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OF
SOUTHAMPTON

DEPARTMENT OF SHIP SCIENCE

FACULTY OF ENGINEERING
AND APPLIED SCIENCE

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1. INTRODUCTION

A description is given of the background design, choice of composite materials and construction of a model of a ship propeller. The propeller was to form part of a propeller/rudder experimental rig which would be used in a wind tunnel to investigate interactions between ship propellers and rudders.

2. OUTLINE OF PROPELLER PARTICULARS

A four-bladed propeller of 800mm diameter was chosen for the projected wind tunnel tests. The design was modelled on a basis ship propeller of known dimensions and performance (Wageningen Series B4.40, e.g. Ref. 1) which would enable validation of the performance of the new propeller to take place in the wind tunnel. Some design adjustments (compared with the basis) were incorporated in order to make the propeller more suitable for this particular application. The rake of the propeller blades was effectively reduced to zero and blade sweep reduced thus minimising root bending moments due to the relatively high centrifugal loads. The blade root thickness was also increased a little above the standard for the basis propeller. Details of the propeller geometry are given in Ref. 2.

It was considered necessary that the pitch of the propeller should be adjustable whereby the range of thrust loadings could be extended if required. This facility was therefore incorporated in the design of the blade at its root by allowing the individual blades to be rotated to the desired pitch setting and then locked in position.

The propeller boss has a maximum diameter of 200mm (0.25 x diameter for a 800mm propeller) and is manufactured from aluminium alloy. A split boss arrangement is employed in order to incorporate/clamp the blades at their roots and to facilitate pitch variation.

3. MATERIALS

3.1 General

Design requirements included the need to have four identical blades, which were dimensionally accurate and whose pitch could be adjusted, at a realistic cost. It was also noted that relatively high revolutions (up to 3000 rpm) would result in high centrifugal (axial) loadings and hence high direct stress levels at the propeller root. These requirements, together with earlier experience in composite propellers at Southampton, led to the decision to use blades manufactured from 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.

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 Ref. 3 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 that for glass reinforced plastic.

The principal glass reinforcement used is 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 is also used in confined areas and areas of complex curvature such as leading and trailing edges and at the blade tip.

The blades would be hollow with a wall thickness of about 3mm near the tip increasing to about 12mm near the root. Estimates of blade loadings indicated that this would lead to combined bending and direct stresses in the root sections of up to 27 MN/m^2.

Published data indicate significant variation in physical properties (e.g. E and UTS) for different reinforcements and layups, Refs. 4 and 5. This is particularly true where wet-lay-up by hand under normal production conditions is to be used, Ref. 6. 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 Fig. 1. It is to be emphasised 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 is necessary to minimise the risk of failure and hence damage to the wind tunnel facility

3.2 Tests to Determine Physical Properties

The test specimens were cut from five flat panels (approx 260mm x 260mm) which had been laminated under vacuum (0.85 Bar). Detailed descriptions of the lay up of each panel are given in Table I. Fibre volume fractions were obtained from the composite density (by weighing panels and specimens of known volume) 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 Araldite. These provided a surface for gripping in the jaws of the Instron tensile test machine without damaging the fibres of the specimen itself. Doubler material was the same as the test specimen for the glass reinforced specimens and aluminium alloy for the glass/carbon specimens.

Details of the orientation and dimensions of the specimens are given in Table II.

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 flexure tests; these were carried out on the test rig in the Department of Mechanical Engineering. The specimen was loaded at mid span. The mid span deflection was measured by means of a linear displacement transducer connected to a microcomputer. The span and precise section dimensions of the specimen are also input and the E value calculated and output.

The tensile tests were carried out on an Instron 1196 machine in the Department of Engineering Materials. 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.

3.3 Discussion of Test Results

The results of the flexure and tensile tests are summarised in Table III.

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 (Fig. 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 III, resulted in some scatter in E value. The range of results is thus recorded in Table III. The results for similar materials do however indicate similar ranges of E values, thus demonstrating satisfactory repeatability for 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 14000 - 18000 MN/m^2 are on the low side for this type of reinforcement. UTS values were also on the low side and showed some difference (443 and 419 MN/m^2) in the 0° and 90° directions.

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 10000 - 12000 MN/m^2 would appear on the low side. 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 (which includes the carbon) provides the highest E values at 25000-34000 MN/m^2 and it is interesting to note that the 45° and 90° orientation values are lower, but similar, at 11000-16000 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.

3.4 General Comments on the Test Results

The results for UTS and E, whilst appearing overall to be on the low side, 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 IV which are summarised from Ref. 5.

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 Ref. 4.

Refs. 5 and 6 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 IV. 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 minimise 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.

Ref. 6 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. Ref. 6 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 III.

Finally, the points made in Refs. 5 and 6 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.

4. 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. In the current design, blade rake (usually aft) has been effectively reduced to zero, hence eliminating bending stress arising due to centrifugal load on a raked blade.

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 12.0mm 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 in Section 3 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 24500 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.

