The design and construction of model ship propeller blades in hybrid composite materials

A.F. Molland and S.R. Turnock

A description is given of the design and construction in hybrid composite materials of a model ship propeller for use in wind tunnel tests. The reasons for the choice of a glass/carbon reinforced composite material for the blade manufacture are discussed. Results are presented for tests carried out on hybrid composite samples prepared by wet-lay-up by hand under practical manufacturing conditions. The design stress levels used in the final design were based on the test results for the samples. A description is given of the blade design and the production method. Successful operation of the propeller has confirmed the suitable application of the chosen material for the blades.

Keywords: hybrid composite design; hybrid composite production; ship propeller

INTRODUCTION

The design and choice of materials for the construction of a model ship propeller is described. The propeller was required as part of an experimental rig for use in the University of Southampton 11′ × 8′ wind tunnel to investigate the interactions between ship propellers and rudders.

The need for a high degree of accuracy in the production of the propeller blades was likely to lead to high production costs if manufactured using conventional materials such as aluminium or bronze alloys. The feasibility of manufacturing the blades in glass and carbon fibre composite materials was therefore investigated.

It was felt that, with the high centripetal and aerodynamic loading on the individual propeller blades, a good understanding was required of the permissible design stress levels. Following discussions with composite manufacturers a blade design was proposed based on the use of hybrid carbon/glass fibres and a wet-lay-up by hand. To ensure that the material properties obtained using the composites were within the design stress levels, representative samples of various areas of the blade were laid up and then tested.

After proving the blade design stress levels a split female mould was manufactured on a 3-Axis Numerically Controlled machine. The use of a single mould allowed identical blades to be manufactured with the required definition of the propeller's complex surface geometry.

PROPELLER PARTICULARS

Blade design

A four-bladed propeller of 800 mm diameter was chosen for the projected wind tunnel tests. The design was modelled on a basis ship propeller of known dimensions and performance which would enable validation of the performance of the new propeller to take place in the wind tunnel. Details of the propeller geometry are given in Reference 1. A maximum propeller boss diameter of 200 mm was chosen. The facility to adjust the blade pitch angle to local flow was incorporated by manufacturing a separate boss and four blades. An aluminium alloy split boss arrangement was employed in order to incorporate/clamp the blades at the desired pitch angle. The pitch could be simply varied by rotating the blade within the boss. The final overall size of the individual blades (including the part within the boss) was a length of 360 mm, maximum width of 195 mm and a minimum composite root diameter of 60 mm.

The need for four identical blades manufactured at a realistic cost which would be capable of running at speeds up to 3000 rev min^{-1} in the wind tunnel led to the decision to investigate the use of composite materials. These materials combine low density with reasonably high strength and in this application would allow identical blades to be made from the same split mould.

Proposed composite lay-up

Based on previous experience at Southampton University and discussions with composite manufacturers a proposed design for the lay-up of the propeller blades was made. The complex shape of the blades restricted the production method to a wet-lay-up by hand under normal production conditions.

Glass reinforcement was considered suitable for the outer portions of the blade. Due to the relatively high axial (centrifugal) loadings, additional strength between the root and inner one third (approx) region of the blade would be provided by axially orientated carbon fibres laminated alternately with the glass. The effective use of glass/carbon hybrids has, for example, been described in

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Reference 2 which suggests that such a hybrid is an attractive compromise (compared with carbon alone) since it has an acceptably high modulus and a fibre dominated failure mechanism, with resistance to shock failure, similar to glass-reinforced plastic.

The principal glass reinforcement to be used was E Glass Quadrax which, as well as having 0°/90° orientation, includes a ± 45° orientation which provides torsional strength. E Glass Twill with 0°/90° orientation and a fine mesh would be used in confined areas and areas of complex curvature such as at leading and trailing edges and at the blade tip.

Published data indicate significant variation in physical properties (e.g., E and UTS) for different reinforcements and lay-ups[3,4]. This is particularly true where wet-lay-up by hand under normal production conditions is to be used[5]. Discussions with the blade manufacturer concerning the material properties led to the decision to manufacture and test production quality samples representing the materials proposed near the root and at 70% (approx) of propeller radius. Thus the test specimens were to be representative of the propeller blade areas shown in *Figure 1*. It is to be emphasized that these would be practical screening tests to confirm acceptable levels of the mechanical properties of the proposed materials, coupled with a relatively conservative approach to assumed maximum design stress levels. A conservative approach was necessary to minimize the risk of failure and hence damage to the wind tunnel facility.

MATERIAL TESTS

Specimens and tests

The test specimens were cut from five flat panels (approx 260 mm × 260 mm) which had been laminated under vacuum (0.85 bar). Detailed descriptions of the lay-up of each panel are given in *Table 1*. Fibre volume fractions were obtained from the composite density in conjunction with the fibre and matrix densities.

