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DESIGN AND DEVELOPMENT OF THE SEA KING COMPOSITE MAIN ROTOR BLADE

by

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#### 1. Introduction

A contract for the design and development of a composite main rotor blade for the Westland Sea King helicopter was placed with Westland by the Ministry of Defence in 1979. This contract had been preceded by an experimental rotor programme to investigate the development of a composite blade using advanced aerofoil sections. This programme was begun in 1978 and provided valuable information for the current programme. For reasons of financial stringency the experimental rotor programme was stopped in 1981, although the composite aspects of the programme were integrated with the present programme.

The basis for the current programme was to produce a true retrofit blade for the Westland Sea King which would provide the operator with a replacement blade with lower life cycle costs, longer life and greater damage tolerance. As part of the requirement to minimise costs it was decided at the outset to reproduce the performance and dynamic characteristics of the metal blade. The evidence upon which this decision was based, was provided by the experimental rotor programme which had shown that any attempt to improve the performance of the blade would inevitably require modifications to the rotor head and control system. Rotor head modification would have been needed to accommodate the increased loads and control system modification would have been required both to provide the extra pitch range needed and also to avoid the pitch lag instability which would be encountered at the higher speeds permitted by the increased performance. Thus the symmetric NACA 0012 section was retained. Any attempt to improve the dynamic characteristics of the metal blade would have undoubtedly needed a considerable programme of resubstantiation of other components of the helicopter and certainly required a lengthy load and vibration survey to revalidate the existing substantiation of components.

# 2. Preliminary Design

Having decided to reproduce as closely as practicable the dynamic characteristics of the metal blade the first step was to investigate possible materials and methods of manufacture. As previously stated some background information was already available from the experimental rotor programme. This blade had been designed using primarily unidirectional glass reinforced plastic for the spar, D shaped as the metal blade, together with carbon, (graphite), trailing edge skins supported by Nomex honeycomb. The basic stiffness characteristics of this blade differed considerably from the metal blade, the flapping and torsional stiffness being lower while the lagwise stiffness was much higher. Clearly to obtain the same flapping stiffness as the metal, something other than glass was required for the spar. Because of the continuous trailing edge used for the plastic blade as opposed to the pocketted construction of the metal blade, the lagwise stiffness tended to be too high, while the use of unidirection carbon in the spar provided insufficient torsional stiffness. Fig 1 shows some of the steps in the development of the basic blade section. The consequence of a high lag stiffness was an unacceptable increase in the second lag frequency which would almost certainly lead to increased inplane 5 per rev forcing at the rotor hub. Given that the lag stiffness had to be kept close to that of the metal blade and that the flapping stiffness had also to be the same both for vibration and to maintain blade clearance over the fuselage, the only remaining parameter to be decided was the torsional stiffness. Solutions 4 and 5 gave the highest torsional stiffness by using carbon trailing edge skins, however the relatively low allowable strain of  $\pm 45^{\circ}$  carbon gave rise to doubts about the strength of the trailing edge. Since dynamic characteristics were being reproduced the strains induced in the discontinuous trailing edge of the metal blade had to be accommodated by the continuous trailing edge of the new blade. The preferred solution was therefore solution 6 with a GRP trailing edge provided that the consequences of the lower torsional stiffness could be accepted. Table 1 shows a comparison of frequencies for solution 6 compared to the datum metal blade. It can be seen that the only significant difference is the torsion frequency.

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	FREQUENCY		FLAP AT TIP (ins)		LAG AT TIP (ins)		TORSION AT TIP (rads)	
Mode	Standard	Retrofit	Standard	Retrofit	Standard	Retrofit	Standard	Retrofit
Ll	0.217	0.218	0	0	1	1	.0008	.0008
F1	1.018	1.019	1	1	0	001	0003	0003
F2	2,584	2.513	1	1	224	223	.0013	.0014
L2	3.369	3.282	.279	.288	1	1	0025	0021
F3	4.730	4.447	1	1	218	225	0033	0034
F4	7.265	7.037	1	1	.174	082	.1570	0353
T1	7.504	6.445	1	.813	318	1	1611	.8075
L3	8.784	8.258	.085	.051	1	1	0370	0397

TABLE 1. Mode frequencies and couplings, 209 r.p.m., 15° Pitch

In order to be sure that the lower torsional stiffness was acceptable an investigation under the following four main headings was instigated.