Ref. 7 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. Ref. 8 indicates that, for epoxy/E glass, ± 15 MN/m^2 leads to failure at about 10^8 cycles whilst Ref. 9 indicates that a fatigue strain of 0.7% would lead to 10^8 cycles to failure. Refs. 8 and 9 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 Refs. 7, 8, and 9 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 in Section 3 and further analysis of the design loadings described in this Section, 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.

5. 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. Such a method is described in Ref. 10. 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 a 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 Fig. 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 directions.

6. 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, Fig. 4. Details of the mould manufacturing process is given in Ref. 2. The final surface was hand finished in preparation for the laying-up process.

7. PRODUCTION OF BLADES

The blades were manufactured by Nick Barlow (Boatbuilder), Southampton.

The face and back of each blade was layed up separately using the female moulds. A vacuum bag was applied to each to remove excess resin and air. The two halves were subsequently bonded together.

The reinforcements were cut and laid up whereby thickness tapered gradually from root to tip. 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 60mm diameter fairly rapidly. The reinforcements were continuous to the innermost part of the blade which flairs out to a larger diameter at the inner part of the 60mm diameter blade root clamping section, as described in Section 5.

Aluminium alloy collars were epoxy resin bonded to the roots of the blades, as described in Section 5.

The whole propeller was assembled (Fig. 5) and was dynamically balanced by a specialist firm before being commissioned in the wind tunnel.

8. COMMISSIONING OF PROPELLER AND RIG

Commissioning tests on the propeller and rig took place in March 1990.

The propeller was used extensively in the range 2000-2200 rpm and for a short period at 2950 rpm (the maximum attainable by the controller). Possible development of looseness of blade attachment or cracking/failure of blade material, was monitored closely.

The overall rig behaved well and the propeller performed satisfactorily without incident.

This report has been concerned with the structural properties and construction of the propeller. The aerodynamic performance characteristics of the propeller are the subject of a separate report, Ref. 11.

ACKNOWLEDGEMENTS

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MATERIALS USED:

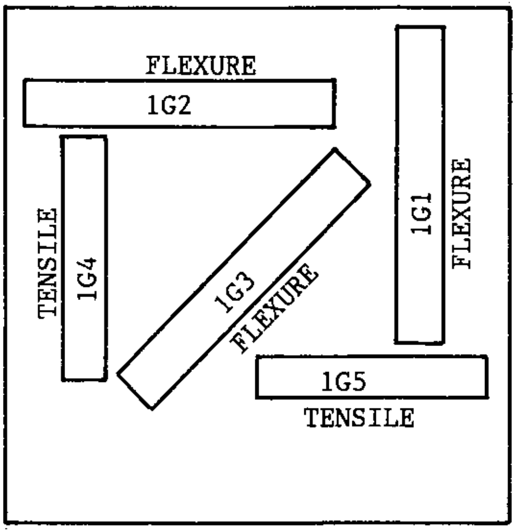
	Mass:	Fibre Orientation:
E GLASS TWILL	210 gm/m^2	0°, 90°
E GLASS QUADRAX	600 gm/m^2	0°, 90°, ±45°
CARBON FIBRE GRAFLOK	200 gm/m^2	0°

RESIN: AMPREG 25 EPOXY (SPS)
ALL SAMPLES LAMINATED WITH CLEAR PRE-GEL ON MOULD SURFACE.

VACUUM PRESSURE: 0.85 Bar.

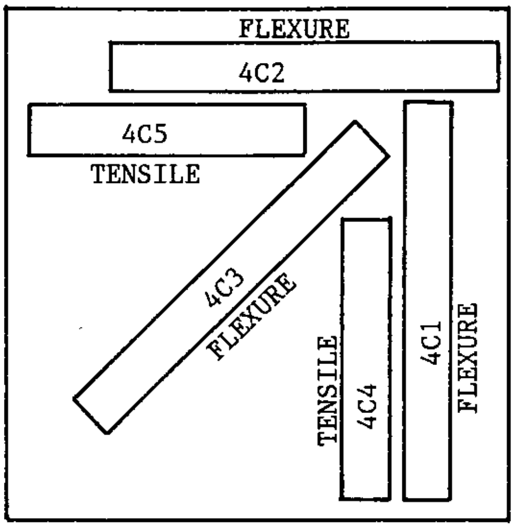
TEST PANEL NO. (Layup date)	MATERIAL/LAYUP	FIBRE ORIENTATION	COMPOSITE ρ kg/m^3	APPROX. VOL. FRACTION %		
				V_M	V_G	V_C
1 (21/11/89)	10 Layers: E Glass Twill	 0°, 90° 105 gm/m^2 in each direction per layer	1570	60	40	-
2 (21/11/89)	4 Layers: E Glass Quadrax	 0°, 90°, ±45° 150 gm/m^2 in each direction 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 each direction 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

TABLE I: DETAILS OF MATERIALS AND TEST PANELS



↑ PRINCIPAL ORIENTATION OF GLASS FIBRES

TEST PANEL 1: EPOXY/CLASS
PANELS 2 & 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/Class):	3.6
	4	(Epoxy/Glass/Carbon):	6.9
	5	(Epoxy/Glass/Carbon):	12.5