After being cut from the panels the specimens were machined to the correct dimensions. In the case of the tensile test specimens doublers were bonded on at each end with epoxy glue. Doubler material was the same as the test specimen for the glass-reinforced specimens and aluminium alloy for the glass/carbon specimens. Details

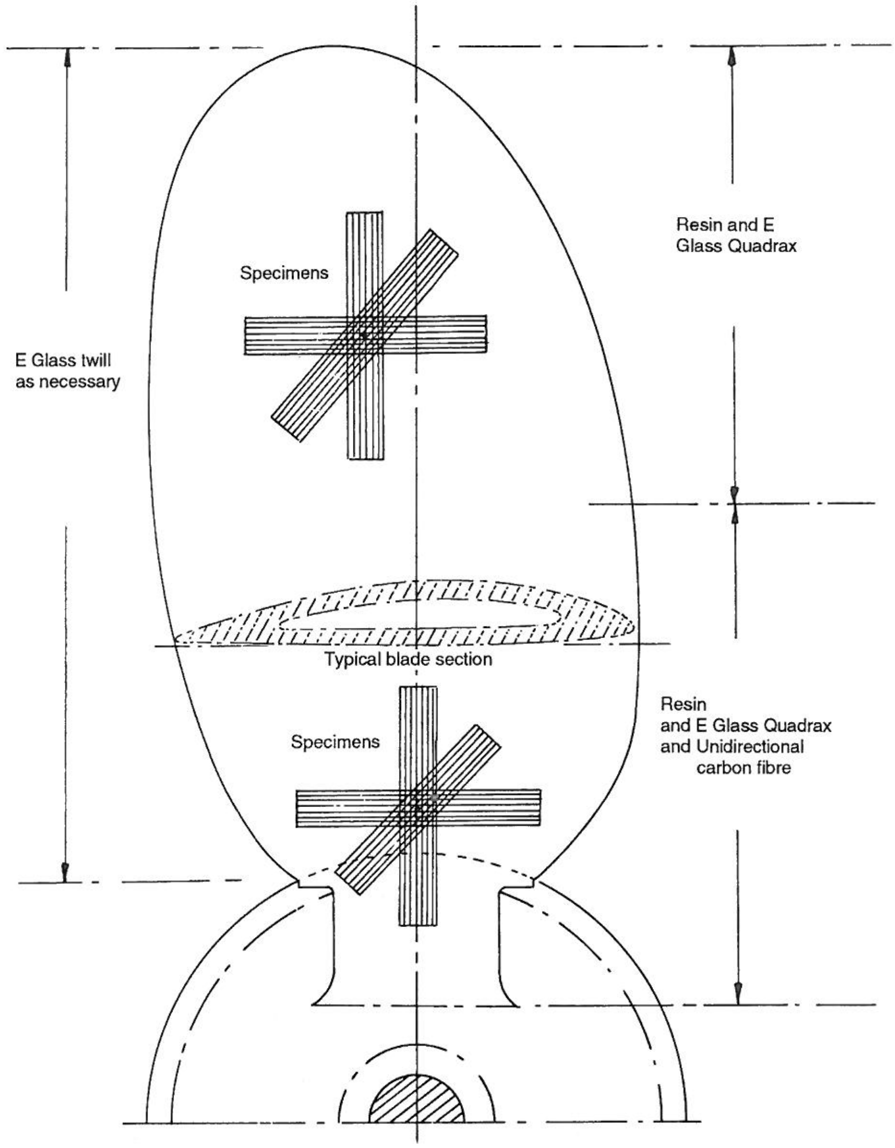


Figure 1 Approximate locations of representative test specimens

Table 1 Details of materials and test panels

Materials used:

	Mass:	Fibre orientation:
E Glass Twill	210 gm m^{-2}	0°, 90°
E Glass Quadrax	600 gm m^{-2}	0°, 90°, ±45°
Carbon fibre Graflok	200 gm m^{-2}	0°

Resin: Ampreg 25 epoxy (SPS)
All samples laminated with clear pre-gel on mould surface

Vacuum pressure: 0.85 Bar

Test panel no. (Lay-up date)	Material/lay-up	Fibre orientation	Composite ρ (kg m^{-3})	Approximate volume fraction (%)		
				V_M	V_G	V_C
1 (21/11/89)	10 Layers: E Glass Twill	0°, 90° 105 gm m^{-2} in each direction per layer	1570	60	40	—
2 (21/11/89)	4 Layers: E Glass Quadrax	0°, 90°, ±45° 150 gm m^{-2} in each direction per layer	1596	54	46	—
3 (23/11/89)	6 Layers: E Glass Quadrax	0°, 90°, ±45° 150 gm m^{-2} in each direction per layer	1543	53	47	—
4 (21/11/89)	9 Layers: E Glass Quadrax 7 Layers: Carbon Laminated alt., Quadrax on outer surfaces, double layer on top surface	Quadrax 0°, 90°, ±45° 150 gm m^{-2} in E (MN m^{-2}) per layer; Carbon 0° 200 gm m^{-2} per layer	1581	53	34	13
5 (23/11/89)	12 Layers: E Glass Quadrax 11 Layers: Carbon Laminated alt., Quadrax on outer surfaces	Quadrax 0°, 90°, ±45° 150 gm m^{-2} in each direction per layer; Carbon 0° 200 gm m^{-2} per layer	1583	64	25	11

of the orientation and dimensions of the specimens are given in *Table 2*.

Tests were carried out on the specimens to determine their modulus (E) and Ultimate Tensile Stress (UTS) values. The E values were derived from three-point flexture tests. The tensile tests were carried out on an Instron 1196 machine. Jaw slippage due to compression did not provide machine measured elongations of adequate accuracy, and instrumentation for measuring elongation directly on the specimen was not available. Thus E values were not derived from the tensile tests. For both the flexure and tensile tests the width and thickness of each specimen was measured using a micrometer at a number of positions and, where necessary, an average value used.

Test results

The results of the flexure and tensile tests are summarized in *Table 3*.

