The Manufacture of Marine Propellers in Moulded Anisotropic Polymer Composites

T. J. Searle

Ph.D. 1998

The Manufacture of Marine Propellers in Moulded Anisotropic Polymer Composites

by

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God saw all that he had made , and it was very good. And there was evening, and there was morning–the sixth day. The heavens and the earth were completed in their vast array.

Genesis 1:31–2:2

The Manufacture of Marine Propellers in Moulded Anisotropic Polymer Composites

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Abstract.

This thesis examines the feasibility of manufacturing small marine propellers from continuous fibre reinforced polymer composite materials. An appraisal of some current applications of composite materials in the marine industry is given, together with the moves shown towards the use of composites in the area of propeller design. It has been shown that manufacturing propellers in composite materials is theoretically more cost effective than traditional materials.

The manufacturing route investigated is Resin Transfer Moulding, where some detailed investigations have highlighted some of the critical processing parameters necessary for successful production of laminates suitable for propellers and other high performance marine structures.

A thorough testing programme of 4 novel designs of composite propeller is reported. Trials at sea on university run vessels has enabled many hours use to be logged, which has shown the fitness for purpose of propellers made from glass reinforced, epoxy composite. Experimental tank testing has helped to shape the remainder of the research by identifying the possibility of using hydroelastic tailoring to improve the efficiency of the propeller when a variety of operating conditions are required from the propulsion system. Further experience is required with respect to the the tooling construction and the life assessment of the propeller.

To facilitate appropriate modelling of the propeller, spreadsheet based load prediction models have been used. Finite element analysis (FEA) was used to model the elastic characteristics of one particular design of novel composite propeller. This indicated that traditional geometries may be too stiff to allow significant performance advantages from the anisotropy of the material. However the potential does exist for modified propeller geometries made from composite to give some performance benefit.

For specific applications, small marine propellers made from continuous glass fibre reinforced epoxy composite are likely to yield cost savings over traditional propeller materials.

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Lastly for the support and encouragement from two **Grandfathers, Mum, Dad, Bec, Mark, Mark, Meghan, Charlie, Rosie,** and friends at MBC–*thank you!*

Author's Declaration

No part of this thesis has been submitted for any award or degree at any other institute.

While registered as a candidate for the degree of Doctor of Philosophy the author has not been a registered candidate for another award of a University.

Publications by the author, in connection with this research, are included at the end of the thesis.

Signed________________

Date 19th Nov 98

Nomenclature

a	thrust moment arm
A	stress section area
A_1	function coefficient
A_2	function coefficient
b	torque moment arm
B_L	number of blades
B_1	function coefficient
B_2	function coefficient
c	chord length
C	dimensionless constant found by experiment
D	propeller diameter
F_c	centrifugal force
K	permeability (Darcies)
K	shape coefficient
L	flow length (cm)
L	centrifugal bending moment arm
m	mean blade thickness
n	propeller RPM
q_x	specific volume output in the x direction
r_0	nondimensional radius of stress section
r	radius
r_0	radius of inlet port (cm)
R	flow front radius (cm)
R	blade rake angle
P_O	inlet pressure (bar)
P_0	propeller pitch
P_s	engine power

p	pressure
Q	torque (Newtons)
S	the specific wetted surface area
t	time in seconds
t	section thickness
T	time (sec)
T	thrust (Newtons)
V_s	speed of vessel
V_a	speed of advance
W_t	taylor wake fraction
Y_p	blade face ordinate
x_c	nondimensional position of blade CoG
X_O	0.7 propeller radius
Z	section modulus
σ_{total}	total stress
σ_T	stress due to thrust
σ_Q	stress due to torque
σ_{CBM}	stress due to centrifugal bending moment
σ_{CF}	stress due to centrifugal direct stress
$\sigma_\perp$	stress due to unknown out of plane bending moments
θ	stress section pitch angle
η_m	shaft efficiency
η_p	propeller efficiency
ρ	material density
σ_θ	radial stress (Conolly)
σ_r	transverse stress (Conolly)
μ	dynamic viscosity
ψ	porosity, the ratio of space available for the liquid to occupy.
μ	dynamic viscosity (centipoise)

Chapter One

Introduction.

1.1 The purpose of the thesis.

1.1.1 Introduction.

This thesis seeks to investigate the viability of manufacturing marine screw propellers in continuous, high modulus fibre reinforced polymer composite materials. In order to set this study in context from other existing work, (reviewed later in the thesis), the propellers considered are low cost small boat propellers that can replace the existing metal propeller by a one shot, monolithic composite alternative. To this end the following aspects have been considered:

- Economic benefits.
- Manufacturing viability.
- Fitness for purpose, strength and longevity.
- Hydrodynamic advantages.

1.1.2 Economics.

The manufacture of a metallic propeller in either Manganese Bronze (HTB1) or Nickel Aluminium Bronze (AB2), is a highly skilled, labour intensive process. The manufacture is multi-staged and the final shaping, finishing and polishing of the propeller is dependent on the skill of the operative. A detailed breakdown of this is given in chapter 3. Part of the hypothesis of this research, is that by moulding a propeller to finished dimensions, no finishing, apart from the removal of a minimal resin flash, would be required when the propeller is ejected from the mould. This would yield a first cost saving over producing the same shaped propeller in metal.

1.1.3 Manufacture.

A reasonable indication that it is possible to make a small boat propeller in composite materials has been show by the author in an earlier study, [Searle 1991]. However, this has been developed in this research. The manufacture of larger, more robust propellers has been undertaken and optimisation of the manufacturing route has been carried out.

1.1.4 Propeller strength.

In order to produce a viable propeller in a different material, it must be strong enough to withstand the operating loads. It is possible to make very strong structures in composite materials, thus, part of the work has been to determine weather a composite marine propeller can be manufactured with sufficient strength.

1.1.5 Propeller life.

Most marine propellers of the type dealt with in this thesis, remain submerged and out of sight for long periods of time. So an investigation was required to learn how long a composite propeller could last in its working environment and what are the life limiting issues.