TABLE II: TEST SPECIMENS: ORIENTATIONS AND NOMINAL DIMENSIONS
(All dimensions in mm)

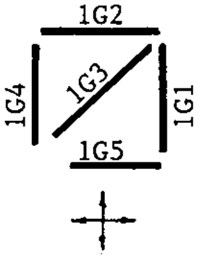
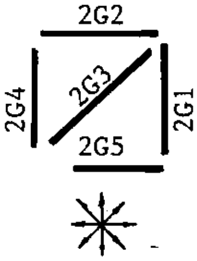
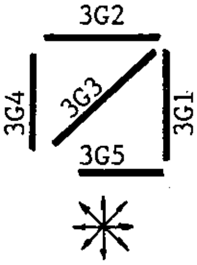
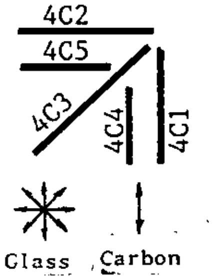
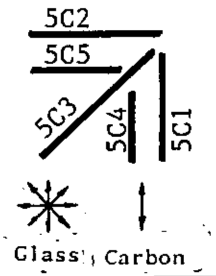
TEST PANEL No.	LAYUP (Nominal Thickness)	ORIENTATION OF SPECIMEN ON PANEL	SPECIMEN NO.	UTS MN/m^2	E (Flexure Tests) MN/m^2	
					Range of Exp'l Results	Mean
1	10 Layers: E Glass Twill (2.4mm)		1G1	-	15800-18400	16770
			1G2	-	13700-18000	15500
			1G3	-	7840-9550	8540
			1G4	443	-	-
			1G5	419	-	-
2	4 Layers: E Glass Quadrax (2.4mm)		2G1	-	10300-11800	10810
			2G2	-	10500-11300	10790
			2G3	-	9860-11500	10670
			2G4	288	-	-
			2G5	236	-	-
3	6 Layers: E Glass Quadrax (3.6mm)		3G1	-	11500-12200	11930
			3G2	-	10200-12300	11210
			3G3	-	10700-11800	11430
			3G4	283	-	-
			3G5	253	-	-
4	9 Layers: E Glass Quadrax 7 Layers: Carbon (6.9mm)		4C1	-	26200-30000	27220
			4C2	-	14000-14800	14380
			4C3	-	14800-16900	15740
			4C4	333	-	-
			4C5	211	-	-
5	12 Layers: E Glass Quadrax 11 Layers: Carbon (12.5mm)		5C1	-	24500-34300	28800
			5C2	-	10700-14300	12700
			5C3	-	11100-14600	13600
			5C4	294	-	-
			5C5	150	-	-

TABLE III: SUMMARY OF RESULTS

SOURCE	MATERIAL	TENSION TESTS		FLEXURE TESTS
		UTS MN/m^2	E MN/m^2	E MN/m^2
*	Unidirectional Carbon/Epoxy	2000	130-160000	55-110000
*	Unidirectional Glass/Epoxy	1100-1300	52-60000	30-45000
*	0°/90° Glass/Epoxy	500-600	33-40000	25-33000
*	0°/90°/±45° Glass/Epoxy	350-500	27-37000	14-22000
+	Woven Roving/Epoxy	150-350	-	15-20000