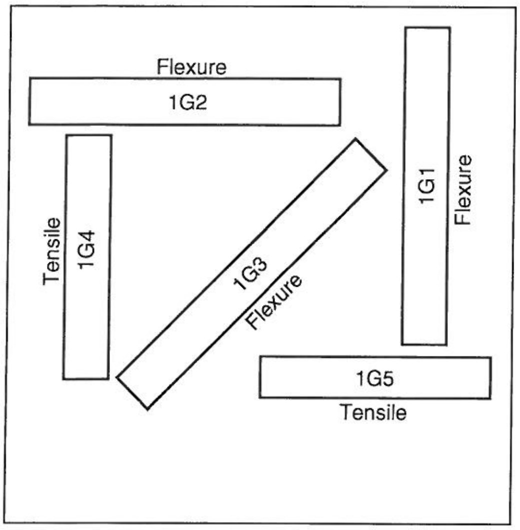
The tensile specimens were tested to failure hence single values were obtained. The results for similar materials are of similar magnitude, indicating satisfactory test techniques. All tensile specimens failed near the edge of the grips (*Figure 2*) which was to be expected since the maximum distortion of the fibres (due to compression of the grips) will occur in this region.

The flexure tests were repeated a number of times for each specimen over a linear range of loadings and, as seen in *Table 3*, resulted in some scatter in E value. The range of results is thus recorded in *Table 3*. The results for similar materials do, however, indicate similar ranges of E values, thus demonstrating satisfactory repeatability by the test techniques used.

Panel 1: Epoxy/E Glass Twill (fibre orientation 0°, 90°)

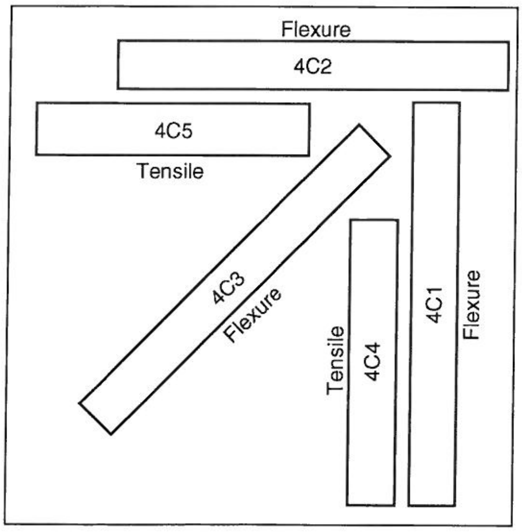
The E values are similar in the 0° and 90° directions and less in the 45° direction, which is to be expected. The magnitude of the values at 14 000–18 000 MN m^{-2} are relatively low for this type of reinforcement. UTS values were also relatively low and showed some difference (443 and 419 MN m^{-2}) in the 0° and 90° directions.

Table 2 Test specimens: orientations and nominal dimensions (All dimensions in mm)



↑ Principal orientation of glass fibres

Test panel 1: Epoxy/glass
Panels 2 and 3: Similar



↑ Principal orientation of glass fibres and unidirectional carbon fibres

Test panel 4: Epoxy/Glass/Carbon
Panel 5: Similar

			Overall length	Width	Support span
Flexure test Specimens	Epoxy/Glass		160	25	150
	Epoxy/Glass/Carbon		200	25	180
					Test length between grips
Tensile specimens	Epoxy/Glass		120	20	60
	Epoxy/Glass/Carbon		140	25	60
Nominal thicknesses:	Panel 1	(Epoxy/Glass):	2.4		
	2	(Epoxy/Glass):	2.4		
	3	(Epoxy/Glass):	3.6		
	4	(Epoxy/Glass/Carbon):	6.9		
	5	(Epoxy/Glass/Carbon):	12.5		

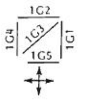
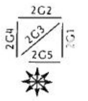
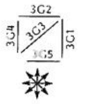
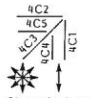
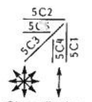
Panels 2 and 3: Epoxy/E Glass Quadrax (fibre orientation 0°, 90° ± 45°)

The results for the specimens from Panels 2 and 3, which are of the same materials but different total thickness, indicate similar ranges of *E* values and similar UTS values. It is noted that the *E* value ranges were similar in all directions tested which is to be expected with a 0°/90°/ ± 45° fibre orientation, although their magnitude at 10 000–12 000 MN m^{-2} would appear to be relatively low. UTS values for specimens from both Panels 2 and 3 have a higher value (288/283 MN m^{-2}) in the primary 0° plane (identified by blue tracer) than in the secondary 90° plane (236/253 MN m^{-2}), although these should have been of similar magnitude. There is no immediate explanation for this as both panels exhibited this same characteristic.

Panels 4 and 5: Epoxy/E Glass Quadrax (0°/90°/ ± 45°)/ Carbon (0°)

The results from both panels indicate similar ranges of *E* values and similar UTS values. The 0° orientation

Table 3 Summary of results

Test panel no.	Lay-up (Nominal thickness)	Orientation of specimen on panel	Specimen no.	UTS ($MN\ m^{-2}$)	E (Flexure tests) ($MN\ m^{-2}$) Range of experimental results	Mean
1	10 Layers:		1G1	—	15 800–18 400	16 770
	E Glass Twill		1G2	—	13 700–18 000	15 500
			1G3	—	7840–9550	8540
			1G4	443	—	—
	(2.4 mm)		1G5	419	—	—
2	4 Layers:		2G1	—	10 300–11 800	10 810
	E Glass Quadrax		2G2	—	10 500–11 300	10 790
			2G3	—	9860–11 500	10 670
			2G4	288	—	—
	(2.4 mm)		2G5	236	—	—
3	6 Layers:		3G1	—	11 500–12 200	11 930
	E Glass Quadrax		3G2	—	10 200–12 300	11 210
			3G3	—	10 700–11 800	11 430
			3G4	283	—	—
	(3.6 mm)		3G5	253	—	—
4	9 Layers:		4C1	—	26 200–30 000	27 220
	E Glass Quadrax		4C2	—	14 000–14 800	14 380
	7 Layers:		4C3	—	14 800–16 900	15 740
	Carbon		4C4	333	—	—
	(6.9 mm)	Glass Carbon	4C5	211	—	—
5	12 Layers:		5C1	—	24 500–34 300	28 800
	E Glass Quadrax		5C2	—	10 700–14 300	12 700
	11 Layers		5C3	—	11 100–14 600	13 600
	Carbon		5C4	294	—	—
	(12.5 mm)	Glass Carbon	5C5	150	—	—