- a) Blade Torsion/Loading
- b) Aircraft Handling
- c) Rotor Performance
- d) Fixed axis Hub Loads

Examination of the torsional deflection of the blade tip for the 124 Kts (Vno at 20,500 lb) condition, Fig 2 indicated an increase in the vibratory component. In its own right this was not a problem but the consequences in terms of blade hub loading had to be evaluated. This was done using the rotor performance programme which has been developed at Westlands. The results showed that both the lagwise bending moments throughout the blade and the track rod loading for the 124 Kts case were identical with the metal blade. In the flapwise sense however a difference was observed at the root of the blade, Fig 3, although the outboard part of the blade was again unchanged from the metal blade. It was also shown that the increased loading was very sensitive to forward speed. Thus at Vno the increase was much less significant that at Vne. Since the Vne case was not the design case for the blade root the increased load in this case was proved to be acceptable.

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It is perhaps worth noting that the increase loading at the blade root was due to an increase in response of the fourth flapping mode. This was due only in part to the reduced torsional stiffness. It was shown to be also due to the change in mass distribution at the tip. This change was brought about by the desire, in the case of the composite blade, to extend the spar to the blade tip and reposition the balance weights at the tip. In contrast the metal Sea King blade has the spar terminating at 95 per cent radius with balance weight also located at this station. These two differences were shown to be sufficient to cause the difference in flap wise loading at the root of the blade in the Vne case.

The possible effects of low torsional stiffness on aircraft handling were investigated and the results in terms of control angles versus forward speed are presented in Fig 4. Although there were differences in the absolute values of the control angles required for trim, the gradients with respect to forward speed remained unchanged and they were deemed to be acceptable.

Rotor performance margins are presented in Fig 5 in the form of angle of attack versus Mach number plots for the two blades at 124 knots and 93% radius, together with the stall boundary for the NACA 0012 section. It is evident that the lower torsional stiffness has pushed the composite rotor closer to the aerofoil static stall condition by about 0.2° although there is still a margin available. It must also be remembered that pitch lag instability limits are encountered prior to the rotor stall boundary at high speed.

The fourth topic to be addressed was the fixed axis vibrating hub loading. The only frequency of importance is the five per rev component and since the rotor is articulated it is only the shear forces acting at the hub centre which are of any significance. Of these the largest component for the datum metal blade case is the vertical shear. Fig 6 shows that this component has in fact reduced with the introduction of the composite blade. This is primarily due to the decrease in the third flapping frequency from  $4.73\Omega$  to  $4.45\Omega$  already noted in Fig 2. In the case of the two in plane shear forces, which are of lesser significance than the vertical shear there is a small increase above 110 kts. It should also be noted that a degree of uncertainty exists concerning the validity of the inplane forces because of the action of the blade lag plane damper. The action of the damper is highly non linear because throughout the forward flight regime the pressure relief valves in the damper are operative, and correct dynamic modelling is extremely difficult. However, it can be seen that the magnitude of the resultant 5 per rev excitation at the hub has been slightly reduced and the direction altered. Overall, therefore, there does not appear to be a significant change in the hub vibratory forcing.

Having assessed all those aspects which could have been affected by the deviation of the blade characteristics from those of the metal blade it was concluded that properties of the proposed composite blade were acceptable.

## 3. Detail Design

Having achieved a broad definition of acceptable properties for the composite blade the next stage was to define in more detail the actual construction of the blade.

Fig 7 shows the general blade section with inner and outer carbon wraps to the 'D' spar to provide the necessary torsional stiffness, a mixture of carbon and glass unidirectional material in the spar itself for flapwise stiffness and glass cloth trailing edge skins laid at +45° in order to control the lagwise stiffness. The trailing edge skins are supported by Nomex paper honeycomb material. The leading edge of the spar is protected by a titanium erosion shield beneath which is located a rebate to accommodate an electrical heater mat to provide blade de-icing if required. Should the heater mat not be required then a dummy GRP mat can be utilised. Within the nose section of the 'D' spar there is a tube to contain balance weights which may be required for spanwise and chordwise mass corrections.