* Derived from Ref. 4: Prepreg/cure/autoclave

\+ Derived from Ref. 3: Hand lay-up

TABLE IV: SOME PUBLISHED TEST VALUES FOR UTS AND E: APPROXIMATE RANGES

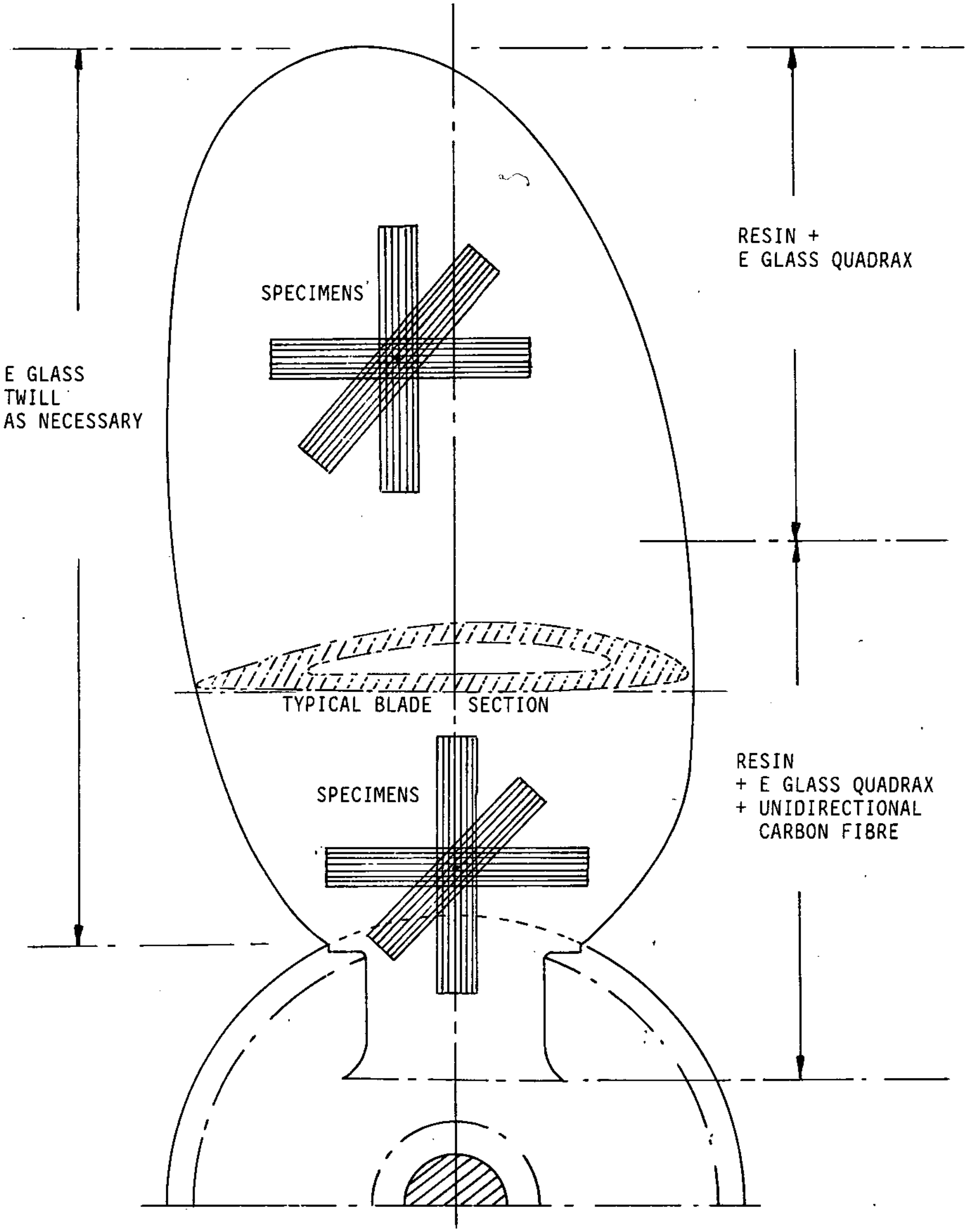