1.1.6 Hydrodynamic advantages.

The anisotropy of continuous fibre composites can be exploited to give particular elastic properties. By allowing the blade to twist under certain loading conditions in a way not possible with an isotropic metal, a hydrodynamic benefit is achievable. To determine the magnitude of this, finite element modelling techniques have been used.

1.2 Background to the project.

During 1991 some early but significant steps were taken to investigate the possibly of manufacturing a small marine propeller from continuous FRP composite. Plate 1.1 shows an early example of a FRP propeller made from glass and polyester resin. At this stage, the general benefits of composite materials are well understood for applications in other fields of engineering but the need existed for a full investigation into the viability for the marine propeller.

Plate 1.1 One composite propeller from the original study.

The early study was carried out using a standard 12 inch, 3 bladed, manganese bronze propeller. The task was to manufacture a geometrical replica in FRP. For reasons that are given in chapter 4, Resin Transfer Moulding (RTM) was chosen for manufacturing and the successful production of 4 FRP propellers was achieved. This manufacturing route allowed the complex shape of the propeller to be faithfully reproduced in composite materials. Traditionally propellers of this type, made from manganese bronze or nickel aluminium bronze, are cast in sand and hand polished. FRP materials processed by RTM were shown to be a realistic alternative to traditional methods and worthy of more detailed investigation. The initial undergraduate project finished after a RTM mould tool and 4 propellers had been manufactured.

It was estimated that during 1985, 10 000 tonnes of polyester resin was used in the U.K. marine sector alone [Marchant 1987]. Some sources have predicted that globally, the use of FRP's will over take the use of steel by 2010 [Flower 1990]. The number of novel applications for FRP is increasing. The marine industry presents a varied range of applications that would lend themselves to a redesign in a composite. Many applications are well established, for example high performance racing yachts. Some more subtle applications like the propeller are on the threshold of emergence. Some FRP propeller designs have been put forward, but it is still early days and they are yet to become widely used. Various designs are discussed in chapter 2 and appendix 1.

1.3 The practical applications of composites.

These fall very loosely into two categories. Firstly, the lower mechanical performance end of the material spectrum, GRP or fibreglass, usually consisting of short fibres of 'E' glass in a chopped strand mat form, laminated in polyester resin. Typically the glass makes up 20-30% by volume of the material content. The cost effectiveness of this material in making complex shapes such as a boat hull quickly, with semi-skilled labour has contributed to its popularity as a production boat building material. Generally production boats built in GRP have not been considered as high performance structures. Their manufacture has been appropriate for this view, usually fast hand lay ups, in a workshop environment that has variable conditions. Thus hull structures tend to be over–engineered to account for the structural inefficiencies and manufacturing variances, so they are heavier than need be and more expensive due to the extra material being used. A more rigorous approach to manufacture considers the material quality, the fibre orientation, the fibre volume fraction and the void content of the laminate. While this lengthens the manufacturing process, savings are made by using less material to create a more effective structure. The product may also have a longer service life and will certainly be lighter Many companies are recognising this and are introducing more sophisticated laminates into their boats. Foam cores are being used and woven glass cloths are replacing chopped strand mats.

When there is a more challenging application such as the design of a competitive racing boat or a fire proof structure, a more sophisticated technology is required. This loosely falls into the category of "advanced composites". Although more akin to airframe technology, it usually falls somewhat short of this ideal. This is for two reasons. Firstly it is much easier, fundamentally to keep a boat afloat, than to keep an aircraft flying. Secondly a rather dubious philosophy that says, if something goes wrong, you can swim but you can't fly.

Before looking at some specific examples of advanced marine composites, it is necessary to understand the properties that can be provided by composite materials, which should influence their selection.

- High specific strengths.
- High specific stiffnesses.
- Good corrosion resistance.
- Possibility of reduced cavitation erosion [Harris 1986].
- Better fatigue performance than metals.
- Potentially higher production rates.
- Potentially healthier production environment.
- Specific material design.
- Low coefficient of thermal expansion.
- Ease of producing complex shapes.
- Anisotropic elastic properties can be utilised to advantage.
- Ease of repair & maintenance.
- A composite material uses about half the energy to manufacture compared to steel or aluminium [Richardson 1987].

Although not an exhaustive list, the above shows some important benefits of composite materials, that makes them worthy of consideration alongside conventional materials.

1.4 The case for marine propellers in composite.

Of the benefits already listed, some that particularly pertain to propeller design include the following:-

- Reduced production costs.
- Component longevity.
- Reduction in cavitation damage.
- Damage tolerance & ease of repair.
- No corrosion.
- Possible reduction in fouling.
- Easer maintenance.
- Higher manufacturing yield (with many composites manufacturing processes).
- New shaft attachment possibilities.
- No need for painting, (as the case for aluminium propellers).
- Introduction of designed deformation of propeller blades under load to achieve greater hydrodynamic efficiency.

- Significantly reduced weight, perhaps as high as 75%, this should mean a reduction in vibration, a smaller prop shaft and faster acceleration to the desired RPM. Associated with this, reduced bearing wear.

As well as this long list of perceived benefits, there are some disadvantages to be tackled:

- Initial higher tooling costs.
- Repair to serious damage could be difficult.
- Erosion damage.
- Change to a new process is difficult to introduce to an established industry.
- Lack of operating experience.
- The material has no ductility.

Both these lists will grow as knowledge in the area deepens, the advantages should lead, on balance to a significant improvement in propeller design. The gap between the ideal propeller design and what is possible to manufacture could, with exploitation of these benefits, be significantly narrowed.

Figure 1.1 summarises the key issues that under pin the feasibility of a composite propeller. These issues are picked up in the remainder of this thesis.