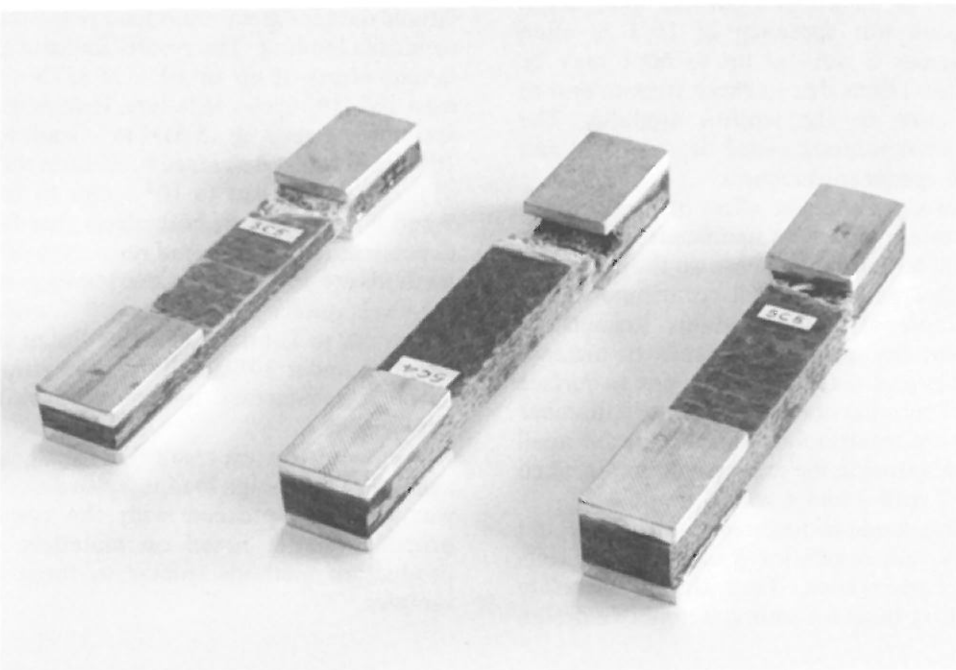


Figure 2 Examples of tensile test specimens (after failure)

(which includes the carbon) provides the highest E values at 25 000–34 000 $MN\ m^{-2}$ and it is interesting to note that the 45° and 90° orientation values are lower, but similar, at 11 000–16 000 $MN\ m^{-2}$ when the carbon would not be making a contribution. In the 45° and 90° cases, therefore, the values tend towards those of the Quadrax reinforcement alone as in Panels 2 and 3.

UTS values are 333 and 294 $MN\ m^{-2}$ in the 0° primary orientation and, as expected, values in the 90° direction are significantly lower at 211 and 150 $MN\ m^{-2}$.

Table 4 Some published test values for UTS and E: approximate ranges

Source	Material	Tension tests UTS ($MN\,m^{-2}$)	Tension tests E ($MN\,m^{-2}$)	Flexure tests E ($MN\,m^{-2}$)
*	Unidirectional Carbon/Epoxy	2000	130–160 000	55–110 000
*	Unidirectional Glass/Epoxy	1100–1300	52–60 000	30–45 000
*	0°/90° Glass/Epoxy	500–600	33–40 000	25–33 000
*	0°/90°/±45° Glass/Epoxy	350–500	27–37 000	14–22 000
†	Woven roving/Epoxy	150–350	—	15–20 000

* Derived from Reference 3: Prepreg/cure/autoclave
† Derived from Reference 2: Hand lay-up

Discussion of test results

The results for UTS and E, whilst appearing overall to be relatively low, are probably of the correct order of magnitude for a wet-lay-up by hand. They are lower than what might be expected from say a prepreg (manufacturer produced pre-impregnated system) as, for example, when compared with the results in *Table 4* which are summarized from Reference 4.

If the simple rule of mixtures is applied to the fibre and matrix properties, corrections to the rule of mixtures values have to be applied in order to achieve composite values comparable with the current test results. The need for such corrections in order to get values comparable with those achieved in commercial production is, for example, discussed in Reference 3.

References 4 and 5 both indicate that caution should be observed in the interpretation of moduli from flexure tests. Moduli in flexure are generally lower than those in tension, as indicated in *Table 4*. A minimum span/depth ratio for the flexure test specimen of 16/1 is often recommended whereas a ratio of up to 60/1 may be required to minimize effects due to shear stresses and to achieve a value close to the tension modulus. The span/depth ratio for these tests varied between 14.4 and 62.5 depending on specimen thickness.