Fig. 1 APPROXIMATE LOCATIONS OF REPRESENTATIVE TEST SPECIMENS

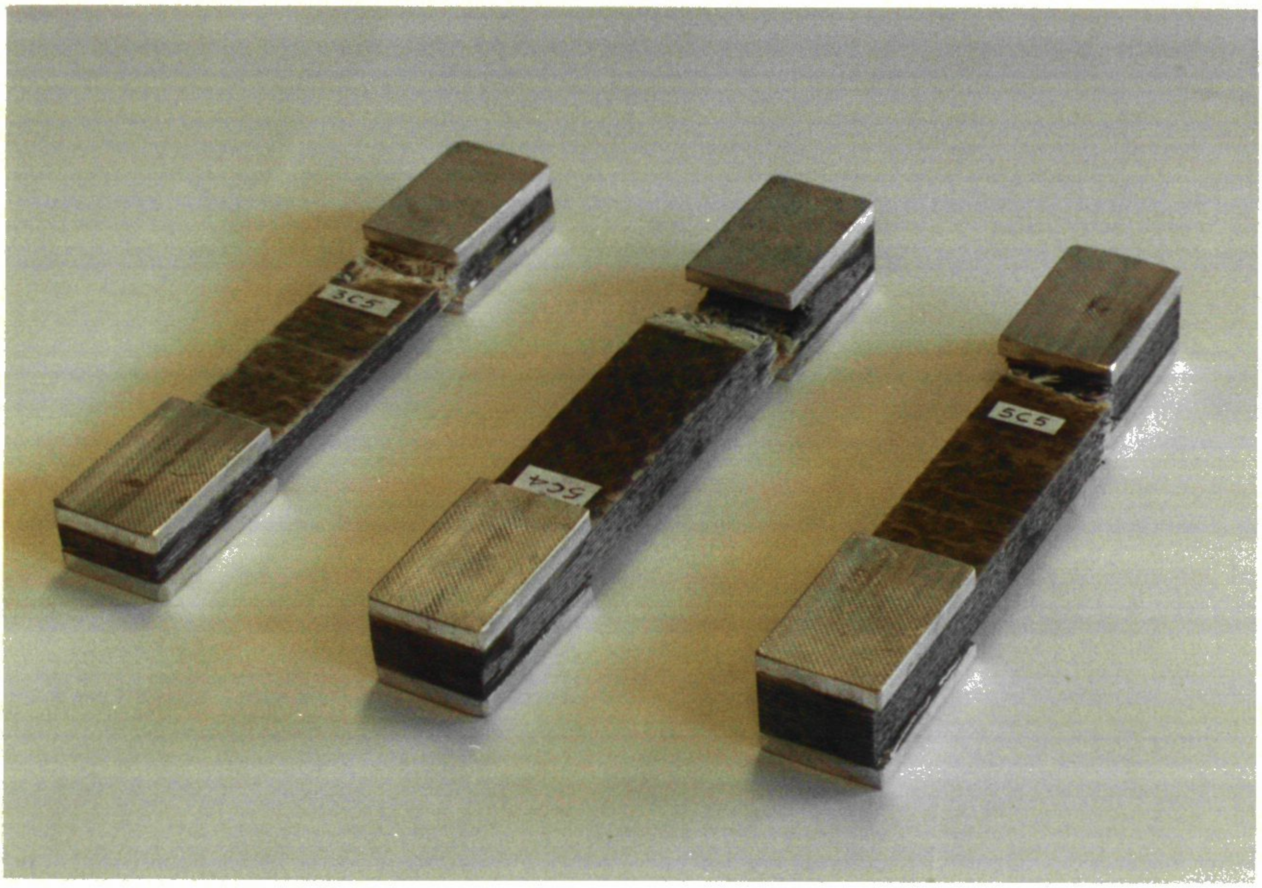


Fig.2 EXAMPLES OF TENSILE TEST SPECIMENS (AFTER FAILURE)