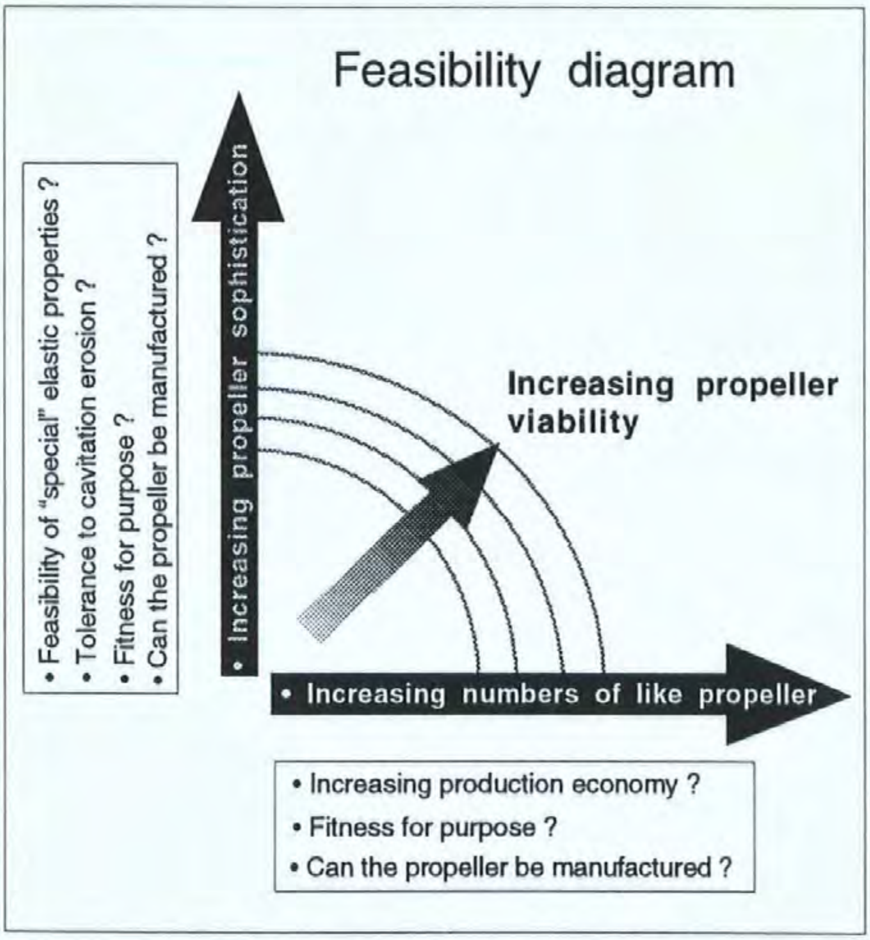


Figure 1.1 Composite propeller viability.

A number of solutions have been put forward for the redesign of the marine propeller by changing its material to composite. Although the widespread use of composite propellers does not seem to have materialised yet, many are still at the development stage but given time successful designs will emerge.

To consider the areas set out at the beginning of this chapter, the thesis is set out in the following order:

Chapter 2
Composites for marine applications.

Chapter 3
Economic benefits.

Chapter 4
Manufacturing of marine propellers by resin transfer moulding (RTM).

Chapter 5
Testing carried out on a range of composite propellers.

Chapter 6
Prediction of the hydrodynamic performance advantages for elastically tailored composite propellers.

Chapter 7
Conclusions.

Chapter Two

Composites for Marine Applications.

2.1 Introduction.

Continuous fibre reinforced polymer matrix composites are having a significant impact on the marine industry. Composite materials are now evident in virtually every area of this diverse market. This chapter reviews a range of marine applications where composite materials are now used to advantage. The benefits are generally specific to the application. and should be viewed in that context.

2.2 Ship and hull structures.

Large hull structures manufactured in composite have in the past been limited to vessels of approximately 60m [Anon 1989a]. From a manufacturing viewpoint, a large vessel with many flat sections is conveniently and cost effectively fabricated from flat or easily curved steel plates. A small yacht, for example one that requires a good surface finish and has a high degree of compound curvature in its hull form, lends its self to production in contact moulded GRP. Generally as the size of a structure increases the modulus of the constituent materials must increase also. In proportion to the overall dimensions the scantlings become very much thinner as the hull size increases. GRP has a significantly lower modulus (8 GPa for chopped strand mat in polyester resin compared to 207 GPa for steel). Another important consideration for larger structures is the increased strain energy. Whilst stress is simply proportional to the area subject to the load and can be scaled proportionally, strain energy is proportional to the size of the structure. For example the scantling of a small and a large vessel can be designed to the same working stress but the strain energies of the larger structure will be significantly higher. Thus the fracture toughness of the material is an important consideration. Composites can have high fracture toughnesses but this must be specified and is not always easily or cost effectively achieved.

The steel industry is experienced in making large volumes of material for big structures. Making composite materials in the same quantity is not yet as well established. The first cost of composite structures can be high, but is usually offset by reduced running and maintenance costs. The life of the structure will be increased because of much reduced corrosion and structural degradation by fatigue, so overall cost savings can be achieved. Where there is sufficient composite fabricating infrastructure, first cost savings should be possible also. First cost savings are already possible over aluminium [Anon 1989a]. Where it is chosen to directly replace an existing ship's structure with a composite the benefits will never be fully exploited and there is little to recommend this approach. However a much more radical approach is to redesign the shape of the ship's structure to accommodate a design more appropriate for composites. So, techniques like filament winding can be used. A recent feasibility study indicated this to be a significant possibility [Summerscales 1987].

For 20 years now mine counter measure vessels (MCMV) have been built in GRP [Anon 1989a]. The reduced magnetic signature of GRP lessens the chance of detonating mines. In 1973 the first GRP MCMV, the HMS Wilton was built by Vosper Thornycroft at Southampton. At 47 metres long and 450 tonnes it was the largest composite vessel in existence. Its predicted hull life was 60 years. The success of this vessel meant 12 Hunt class vessels were built shortly after, each 57m long and 680 tonnes. Two of them were involved in mine clearing operations in the Falklands during 1982. Several years later they are still in operation. In 1988 Vosper Thornycroft launched the GRP single role mine hunter HMS Sandown , this vessel at 52.7m represents weight savings of 50% and cost savings of 40% [Anon 1989a], transcending cost barriers sometimes associated with GRP construction. The US Navy plan to add 17 new GRP mine hunters to its fleet during the 1990's. Plate 2.1 shows the fabrication of a mine sweeper hull by machine wetted glass cloth.