Reference 5 points out that the effect of surface resin layers on flexural modulus can be significant since outer surfaces of resin will have little influence on the deflection of a laterally loaded beam, but will contribute to the thickness used in computing the modulus. Reference 5 also points out that flexure modulus tends to increase with number of plies and that this may be due to surface resin layer effect. The influence of surface resin/number of plies on flexure test results might account for the small increases in mean E values in the principal direction when comparing Panel 2 with 3 and 4 with 5 in *Table 3*.

Finally, the points made in References 4 and 5 would suggest that the current results for E using flexure tests are likely to be conservative. They should therefore provide a satisfactory basis for setting acceptable design limits.

BLADE DESIGN STRESS CRITERIA

Maximum stresses for this propeller type will occur near the root of the blade and are made up of a combination of bending stresses due to thrust and torque loading and direct stress due to centrifugal loading. Bending moments due to thrust and torque loadings and direct centrifugal load were estimated for the most heavily loaded condition for the propeller. Based on an assumed wall thickness of 12.0 mm at the root of the propeller the estimated maximum bending moments and direct load lead to a maximum combined stress of 27 $MN\,m^{-2}$.

The tests on the specimen samples discussed earlier suggest that 27 $MN\,m^{-2}$ is a satisfactory maximum design stress. Sample 5, which was representative of the lay-up at the root, had an E value (min) of 24 500 $MN\,m^{-2}$ and a UTS of 294 $MN\,m^{-2}$. Thus, in the most onerous condition, strain at the root would be of the order of 0.11% and maximum stress 9.2% of UTS. Both of these figures are deemed to be within satisfactory design limits.

The propeller will be working primarily in uniform flow and hence will not normally be subjected to significant fatigue loading. Some fatigue loading may, however, occur if the propeller is working in an oblique flow or if, sometime in the future, a non-uniform wake is simulated upstream of the propeller.

Reference 6 brings together from a number of sources fatigue data for glass-reinforced polyester when subjected to tensile loading. The results indicate that a maximum fatigue stress of up to 10% of UTS should lead to at least 10^8–10^9 cycles to failure. Reference 7 indicates that, for epoxy/E glass, ± 15 $MN\,m^{-2}$ leads to failure at about 10^8 cycles whilst Reference 8 indicates that a fatigue strain of 0.7% would lead to 10^8 cycles to failure. References 7 and 8 do, however, both stress that fatigue life is very dependent on the choice of resin, type of glass and lay-up methods etc. However, fatigue loadings will not approach the levels quoted in References 6, 7, and 8 which lead to 10^8 cycles to failure, hence the design steady maximum stress of under 10% UTS (0.12% strain) is considered to be a satisfactory maximum working level in this application.

Following the test results described earlier and further analysis of the design loadings also described, the decision was made to proceed with the construction of the propeller blades based on materials, thicknesses and production methods similar to those used in the test samples.

ROOT ATTACHMENT DESIGN

Stresses will be high near the root and the attachment of the blade to the boss presented the need for careful design. Design requirements included the ability to adjust the pitch of the blades, and a simple means of doing this was required to be incorporated.

A number of techniques were considered including the moulding into the blade of an aluminium alloy root spigot, which could be bolted or clamped to the boss.