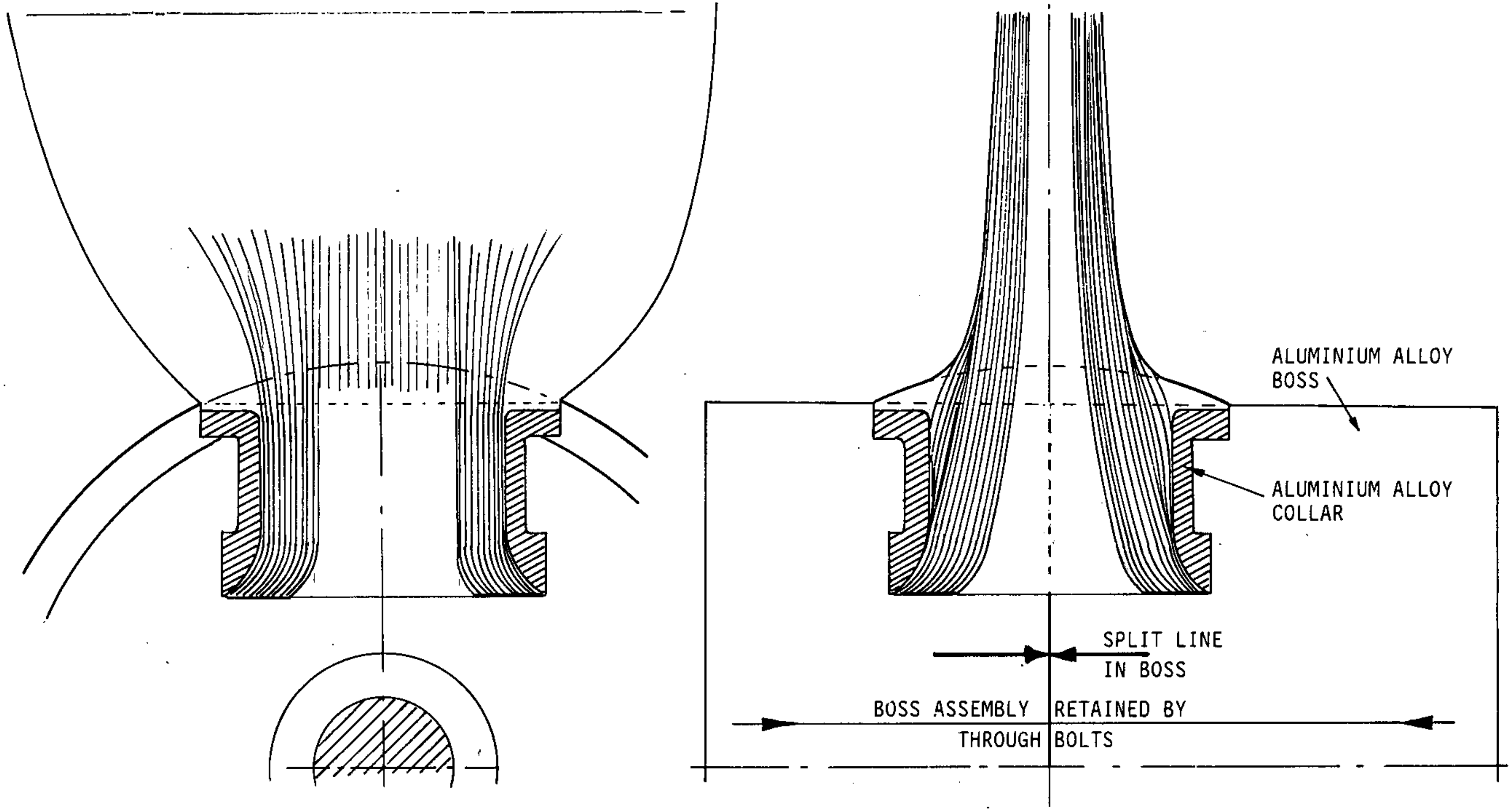


Fig.3 ROOT FITTING AND ORIENTATION OF FIBRES

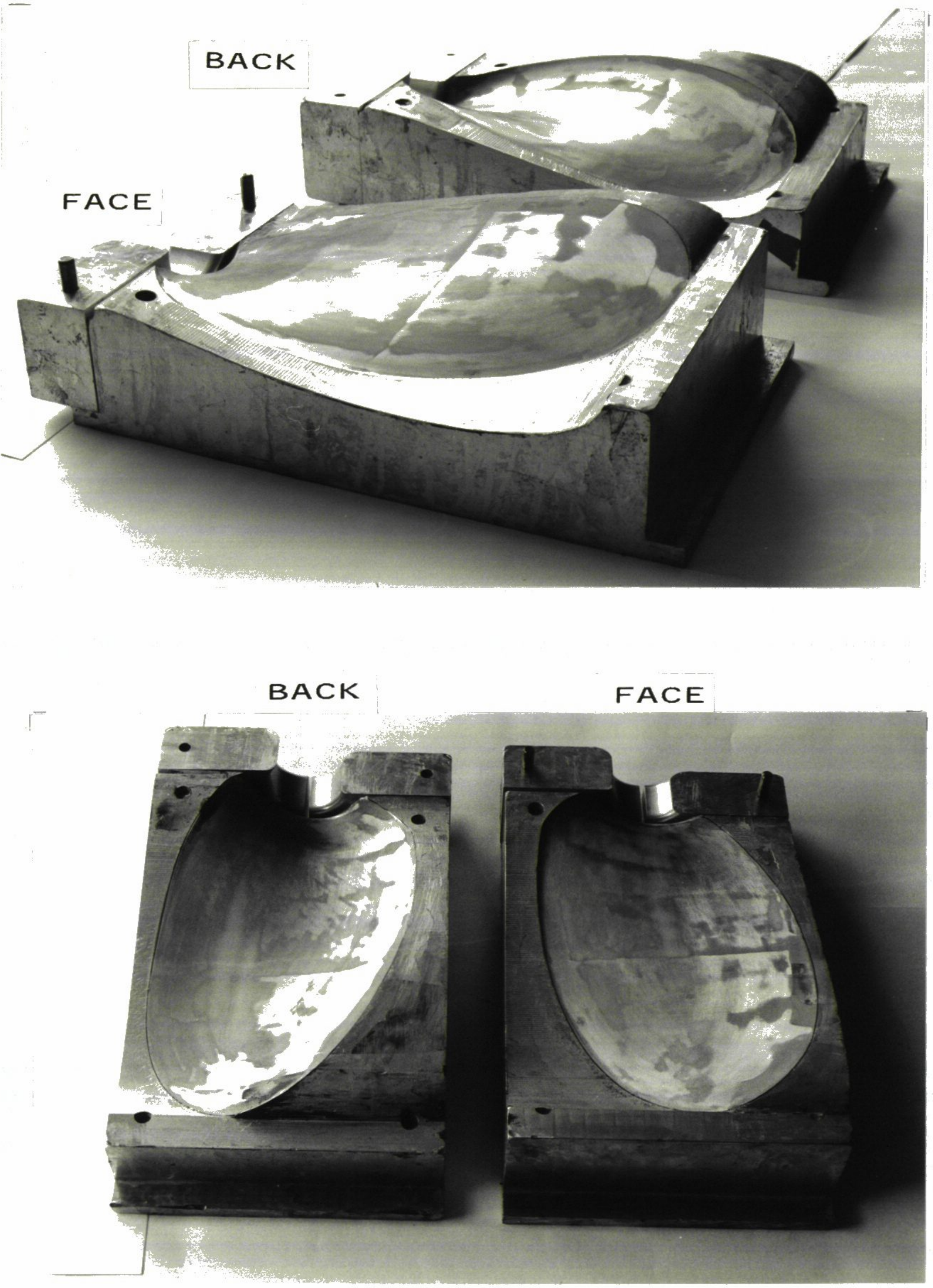


Fig.4 BLADE MOULDS