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Because the blade has to be retrofittable to existing rotor hubs, is was decided that the method of attachment of the blade should not require any resubstantiation of hub components. The most effective way of achieving this objective was to bolt the blade to a cuff fitting in a manner similar to the metal blade. After some preliminary tests this was shown to be feasible from a structural point of view thus allowing considerable cost savings in production. This method also minimised structural changes to the rotor system particularly with regard to blade folding, although the slightly different transition profile of the trailing edge does entail a minor modification to one hydraulic hose to allow for blade folding. The use of bolts to attach the blade spar to the steel cuff relies on the interleaving of +45° woven glass in the area of the bolts to take the bolt load into the unidirectional material of the spar. (Figs 8 and 9).

# 4. Manufacturing Process

A description of the manufacturing process is covered at some length in Ref l. But briefly the process involves the use of tape laying machines to provide packs of material which are cold pressed to provide additional consolidation and chordwise shape before being assembled on to a mandrel. The mandrel is first covered with a rubber membrane which can be inflated during the moulding process to provide consolidation pressure. The wrapped mandrel is placed in the spar mould which is then closed and placed in a 30ft platten press. The complete cure cycle takes 8 hours with a maximum temperature of 120°C and internal air pressure in the mandrel bag of 200 p.s.i. Control of the cure is automatic to provide consistent quality and consistent thermal history ensuring that built in stresses and deformations do not change between blades.

The trailing edge structure is fitted in a second moulding operation again in the 30 ft platten press. Uncured skins are placed in the two mould halves with adhesive on the surfaces adjacent to the honeycomb core. The skins are then co-cured onto the spar to form the trailing edge and attach it to the spar in one operation.

The root end attachment cuff fittings are attached to the blade by drilling and bolting techniques similar to the present metal blade. Metal shims are bonded to the composite to control fretting at the joint and allow easy replacement of the cuff if required.

#### 5. Substantiation Philosophy

The aim of the substantiation philosophy is to establish, by testing full scale components, all of the potential failure modes that could be initiated and propagated by all possible loading actions during the service life of the blade. The philosophy, at the moment, for main rotor blades, is a safe life one. However differential pressure operated monitoring systems are still being studied to evaluate their efficiency in monitoring the condition of the blade.

Every potential failure mode that could cause catastrophic failure of the blade must be characterised by its S-N curve and modified Goodman diagram, and a statistical analysis made of its probability of occurrence. Only when every failure mode can be shown to have an acceptably low probability of occurrence during the promulgated service life of the blade can the substantiation process be considered to be complete.

Demonstration of any failure mode requires the evaluation of the following data with respect to both fatigue and static failure.

- (a) Definition of the appropriate S-N curve.
- (b) Validation of Miner's cumulative damage law for fatigue life assessment.
- (c) Determination of strength scatter factor.

Three sources of data were used in the case of the Sea King composite blade viz:-

- (i) Coupons made from the basic materials, using the correct production processes and relevant orientations.
- (ii) Parts made similar to or cut from the production component. (Structural elements).
- (iii) The production component.

For the definition of an S-N curve shape the minimum statistically significant number of test specimens is considered to be 20, tested at constant amplitude.

For verification of Miner's Law the minimum number of specimens is 10 tested at variable amplitude.

For mean static strength determination five specimens are required.

Scatter factors are calculated to yield a probability of failure of  $10^{-7}$  at expiry of the promulgated life of the component using a log normal distribution and Bullen's work. (Ref 2).

The three sources of data referred to above are described below:

5 (i) Coupons

The following coupons, manufactured to same acceptability criteria as the full scale component have been tested:

uni-directional glass
uni-directional carbon
+ 45° glass
+ 22.5° glass

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- + 45° carbon - + 22.5° carbon - woven glass
- woven carbon

In total 6,000 coupon specimens have been manufactured and tested. A typical Goodman diagram is shown in Fig 10.

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#### 5 (ii) Structural elements

In addition, the following structural elements configured to demonstrate the anticipated failure modes of the blade have been designed and tested. Four failure modes have been considered:-

- (i) Root end. (Interlaminar shear and Transverse tensile failure).
- (ii) Transition section. (Delamination of doubler stack and interlaminar shear).
- (iii) Outboard section spar. (Fibre failure).
- (iv) Trailing edge. (Fibre failure).

