have been tailored to provide adequate strength under the full range of design loads. Table 1 summarises the main laminates in the CFRP arm structure. We see that there is a range of thicknesses from 1.4 to 9.1 mm, with between 5 and 35 fabric plies. The thicker laminates are required at the wheel mounting U-shell and in the two-cell section where the bending moments are a maximum. The structure has additionally taper regions between the two main shell constructions with a smooth drop-off in plies, and load introduction regions at the damper bracket and at the bushes, with extra 0/90° fabric plies to take the direct transverse loads, see [7] for details.

Table 1 Laminate constructions in the CFRP arm

	3-cell section			2-cell section			U-shell		
	Thickness mm	No. of plies Fabric 45°	UD	Thickness mm	No. of plies Fabric 45°	UD	Thickness mm	No. of plies Fabric 45°	UD
Shell	1,4	5	0	3,1	11	0	9,1	13	22
Flange	3,4	5	8	5,6	11	10	-	-	-
Web	1,4	5	0	2	7	0	-	-	-

3.2 FEA of the CFRP arm structure

A detailed FEA of the structure is required to determine structural stiffness and to confirm strength safety factors for the CFRP laminates especially under combined loads, which could not easily be estimated from the simplified analyses. A standard FE program with orthotropic shell elements could be used for the analysis, with the composite shell laminate properties first determined by laminate analysis as in Section 3.1. However, this is very time consuming, especially in the post-processing, and can lead to errors through the implicit assumption that laminate in-plane and bending properties are the same. As a result integrated laminate/FE programs such as PERMAS-LA [10] have been developed for composites shell structures. Fig. 5 shows the FE model of the half suspension arm, which is symmetric about the middle line and contains about 5000 elements. The CFRP laminates are modelled by the SHELL4 elements required by PERMAS-LA, which are orthotropic thick shell elements with membrane, bending and transverse shear forces. The aluminium inserts are modelled by isotropic QUAD4 shell elements, with BAR2 beam elements used for the very stiff damper strut and for the loading rings in the wheel mounting. Coupling between the metal inserts and the CFRP shell is either by direct node coupling as at the wheel mount, or through an adhesive layer modelled by HEX8 volume elements.

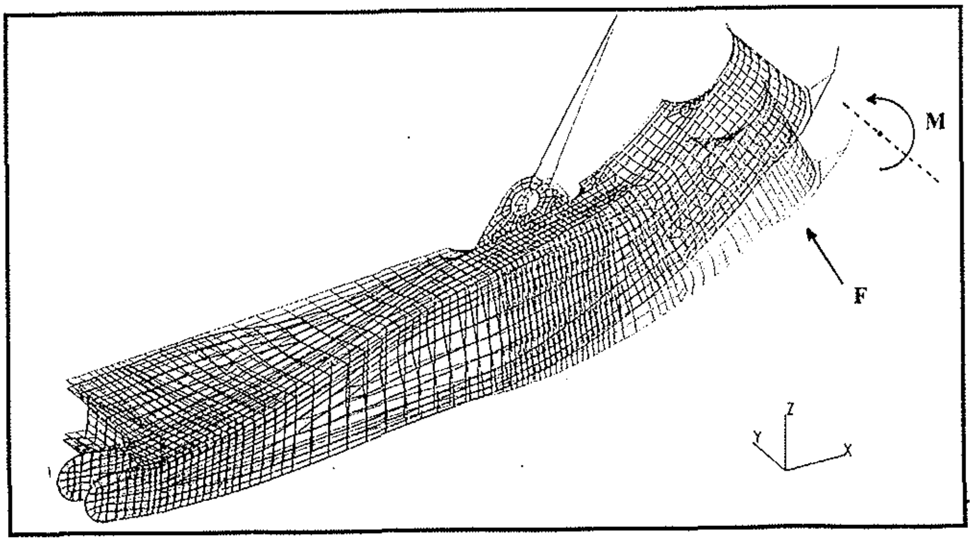


Fig. 5 FE model and computed deformations (not to scale) in the flexural load case

Appropriate materials data for the model based on the various laminate constructions described above and materials property data for the two chosen CFRP ply materials are required. A feature of PERMAS-LA is the creation of a laminate databank in which the ply materials and laminate lay-up in the structure are defined. A pre-analysis computes the laminate stiffnesses which are then assigned to the SHELL4 elements in the FE model. This de-coupling of the laminate properties from the FE analysis allows laminate constructions to be easily changed during refinement of the structure. After completion of the analysis, nodal displacements and residual element stresses are computed which are then converted during post-processing to provide individual ply stresses. From these ply stresses strength factors R for each ply, based on the Tsai-Wu failure criterion with first ply failure (FPF), are then computed for display. Material strengths used in the analysis were design allowable values for CFRP, which should be higher than measured values thus giving a conservative R-value. With this definition $R<1$ implies strength in reserve, whilst $R>1$ implies a failed ply in the laminate. It should also be emphasised here that FPF implies some damage in the failed ply, which could for example be transverse cracking in the UD plies. Since in the composite laminate a cracked ply may be surrounded by undamaged plies, this does not necessarily represent ultimate failure of the structure. Thus the computed failure load of a composite structure as defined by $R=1$ will usually be below the measured failure load.