Fig.5 INDIVIDUAL BLADES, BOSS AND ASSEMBLED PROPELLER

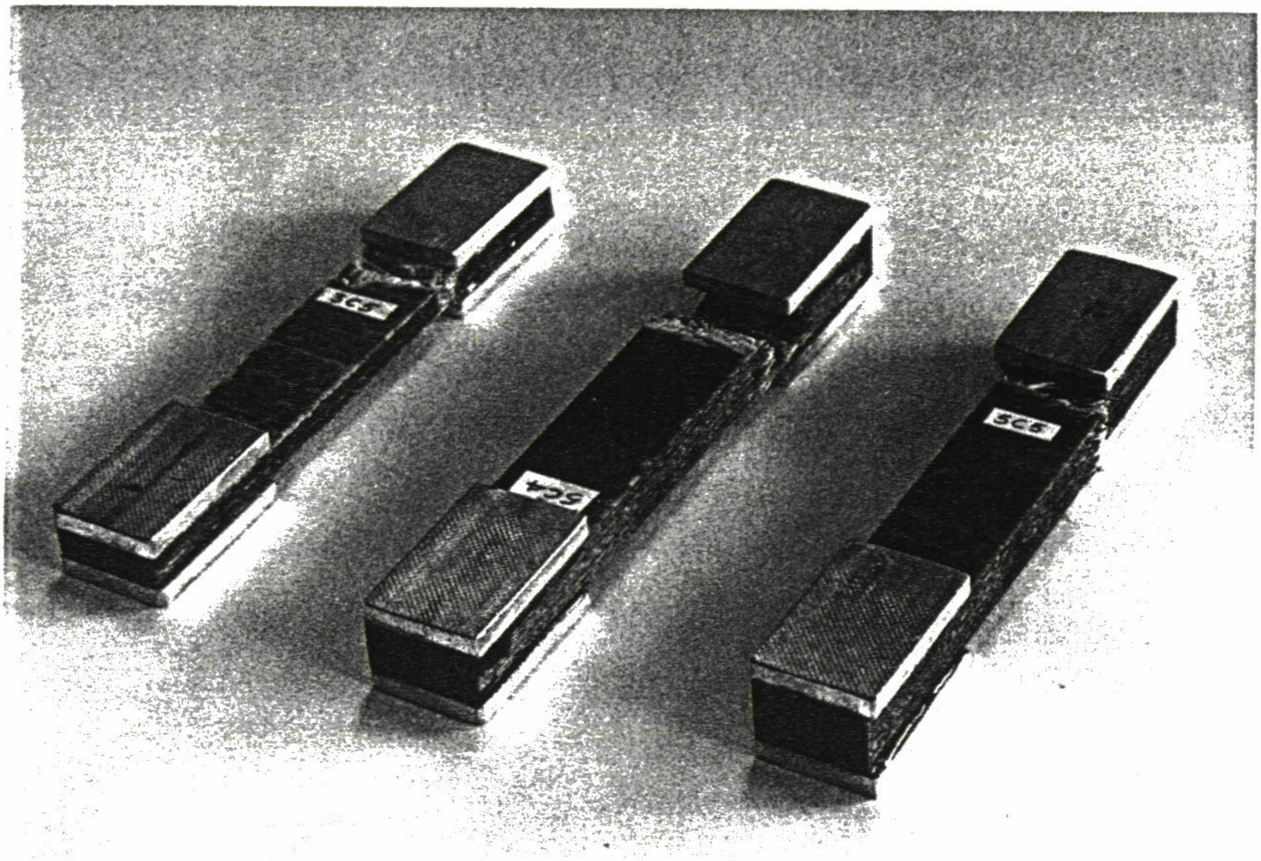


Fig.2 EXAMPLES OF TENSILE TEST SPECIMENS (AFTER FAILURE)