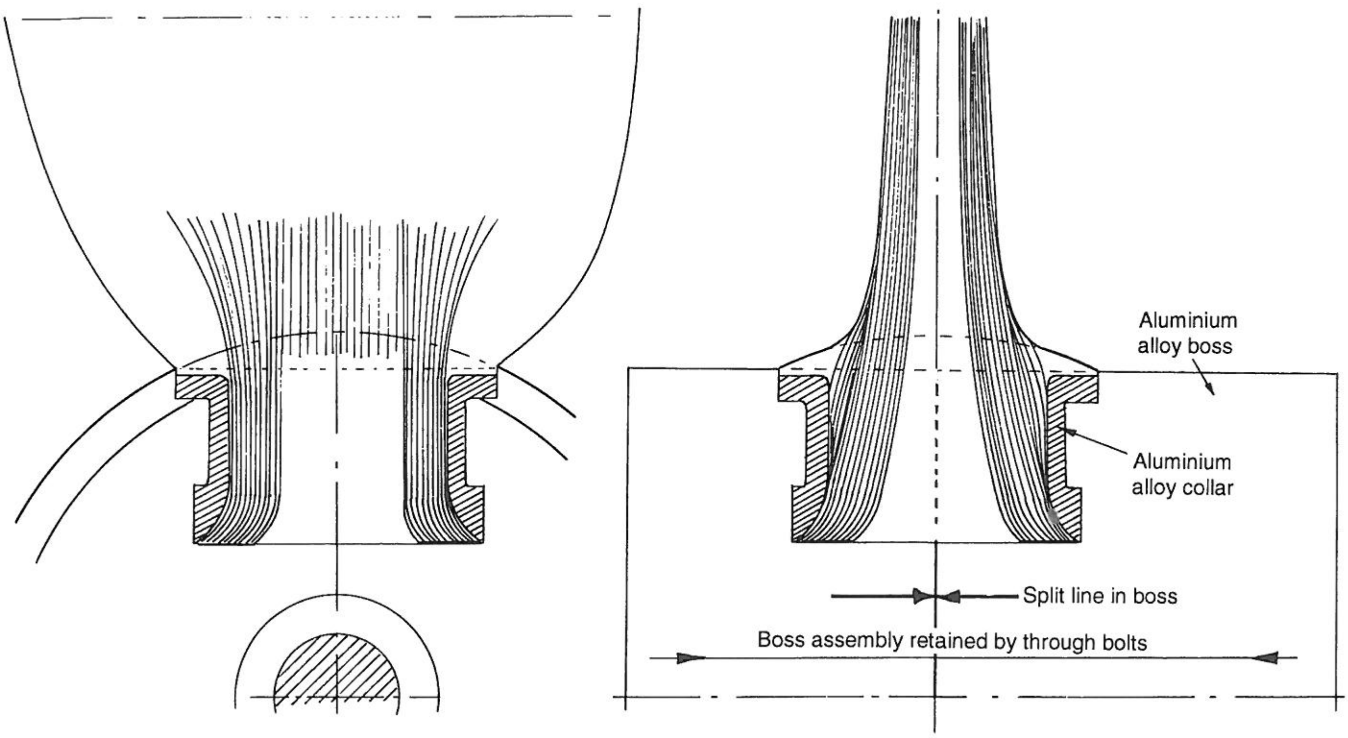


Figure 3 Root fitting and orientation of fibres

Such a method is described in Reference 9. This technique would require careful design and manufacture at the root attachment/composite interface, and accurate (probably jigged) alignment between the spigot and the blade.

Clamping the root of the blade composite material using an aluminium alloy split boss had been used successfully for earlier aircraft and wind turbine model composite propellers in the Southampton University Wind Tunnel. Although in those cases the blades were of much smaller area and hence mass, the clamping technique had proved successful and was therefore adopted for this propeller.

Details of the root fitting and orientation of the fibres in this region are given in *Figure 3*. The fibres are continuous through the root section and bell out from the minimum diameter. In this particular design, after laying up the blade, the root section is encased in an aluminium split collar which is bonded to the blade (using the split boss as a clamping device during bonding to provide bonding pressure and ensure correct alignment). Thus the clamping sections now bear on the aluminium alloy collar rather than on the composite material itself. This prevents damage to the resin and fibres during blade pitch adjustment. Care was taken with tolerances on the diameters of the moulded blade, alloy collar and receiving boss recess whereby the blade is firmly clamped without incurring significant distortion in the root fibres. The bell-shaped form of the sections and fibres at the root, and the clamping action of the boss, constrains the blade axially and in all other diretions.

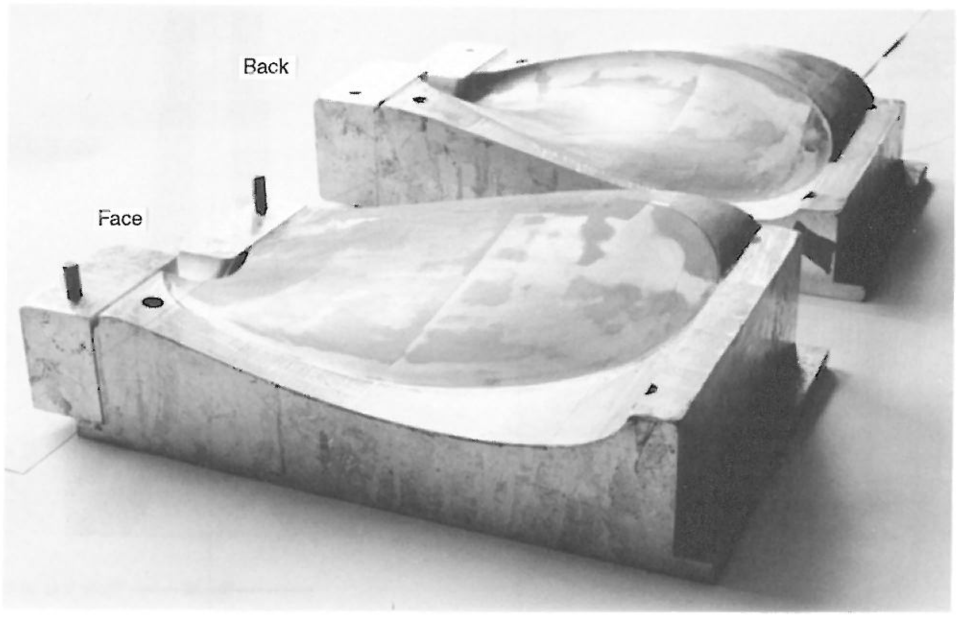
PRODUCTION OF MOULD

The propeller design and drawing had been developed on a computer. This also enabled software to be written for the NC production of the female blade mould which was of split form (for face and back of blade). Each mould was NC machined from a solid block of aluminium alloy (*Figure 4*). Details of the mould manufacturing process are given in Reference 1. The final surface was hand finished in preparation for the laying-up process.

PRODUCTION OF BLADES

The blades were manufactured by Nick Barlow (Boatbuilder), Southampton. The face and back of each blade was laid up separately using the split female mould. The glass and carbon fibre reinforcements were cut and laid so that the blade wall thickness tapered gradually from root to tip. This resulted, per the test specimens, in a maximum blade wall thickness of 12 mm at the root reducing to 3 mm at about 75% of the blade span. Between 75% of the blade span and the tip the blade halves merge into a solid section with an overall thickness which varies linearly to a minimum value of 1 mm at the tip itself. Great care was taken to ensure that the reinforcements were laid with the correct orientation (relative to the blade axis) and with no abrupt changes in shape. This was particularly important near the root where the blade sections change from aerofoil shape to a 60 mm diameter fairly rapidly. The reinforcements were all continuous to the innermost part of the blade which flairs out to a larger diameter at the inner part of the 60 mm diameter blade root clamping section.