For each of the above, 35 structural elements have been tested, consisting of:

- 20 constant amplitude for S-N scatter

- 10 variable amplitude for Miner's Law verification
- 5 for determination of static mean strength

Thus a total of 140 specimens in all have been tested.

## 5 (iii) Full scale component

Here the requirement is for six specimens tested in fatigue and three tested statically. Again the areas under consideration are root, transition, spar and trailing edge.

The rigs used to test these components are computer controlled with continuous monitoring to ensure immediate shut-down when loads deviate by a preset amount from the required value. The loads applied by the rig represent flap and lag bending and shear together with torsion.

The root specimens are of the simple cantilever type, fully strain gauged to monitor load distribution. The transition specimens are propped cantilevers using an elastic prop to correctly locate the peak bending moment in the doubler stack area.

Spar specimens are tested as double ended cantilevers and each specimen has a fully formed trailing edge.

## 6. Additional Pre-Flight Tests

As a check on the calculated stiffnesses used in the design calculations one of the first flight blades was subjected to a stiffness and frequency check. In order to carry out the stiffness test the blade was mounted, root fixed, vertically from the roof of the universal test frame. The stiffnesses in lag and torsion were

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in close agreement with calculation but both measurements were greater than calculated values. In the flapping sense the measured value was again greater than the theoretical value but in this case by approximately 15%. As a further check a frequency "bonk" test was carried out and the resulting frequencies compared to the calculated values. The calculation of frequencies was carried out using the same programme as is used for rotating frequency calculations but with boundary conditions appropriate to the test condition. Fig 11 shows a typical frequency test result in this case for the lagwise "bonk" although the third flapping frequency at 11.625 Hz is clearly evident.

In contrast to the stiffness check the comparison of frequencies in Table 2, shows close agreement in the flap and lag sense but a discrepancy of the order of 10% in torsion. Overall it is considered that the stiffnesses used in the design calculations are within acceptable limits.

	FLAP (Hz)		LAG	(Hz)	TORSION (Hz)		
	Calculated	Measured	Calculated	Measured	Calculated	Measured	
W1 W2 W3 W4	.73 4.34 11.69 22.75	- 4.34 11.63 22.25	2.18 13.72 38.16 74.88	2.25 13.38 37.25	26.74 80.11	23.63	

Table 2 Frequency Comparison

In addition to the tests already described, the first six blades, that is one flight set plus one spare, have been spun on the whirl tower to check the dynamic and aerodynamic matching of the blades. The whirl tower has only a three bladed hub and therefore each blade is checked against an arbitrarily chosen master. At the time of writing this paper which, due to the requirement of providing preprints, has to be considerably in advance of the date for the Forum itself, the blades have successfully completed these whirl tests.

# 7. Further Developments

During the course of the design and manufacturing stages of the current standard of blade many lessons have been learned some of which require minor modifications to be introduced prior to a full scale production launch of the blade. As an example minor changes to the lay-up in some areas of the blade will enable greater use to be made of automated techniques. These modifications, together with the flight data gathered from the preliminary flight test programme, will be used to define the production standard of the blade which it is anticipated will be available during the latter part of 1984.

#### 8. Conclusions

A retrofit composite main rotor blade for the Sea King helicopter has been designed. Testing of material coupons, structural elements and full scale blade specimens has reached a stage sufficient to give clearance for intial flight trial. A flight set of blades has been manufactured and has successfully completed pre-flight whirl checks. The first flight of these blades is dependent on the availability of the test aircraft but it is hoped that the initial flight trials will have taken place by the date of the Forum and that additional data will be available at that time.

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FIG 2 124 KTS TORSION





FIG 4 CONTROL ANGLES

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# FIXED COORDINATE FORCINGS 20500 LB

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FIG 6 HUB SHEARS (X, Y & Z)

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FIG 9 ROOT END CONSTRUCTION



FIG 10 TYPICAL GOODMAN DIAGRAM

# SEA KING MAIN ROTOR COMPOSITE BLADE FLAP BONK CHECK



FIG 11 TYPICAL FREQUENCY CHECK

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