Plate 2.1 Fabrication using pre-wetted glass cloth. (After Anon 1989b).

GRP is not the only composite structure to be used for this application. Foam sandwich construction has been successful too. During 1981 a Swedish coast guard vessel, the TV171 from Karlskrona Varvet AB was the largest vessel to be built from foam sandwich . High density PVC foam was used as a core, and little internal framing was used for the 300 tonne, 43.9m vessel [Anon 1981].

One of the latest novel foam sandwich applications is the introduction of the new Mersey class lifeboat. This Carriage Launched Craft (CLC) is built in a female mould and consists of an unbalanced foam sandwich laminate. The outer skin is a pre-preg and is consolidated with a vacuum bag and post-cured , the foam is vacuum bagged in place also. Finally the inner skin is laid up by hand and similarly vacuum bag consolidated. 50mm core thicknesses are a feature of the frameless interior monocoque design. 25 vessels are on order and the first is in service. The original design was for a top speed of 15 knots, in fact 16.5 knots have been achieved in practice [Beevers 1990].

The Arun class lifeboat replacement FAB3 (Fast Afloat Boat 3) has made good use of composite materials to replace the wood steel and aluminium that the class was made from before. Plate 2.2 shows the similar "Severn Class". The vessels are 17m long and previously had a top speed of 18 knots, the new design was to have a maximum speed of 25 knots. Service speeds of this order require close attention to detail, to achieve stiff lightweight structures, so the vessel can perform. To do this, the hull was made from 6.5mm glass/aramid in a polyester resin, and designed to maintain structural integrity after an impact of 1000J over a 20mm diameter area, this being comparable to the impact load of a bowsprit from a large yacht striking the hull in a large seaway [Beevers 1990]. Top sides and the deck were foam sandwich, 3.5mm glass/aramid/polyester skins either side of PVC foam. This was consolidated with a vacuum bag. The weight of the hull, deck and superstructure was less than 9.25 tonnes.

Plate 2.2 Severn class lifeboat.

2.3 Propulsion Systems.

2.3.1 Propeller Brackets.

In 1990 a study was carried out at the Southampton University Department of Mechanical Engineering [Shenoi 1990], to investigate the feasibility of producing propeller brackets (for supporting the propeller shaft as it emerges from the hull) in a composite material, plate 2.3 Particular problems were identified with the production of propeller brackets in conventional metal materials like bronze alloys or steel:

- High weight.
- High cost.
- Difficulty in production.
- Fitting problems.
- Corrosion.

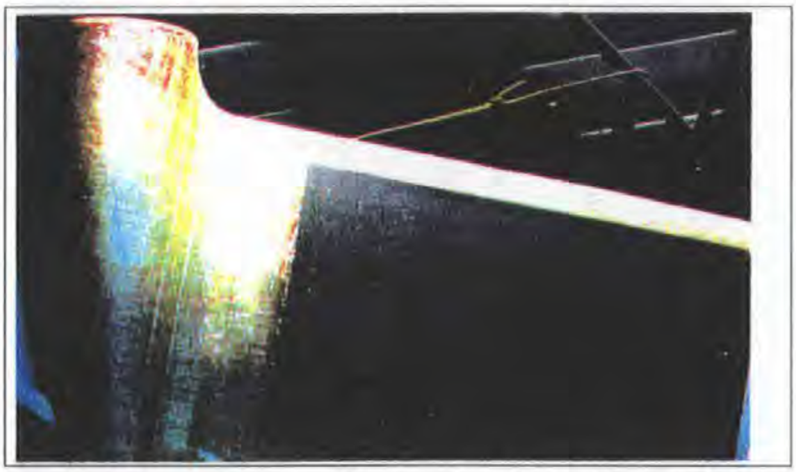


Plate 2.3 Composite propeller bracket. (After Shenoi 1990)

A bracket for a 30m patrol vessel was selected for redesign. The first stage in the structural design was to identify the loads upon the bracket. This analysis is particularly important for a composite structure due to the unique tailoring of composite materials for their application. A factor of safety of 2 was still used in the design. Geometry and materials were chosen so that there was:

- Strength to withstand loads.
- Resistance to cavitation onset.
- Minimum drag.

The final design consisted of a uniform carbon/glass laminated skin with extruded carbon stiffeners at 30, 40, 60, & 70% cord length. Two hollow square carbon pultrusions were to be used as longitudinal stiffeners to take 48% of the bending loads. This longitudinal stiffener increased the torsional stiffness significantly by connecting the two outer skins. The skins were laid up in two halves and joined at the leading and trailing edges. The skins consisted of Unidirectional plies for bending loads and stiffness and woven roving plies to supply adequate torsional stiffness and shear strength. The structure was designed as a thick skinned sandwich so the buckling resistance of the skin was not reliant on the core.

Production was by usual boat building methods i.e. a hand lay up in two part moulds with vacuum bag consolidation. The core was of syntactic foam, that could be poured in to the bracket after the mating of the two moulded bracket halves. This meant that no prior shaping of the foam was required, so some labour could be saved. In summary the manufacturing process comprised the following:

1. Production of a GRP mould,
2. Hand lay up,
3. Vacuum bag consolidation,
4. Removal of part from the mould,
5. Fitting a PVC foam block and GRP boss tube,
6. Mating of the two halves and pouring in syntactic foam in several stages.
7. Post curing and finishing.

The following analysis was carried out on the bracket:

- Mechanical test for bending: Deflection/Strains/ Acoustic emission,
- Mechanical test for torsion: Deflection/Strains/ Acoustic emission,
- Finite element analysis.

The tests showed that the material and the process catered well for bending and torsional loads, particularly the jointing of the shells. However further work is required to close the gap between the finite element and the experimental results. The end result of this production technique was a slight reduction in fabricating cost, the final weight of the bracket was 70kg, this represents a 77% reduction over usual production methods.