When each blade half had been laid up, a vacuum bag (at 0.85 bar) was applied to each to remove excess resin and air. The laying up process was carried out under normal workshop conditions and the blade halves were cured at a temperature of 70°C for 6 h. Once cured, the blade halves were left in the mould while excess material was removed from around the blade edge. The mating surfaces of the blade halves were prepared and epoxy resin applied. The two halves of the split mould were then clamped together until the resin had cured. On



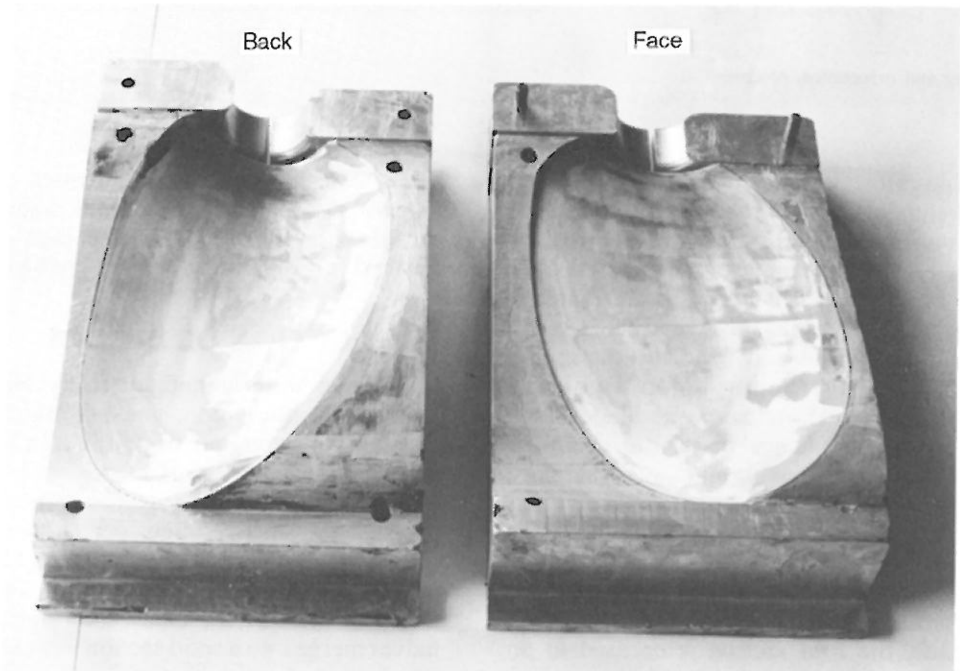


Figure 4 Blade moulds

removal of the completed blade, aluminium alloy collars were epoxy resin bonded to the roots of the blades. The final stage of manufacture was the assembly of the hub and four blades, as shown in *Figure 5*. The whole propeller was dynamically balanced by a specialist firm before being commissioned in the wind tunnel.

COMMISSIONING OF PROPELLER AND RIG

Commissioning tests using the propeller took place in March 1990 and further tests took place in August 1990. The propeller was used extensively over the entire range of speeds between 0 and 3000 rev min^{-1}. The possible development of looseness of blade attachment, or cracking/failure of blade material, was monitored closely but no such problems have occurred.

CONCLUSIONS

A description has been given of the application of composite materials to model propeller blades which have a complex shape and which are subjected to relatively high loadings. Satisfactory operation of the propeller confirmed the suitable application of these materials.

Costs, and the complex shape of the blades, restricted the production method to a wet-lay-up by hand under normal production conditions. Prior to blade manufacture, test samples were produced using the proposed