Results are presented here for one of the most severe load cases, the hard landing (HL) flexural load case which corresponds to a 6 m/s impact. In this case the arm is symmetrically loaded through application of an equivalent static transverse load $F = 39\ 700$ N and a bending moment $M = 11\ 150$ Nm about the y-axis at the wheel mounting, as shown in Fig. 5. The arm is free to rotate about the y-axis at the pivot bushes, but is constrained in the x and z directions at the pivots. The arm then bends about the y-axis under constraint from the shock absorber, which is modelled here as a very stiff lever arm. The HL is an ultimate load case which means the arm may be damaged by the loads but should not fracture.

Table 2 FEA results for CFRP arm under flexural load

	Max. vertical displ. w	Strength reserve factor R		von Mises equiv. stress MPa	
	mm	ave.	max.	ave.	max.
CFRP shell top	4,2	0,65	1,2	-	-
CFRP shell sides	-	0,25	0,5	-	-
Al bushes	0	-	-	70	170
Al damper bracket	4,2	-	-	100	550
Al wheel mount	12,5	-	-	75	250

Fig. 5 shows the computed structural deformations under this loading (not to scale), and Table 2 lists maximum displacements, maximum strength factors R in the CFRP laminates and maximum computed von Mises stresses in the aluminium components. As the figure shows the arm bends about the damper bracket with a maximum vertical displacement w = 12.5 mm at the loaded end. The damper bracket displacement is only 4.2 mm, showing that most of the deformation takes place between the wheel mount and the damper bracket. In addition to this overall beam bending there are local shell deformations in the front shell upper surface because the outer box beams in the three-cell structure twist towards the centre line.

Fig. 6 shows a set of contour fringes for the strength factor R for the CFRP shells. The values plotted are the highest values for each shell element obtained by searching the computed R factors for each ply in the element. The results are briefly summarised in Table 2. Typical average values for R in the CFRP laminate are 0.65 in the upper and lower faces of the arm, with a value 0.25 in the webs and side walls. Maximum R-values are 0.5 in the side walls and R = 1.2 in the front shell upper surface, where the local shell deformations take place. Fig. 6 confirms that the peak stresses are in this compression loaded shell surface. The results show that for most of the structure the CFRP laminate has more than adequate reserve strength, with some local damage but not complete failure predicted in a small region of the 1.4 mm thick front upper torsion shell. This damage would probably be prevented here by the local addition of a further fabric ply. The average von Mises equivalent stresses in the metal inserts listed in Table 2 are all below 100 MPa, with peak values in the bushes and wheel mount up to 250 MPa. These values are well below the design allowable stress values of 435-495 MPa for the alloy used. The maximum stress in the damper bracket of 550 MPa, which exceeds the allowable value, was a local value in the damper loading ring which thus needs further reinforcing. The computed FEA results therefore show that the CFRP arm is in general overdesigned, especially the aluminium inserts, with adequate reserve strength except in one or two positions where small detailed design improvements could easily be implemented.