2.3.2 The Composite Engine and Propeller Shaft.

Research has investigated the use of composite materials for engines. This application is very much in its infancy and has been confined to small petrol engines for cars. Success at this level is necessary before work can begin on larger marine engines. However results from Polimotor Research Inc. more than 10 years ago [Wise 1980] and more recently the B.R.I.T.E. (Basic Research in Industrial Technologies for Europe) engine in the late eighties have been significant plate 2.4

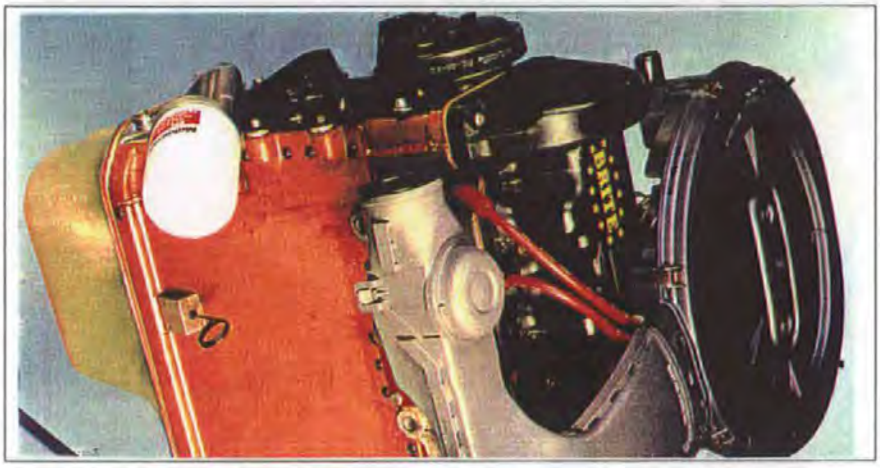


Plate 2.4 The BRITE engine. (After Anon 1992a)

Neither engine was wholly composite, rather the best properties of metals and composite were utilised. With more research the shift will be towards a higher proportion of composite materials.

The Polimotor engine exhibited the following benefits:-

- Carbon fibre engine block was 50% lighter than an aluminium one.
- 60% weight saving on reciprocating parts.
- 30% quieter than the equivalent metal one.
- Lower thermal conductivity materials give a better piston/cylinder fit at variable temperatures, and result in more efficient combustion.
- 12-15% more fuel efficient.

For marine applications the benefit of reduced corrosion in polymer composites is significant.

The potential to filament wind or braid, propeller shafts from high modulus fibres, has a number of benefits:-

- Reduced weight that leads to reduced vibration.
- Larger spacing between bearings.
- No corrosion
- Less torsionally stiff shaft to reduce shock loading on the gear box.

An automated process for manufacture may allow some initial cost savings. Weight savings would lead to a reduction in bearing wear, vibration, installation and maintenance costs.

2.3.3 Propellers.

The argument for composite propellers has been outlined in chapter 1 of this thesis. Some important work has been done in this area already, details are given in appendix 1.

However, the important details of the most significant work to date is summarised in tables 2.1a, 2.1b, 2.1c.

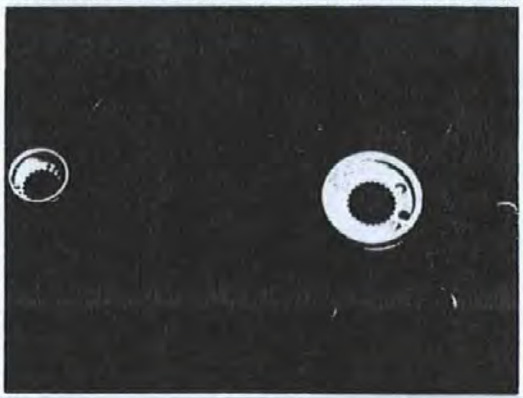
Propeller	Torpedo Propellers
Company	Reinhold Industries
Size	0.2-0.25 m
Application	Military
Material	E-glass/polyester
Figure	

Table 2.1a Reinhold Industries Torpedo Propellers.

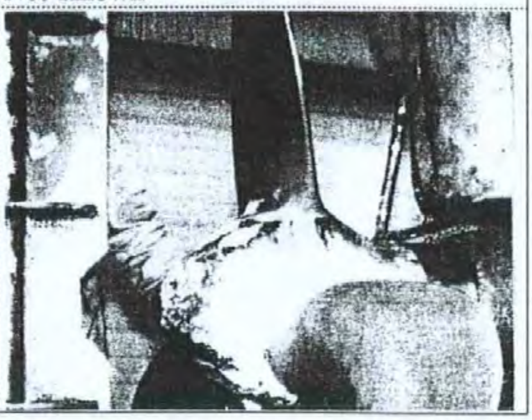
Propeller	"FlexProp"
Company	Karskronavaret
Size	2m
Application	Various
Material	Not Known
Figure	

Table 2.1b "FlexProp".

Propeller	"Contur Propeller"
Company	AIR
Size	1 m
Application	Various
Material	Carbon
Figure	

Table 2.1c "Contur Propeller".

So far, this is the extent of the available information on the development of FRP composite propellers. Little is known regarding the manufacture and the material used for each propeller. However the following points are evident from the literature and accompanying illustrations.

- The "Contur Propeller" consists of machined rather than moulded separate blades, assembled on a metallic boss.
- The "Flexprop" is a controllable pitch propeller, thus individual blades are attached to a mechanical hub.
- There is tentative evidence that the torpedo propellers are made from Dough Moulding Compound. A probable consequence of their size.

It is clear that for certain sectors of the marine industry continuous fibre polymer matrix materials have a firm footing because of the important performance benefits they yield. However the difficulty in manufacturing components that have consistent mechanical properties is an issue to be resolved. The material benefits coupled with potential for producing consistent parts cost effectively by RTM are taken up in chapter 3 and 4.

Chapter Three

Economic Benefits.