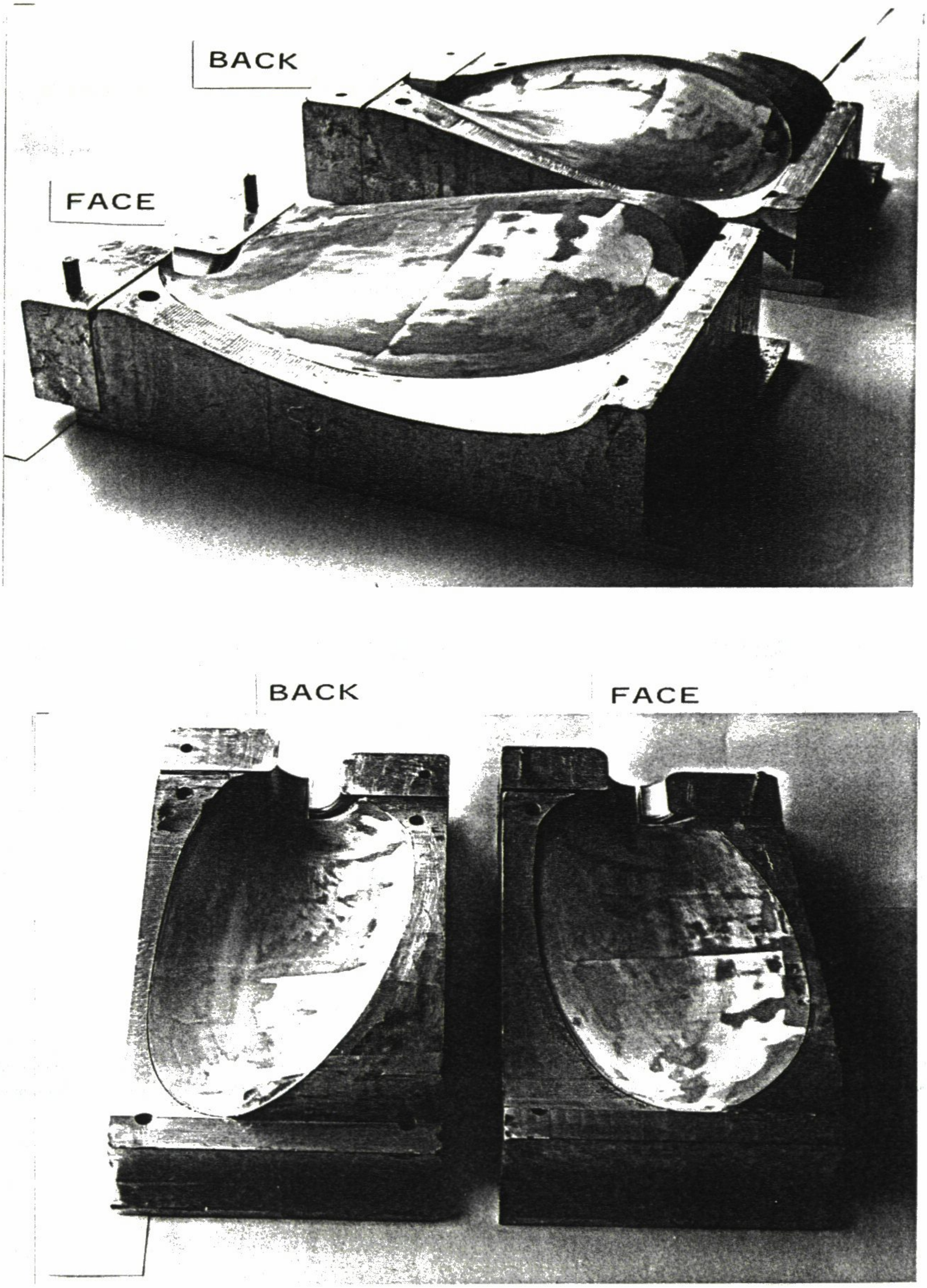


Fig.4 BLADE MOULDS

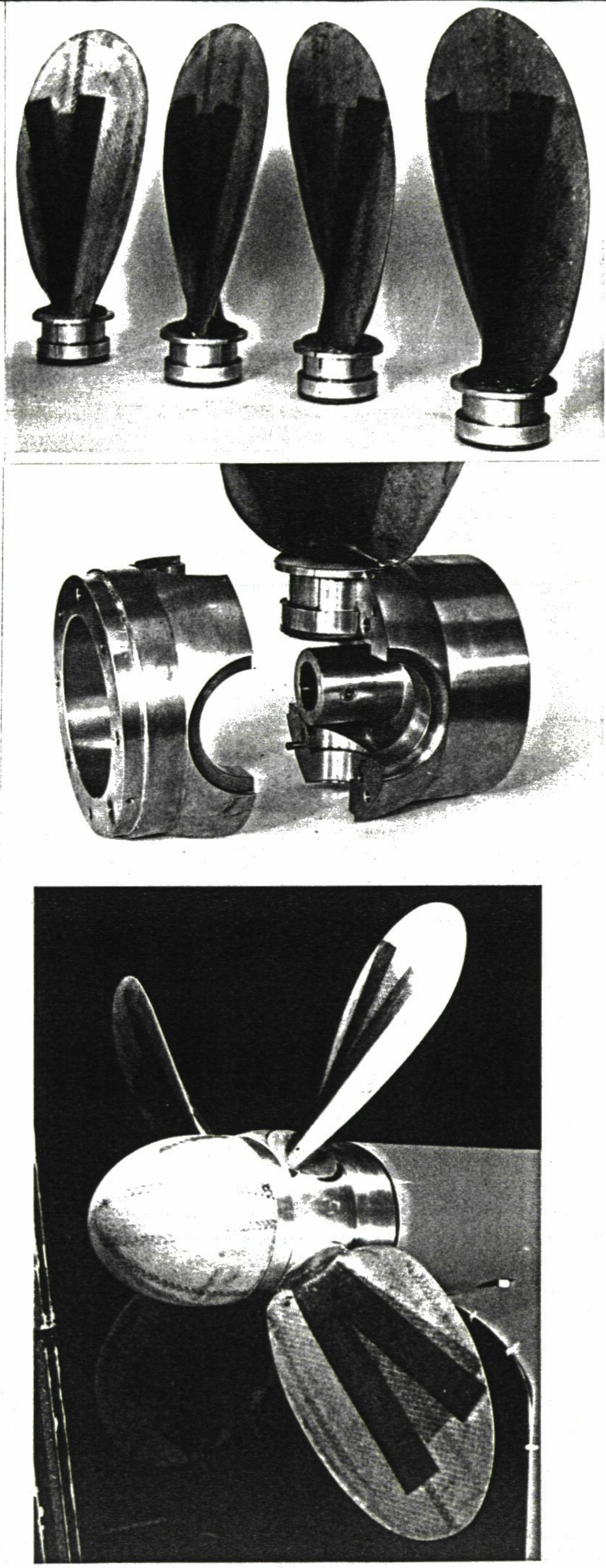


Fig.5 INDIVIDUAL BLADES, BOSS AND ASSEMBLED PROPELLER