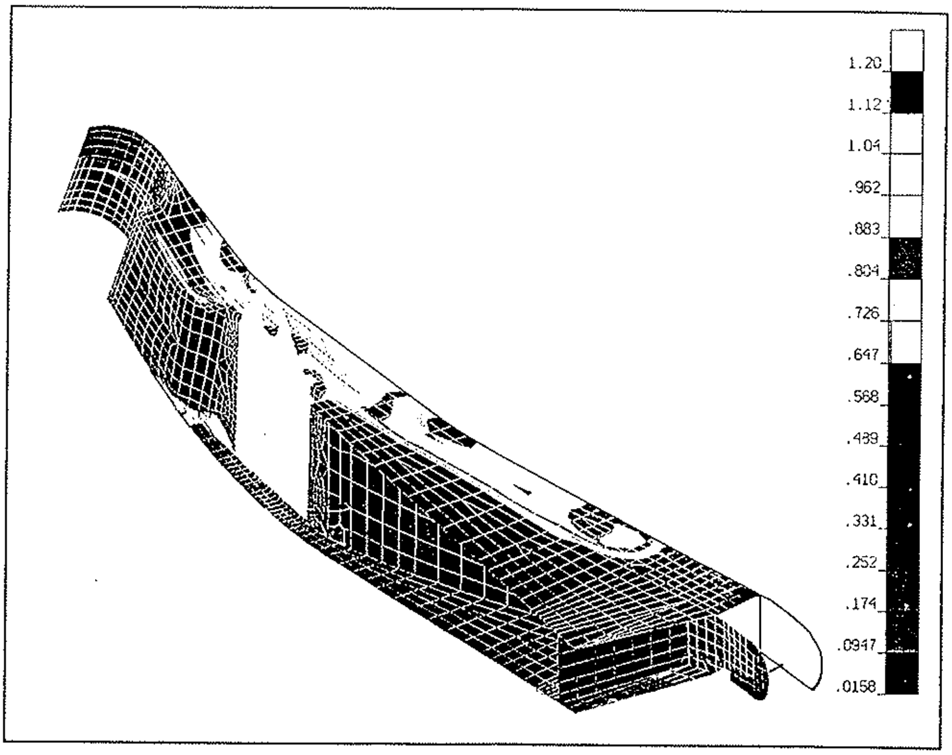


Fig. 6 Strength R-factors in the flexural load case

4. FABRICATION AND EVALUATION OF THE CFRP ARM

4.1 Fabrication

In order to check the construction concept a CFRP prototype arm was fabricated using hand lamination technology with vacuum consolidation. For the hand laminated prototype it is sufficient to manufacture the tooling from a plastics tool material which can easily be shaped by hand. Positive tooling was first fabricated for the torsion shells (4) and wheel bearing cap (6) in Fig. 3, based on detailed drawings of the required component geometry, and the shell components were overlaminated. Negative tooling was required for the shear webs (2) and end closure (7). With this choice of tooling the structure always has good moulded surfaces in contact with the aluminium inserts and where the CFRP subcomponents are bonded together.

For the prototype component a balanced 2/2 twill carbon fibre fabric (Interglas 98151) with weight 245 g/m^2 was used for the main laminates. The UD reinforcement was also a fabric, Brochier G 808 with weight 220 g/m^2 and a 90:10 fibre distribution in the warp and fill directions. Fabrics have advantages in handling and drapability for hand lamination compared with UD carbon prepregs. The epoxy resin system chosen was Bakelite L20/SL, with Redux 410 as the adhesive, both of which after postcure at about 80°C meet the temperature requirements in the specification. Aluminium alloy 3.4394 was used for the inserts which were machined to size. Attention was given to the overlap regions between inserts and CFRP shell, which have to be large enough to transfer loads into the shell.

Assembly of the prototype arm took place on a steel fixing jig. Because of the high transfer loads, the brackets (1) were both riveted and adhesively bonded to the CFRP webs (2). The remaining subcomponents were bonded with the epoxy adhesive.

Tests carried out on offcuts from the CFRP laminates showed that the hand laminated structure had a fibre volume fraction of 35%. This is well below the value of 50% typically achieved by autoclave technology. Since the structural stiffness and strength are mainly due to the carbon fibres, it follows that the hand laminated component should have the same mechanical properties as an autoclave component, but contains excess resin which requires squeezing out. In the CFRP arm this leads to a weight increase of about 25% in the CFRP shell and of about 15% in the complete structure compared with an autoclave fabricated component. Note that an autoclave could not be used to improve the quality of this first prototype since this would require more expensive metal tooling to withstand the higher fabrication pressures and temperatures.

4.2 Structural testing

The structural concept and design analysis were then validated by statically testing the CFRP prototype arm in a special test rig and comparing its behaviour with a typical aluminium arm. The most severe loading case was selected during a hard landing when the arm is loaded in bending through application of a transverse load at the wheel bearing, whilst being constrained at the damper attachment. The arm was tested by loading at the damper attachment whilst being supported at the wheel bearing. The first test was to check for damage, whereby the CFRP arm was coated with a brittle lacquer and loaded up to its design ultimate load of 40 kN. The CFRP arm was undamaged at the ultimate load, with the test showing uniform surface strains and damage to the lacquer only at the damper attachment. The displacement was 7.6 mm at the ultimate load.