3.1 Introduction.

Part of the hypothesis of this work, is that certain types of marine screw propeller are more cost effectively manufactured in fibre reinforced plastic materials. This chapter seeks to outline the economic, manufacturing and technical issues required to support this thesis. The evidence and experience presented, (both anecdotal and scientific) will substantially make the case for the economic viability of FRP propellers.

It is beyond the scope of this chapter and report to deal in any depth with the through life costs of a composite propeller. (Some catastrophic damage has been experienced on composite propellers in service. This is discussed later in chapter 5). The focus of this thesis is manufacture, the following longevity issues have not been measured:-

- Corrosion.
- Cavitation.
- Wear due to abrasion.
- Fatigue.

These will be investigated in further studies.

In order to create an economic bench mark, the processes and materials by which and from which metallic propellers are made should be understood. Also, the potential of the rapidly maturing manufacturing technology available to the composites industry, which gives the capability to produce high quality structural parts economically, must be accepted. This chapter compares the processes on a cost basis in the following way:

1. Material cost.
2. Processing cost.
3. Tooling cost.

3.2 First costs.

3.2.1 Material Costs.

The traditional materials for manufacturing propellers include: manganese bronze (high tensile brass HTB1) and nickel aluminium bronze AB2. Table 3.1 and figure 3.1 give the comparative costs for these materials, aluminium and some composite material. The prices are given per kg. However, since marine propellers are constrained geometrically by hydrodynamic requirements, a more meaningful material cost comparison is by volume. Table 3.1 and figure 3.2 show this, where in fact composite materials are economically very favourable.

Material	Cost / m^3	Density (g/cc)	Cost / kg
HTB1 (Mag bronze)	£ 11869.00	8.3	£ 1.43
AB2 (Nickel aluminium bronze)	£ 12013.00	7.75	£ 1.55
Aluminium	£ 6480.00	2.7	£ 2.40
Epoxy	£ 7200.00	1.2	£ 6.00
Glass	£ 5100.00	2.55	£ 2.00
50% vol. glass, epoxy composite	£ 7500.00	1.88	£ 4.00

Table 3.1 Typical material costs.

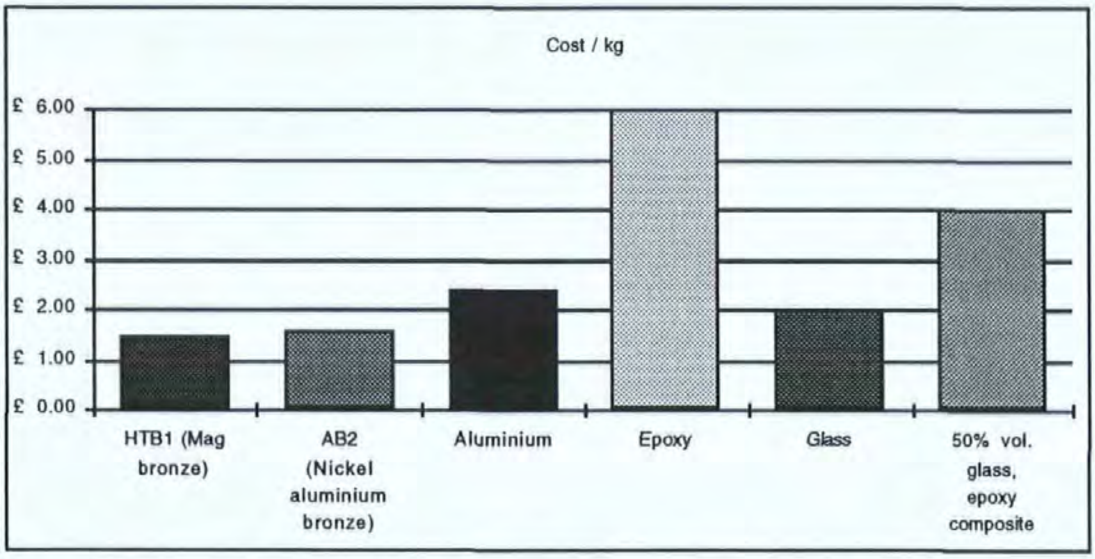


Figure 3.1 Cost per kg of traditional propeller materials compared to some composite materials.

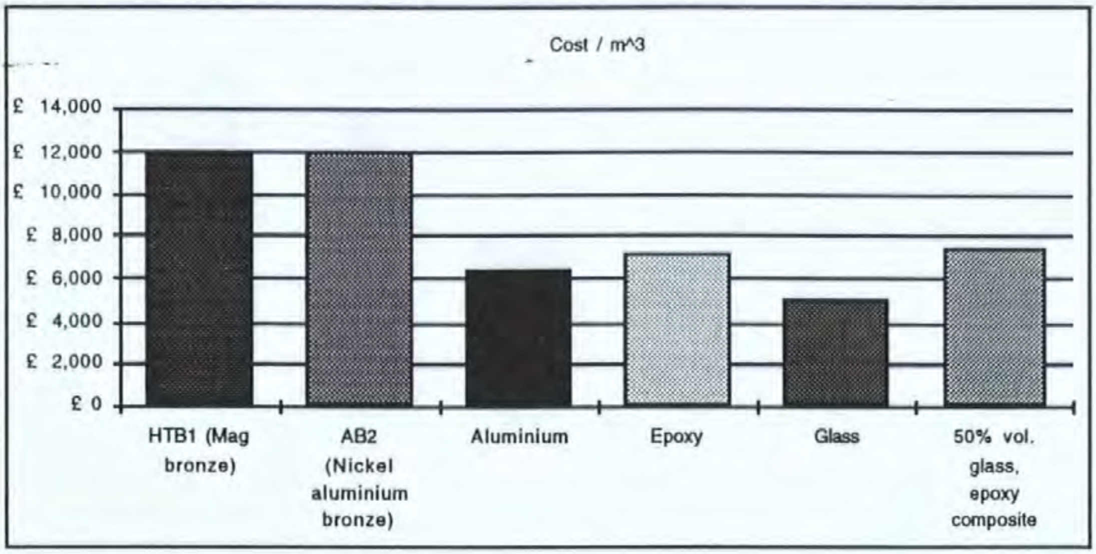


Figure 3.2 Volume cost of traditional propeller materials compared to some composite materials.