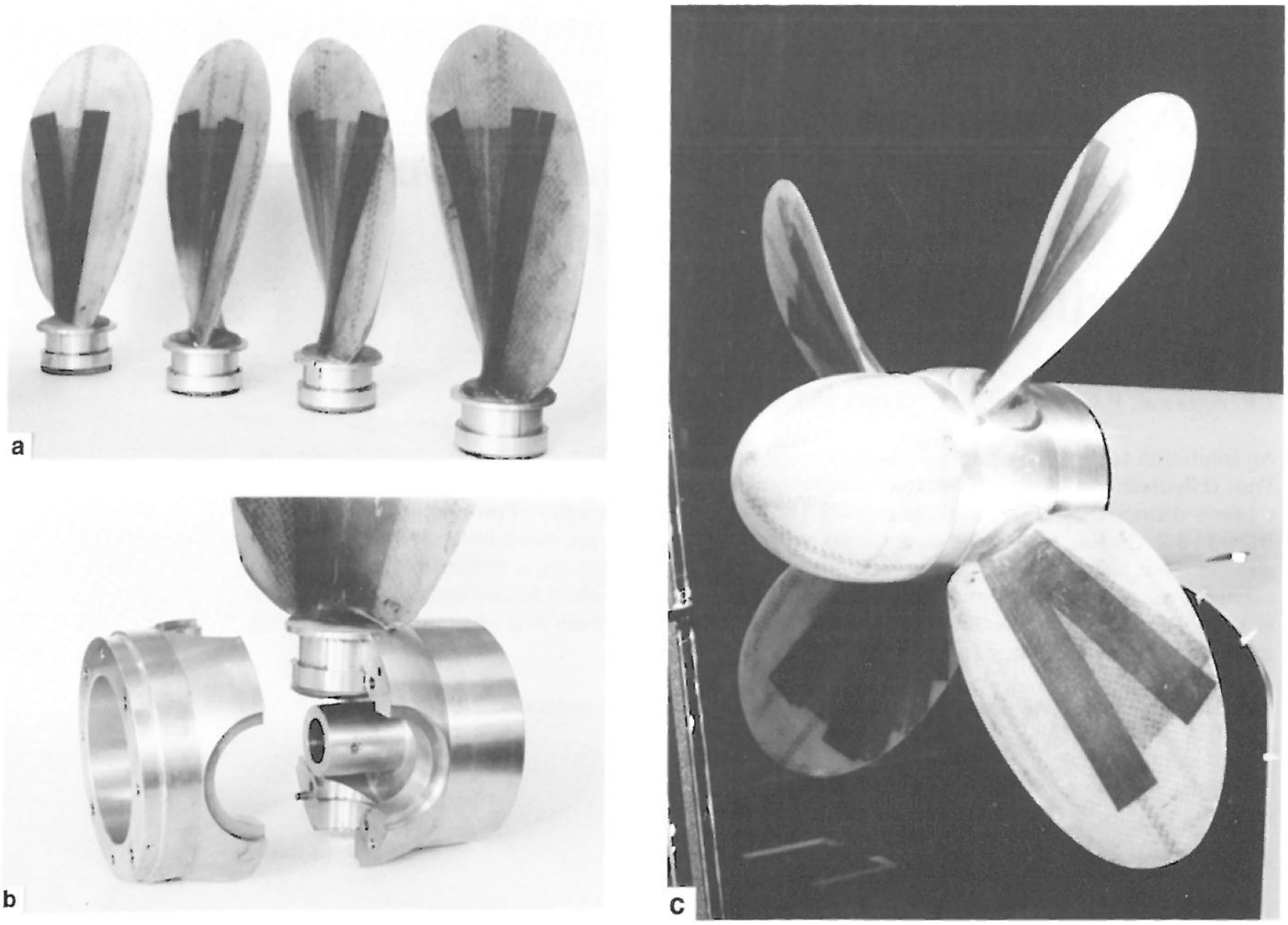


Figure 5 (a) Individual blades, (b) boss and (c) assembled propeller

materials, thicknesses and lay-up method. Test results for the samples indicated relatively low physical properties. The results obtained have therefore demonstrated the importance of such tests where a hand lay-up is to be used and where a realistic assessment is required to be made of the maximum design stress levels.

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Fibre-reinforced plastic fabrication based technique for inhibition of composite propellants

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An inhibition technique using a fibre-reinforced plastic fabrication concept has been developed. The polyurethane derived by the reaction of hydroxy-terminated polybutadiene (HTPB), toluene-diisocyanate (TDI) and butanediol (BD) as a chain-extender (Formulation-HTPB : TDI : BD :: 1 : 3.2 : 2) has been used as a matrix with reinforcement provided by a rayon thread. The sleeves have been fabricated by a filament winding technique using a collapsible mandrel and serve the purpose of an inhibitor for composite propellants. The chief advantage of this technique is a reduction in inhibition thickness and, consequently, an increase in propellant weight leading to an increase in the range/payload of a rocket/missile.

Keywords: composite propellant; inhibition technique; chain-extender; sleeve fabrication

INTRODUCTION

Rocket propellant technologists require a definite pattern of propellant burning which can be achieved by applying inert polymeric material over the propellant surface. This polymeric material is called the 'inhibitor', and the process of its application is known as 'inhibition'. Hydroxy-terminated polybutadiene (HTPB) is considered a high energy fuel-binder for composite propellants which are generally inhibited by the 'casting technique' using the same fuel-binder filled with inert fillers[1,2]. The main disadvantage of this technique is that it demands a higher inhibition thickness resulting in a decrease in the range/payload of a rocket/missile.

With the salient feature of fibre-reinforced plastics (FRP) being a higher strength-to-weight ratio[3], it was considered of interest to develop a new inhibition technique for composite propellants by using the FRP fabrication concept. As composite propellant is based on HTPB, the matrix is also based on a HTPB-derived polyurethane (PU) to provide an excellent bond between propellant and inhibitor. Also, HTPB-derived PUs possess superior hydrolytic stability and outstanding physico-chemical properties as compared to PUs derived from polyester and polyether glycols.[4,5]

The present work describes the preparation/synthesis of polyurethanes derived from HTPB, toluene diisocyanate (TDI) and different diols as chain-extenders, and the effect of fillers on them. Also, a method for fabrication of sleeves based on talc-filled HTPB-derived PU as a matrix and rayon thread as a reinforcement has been developed and sleeves have been found suitable for inhibition of composite propellants.

EXPERIMENTAL

Materials

R-45 M HTPB (ARCO, USA) and toluene diisocyanate (TDI) (Bayer, Germany) were used as received. The HTPB is a colourless viscous liquid, possessing number average molecular weight, $\bar{M}_m \approx 2600$ and hydroxyl content of 45 mEq kg^{-1}.

The low molecular weight diols ethylene glycol (EG), 1,2 propanediol (PG), 1,4 butanediol (BD), polyethylene glycol mol wt 200 (PEG-200), and polyethylene glycol mol wt 400 (PEG-400) (all British Drug House, Laboratory Reagent, BDH, LR) were also used without further purification. Dibutyl tin dilaurate (Fluka, Switzerland) was used as a catalyst.

Rubber grade carbon black, talc and silica (Arosil) were used as fillers. Rayon thread (average denier 1650, breaking load, 7.5 kg, elongation at break, 25%) was used for reinforcing the filled polyurethane.

Methods

Elastomer preparation

The method of preparation of PU is similar to the method reported earlier in the literature[6] and is given below.

One mole of HTPB was allowed to react with 3.2 moles of TDI at room temperature under nitrogen atmosphere, followed by the addition of 2.0 moles of diol and then stirring for 15 min. The reaction mixture was degassed, dibutyl tin dilaurate (catalyst) was added and mixed. This product was poured into different wooden moulds