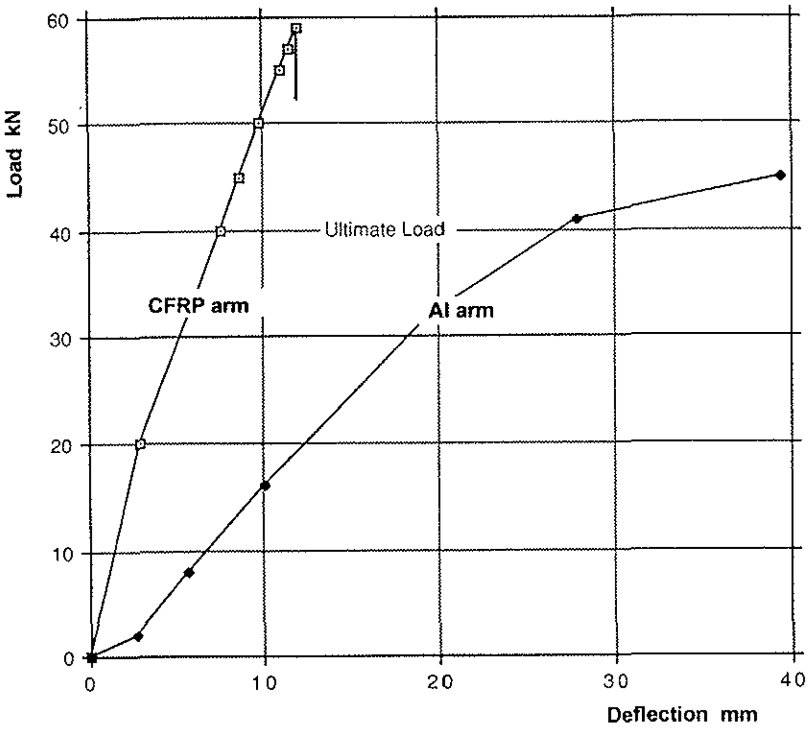


Fig. 7 Bending test results for the CFRP and aluminium suspension arms

In a second test the CFRP arm was loaded to failure in the same bending mode. Fig. 7 shows the measured load-deflection curve measured at the wheel axis, which is essentially linear to a brittle failure at a load of 59 kN. The first cracks appeared accompanied by a crackling noise shortly before the sudden final fracture. On investigation it was found that failure had occurred in the shear webs at the wheel bearing. For comparison Fig. 7 also shows results from tests on an aluminium arm. This is seen to be less stiff and shows plastic yielding just above the design ultimate load.

The test data may also be used to validate the FE calculations, although it should be noted that the test set-up is not exactly the same as the design case analysed. The FE results in Table 2 show a 12.5 mm deflection at the wheel bearing for an arm under a combined load F = 39.7 kN and bending moment M = 11.2 kNm, applied at the wheel bearing. In the test the arm pivots about the end bushes and is fixed at the wheel bearing, with the load applied and the displacement measured at the damper attachment. Under a load of 40 kN the measured deflection was 7.6 mm. This deflection is the relative deflection of the wheel bearing to the damper. From Table 2 the computed relative deflection is 12.5 - 4.2 = 8.3 mm. Thus there is good agreement between the predicted and measured arm stiffnesses. The test results also show that the Tsai-Wu failure criterion based on first ply failure as used in the FE analysis is conservative, as discussed in Section 3.2. The measured failure load is seen to be about 50% above the predicted damage load. The test results thus give some confidence in the use of PERMAS-LA for the analysis of composite structures.

5. CONCLUSIONS

In order to assess the potential for weight saving in the suspension system through the application of CFRP materials, a helicopter tail wheel suspension arm was designed, produced as a prototype by hand lamination and statically tested.
The CFRP arm concept was a thin-walled multicelled shell structure in carbon fabric/epoxy, with aluminium inserts for load introduction and attachment to the helicopter tail.

Preliminary design calculations based on laminate analysis software and spreadsheet calculations were used to determine a suitable CFRP laminate construction. This was followed by detailed design analysis using a coupled laminate analysis/FE software.

The detailed FE analysis showed that, with some very minor modifications, the arm should have adequate stiffness and reserve strength in the hard landing flexural load case, and that in many areas the CFRP component is overdesigned giving scope to selectively reduce the number of fabric plies and the size of the metal inserts.

A prototype CFRP suspension arm was fabricated by hand lamination with vacuum consolidation using low cost plastics tooling. Because of the hand lamination process based on wet resin the CFRP component was found to be about 20% heavier than an aluminium suspension arm. Thus the primary objective of weight saving was not achieved in the first prototype. It is estimated that fabrication by autoclave technology with carbon fibre prepregs would reduce the CFRP arm weight to that of the aluminium arm. Furthermore 40% of the prototype weight consisted of the aluminium inserts giving further scope for weight reductions.

The static bending tests showed that the CFRP arm failure was by sudden fracture at a load about 50% higher than the design ultimate load, confirming that it is overdesigned. Tests showed that the CFRP arm was both stiffer and stronger than an aluminium arm.

Taking into account the higher performance found by the test results and the possibilities of weight reduction through better fabrication technology and improved design of the attachment points, we conclude that a CFRP arm could be developed with weight savings of about 25% over an aluminium arm. Bigger savings could be achieved within a re-designed suspension system in which the CFRP arm is integrated with the shock absorber or combined with a composite crash energy absorber.

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