3.2.2 Processing Costs.

Whilst the material cost is important, usually this is only a small proportion of the overall component cost. Processing the material is often the largest cost. Figure 3.3 summarises research carried out which concludes that as the geometry of a component increases in complexity, then it becomes progressively more cost effective to manufacture the part from composite materials. The marine propeller is likely to be a significant example to confirm these generic findings.

In order to compare closely the manufacture of metallic propellers with the proposed composite alternative, the stages of both processes are given in figure 3.4. The shaded areas represent the production sequences of the manufacturing processes.

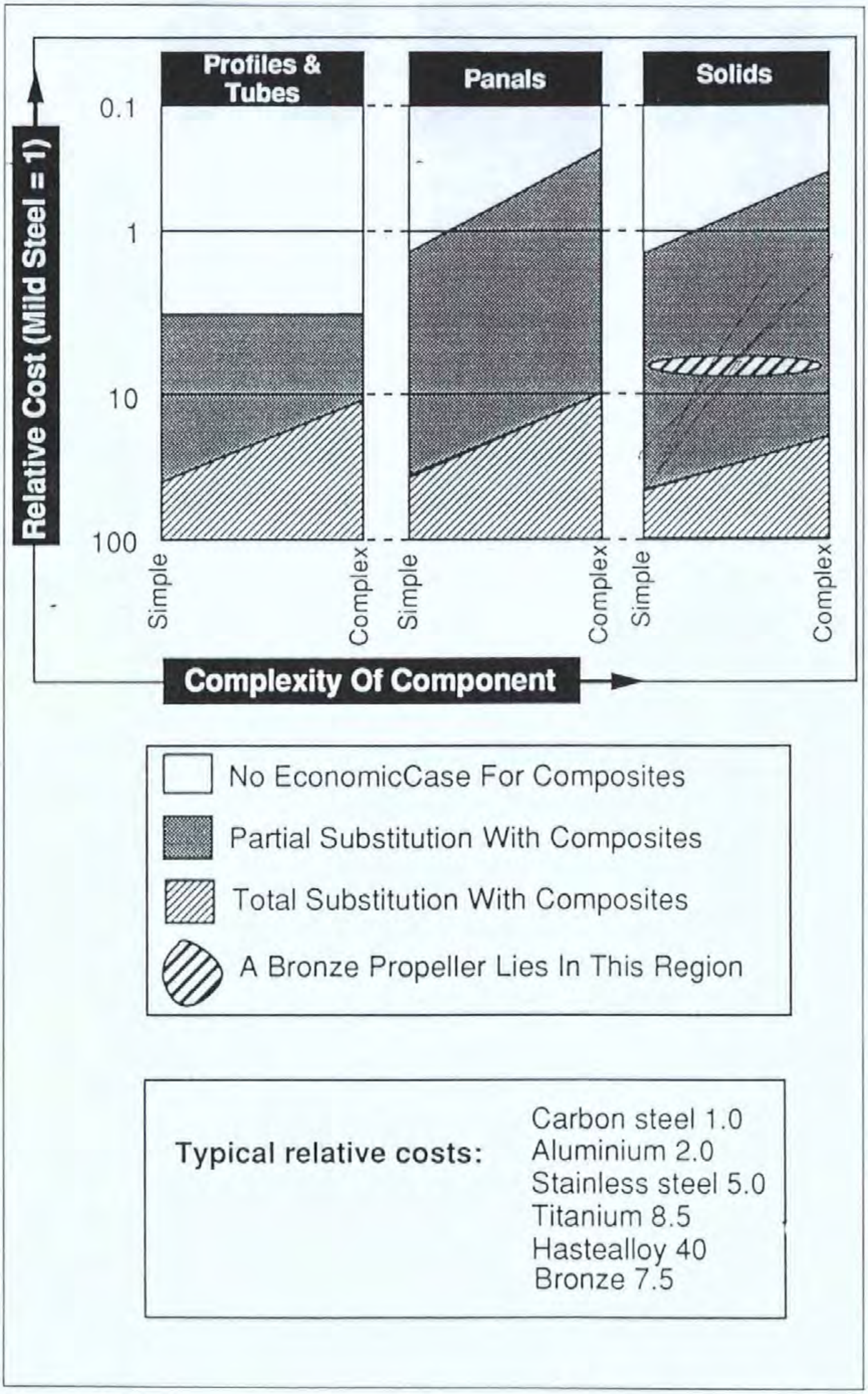


Figure 3.3 Component geometric complexity vs. manufacturing cost. [Modified from Flower 1990]

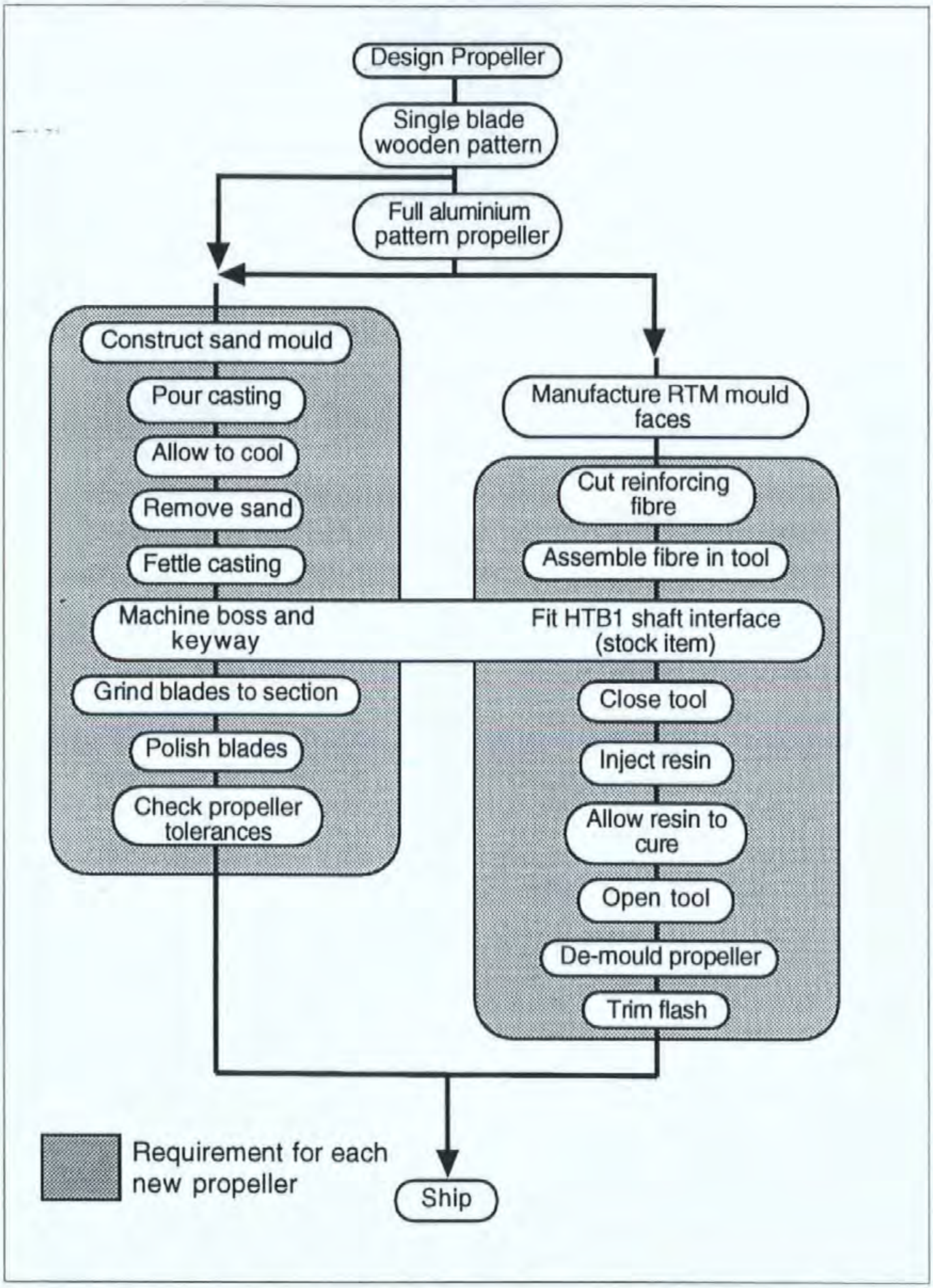


Figure 3.4 Process stages for the manufacture of metallic and composite propellers.

3.2.3 Design and Pattern Making.

Common to both manufacturing routes is the need for a master pattern of the propeller design. For metallic propellers this starts life as a single blade wood or plaster pattern. This remains the production pattern for producing the sand mould if only small numbers of the particular propeller design are required. However if larger numbers are required then a full bladed aluminium pattern is made. The sand mould can be produced quicker from this.

3.2.4 Production in Metal.

Once the pattern is available then work can begin on forming the sand that will define the rough casting shape of the metallic propeller. Producing the sand mould is a skilled, time consuming job. Table 3.2 gives estimated times for a variety of propeller types.

Diameter	Number of blades	Time to produce sand mould
48 inch	5 (0.7 DAR)	7 hours
24 inch	3 (0.5 DAR)	2 hours
12 inch	3 (0.5 DAR)	1 hour

Table 3.2 Timings for production of sand moulds.

Having produced this tooling, the propeller is cast and left to cool. For larger propellers, shrinkage voids can be a problem during cooling. These occur in the boss and result from the outside of the boss cooling and becoming rigid before the inside of the boss. To prevent this from happening, the top of the boss is kept hot. Exothermic powder is periodically poured over the molten boss. (This powder is a mixture that includes some fine magnesium).

After cooling, the mould is taken apart and the sand broken away. The sand is discarded, the casting is fettled and taken for machining. Here the blades are ground and polished to section and the keyway and shaft taper are cut. Finally the propeller is balanced, measured and shipped to the customer.

3.2.5 Production in Composite.

Plate 3.1 Composite propeller showing the flash line that can be removed quickly.

In composite, the key difference is the requirement for a reusable set of moulds that accurately replicate the final propeller geometry. The advantage is that only minimal finishing will be required after moulding, an example is shown in plate 3.1. The disadvantage is that this type of tooling is expensive compared to making a sand mould for metal casting. RTM propeller tooling is discussed in detail in chapter 4. However at this stage it is adequate to say that considerable industrial development is underway to produce a format of cost effective tooling [Harper 1997]. Essentially, this consists of producing mould tooling faces that are separate from the peripheral mould clamping mechanisms, injection peripherals and other mould furniture items. Composite mould faces on their own with integral heaters can be produced relatively cheaply.

Common to both composite and metallic propellers is the need for a machined shaft interface. Thus some machining time must be costed to the composite propeller. However this metallic boss can be produced much more cost effectively on its own. It can be produced as a stock item, defined only by its length, shaft taper, and key dimensions.

A key to success in RTM is the need for a well made fibre preform. Preforming automation is expensive, and particularly for complex shapes is not well advanced. However, cutting the fibre manually using templates and assembling the preform by hand can be accurate and effective.

Equipment to automate RTM is now available for only modest investment. The handling of tool closure, resin injection, flushing, cleaning of mixing heads, associated pipe work and finally the opening of the mould on resin cure, can now be handled automatically. The entire cycle for modest components can be less than 4 minutes with total equipment investments of less than £40 000. This also allows for a "clean process" where the only time resin is seen and handled is in the cured finished part and styrene emissions are negligible.

3.3 Example cost comparisons.

To break down and illustrate the cost comparison between a typical metallic propeller and the composite equivalent, the details of a 24 inch propeller are used (table 3.3).

Diameter	24 inches
Number of blades	3
Material	HTB1
DAR	0.5
Market cost	£450

Table 3.3 Comparison propeller details.

The manufacturing parameters and assumptions which are kept consistent for each propeller are as follows:

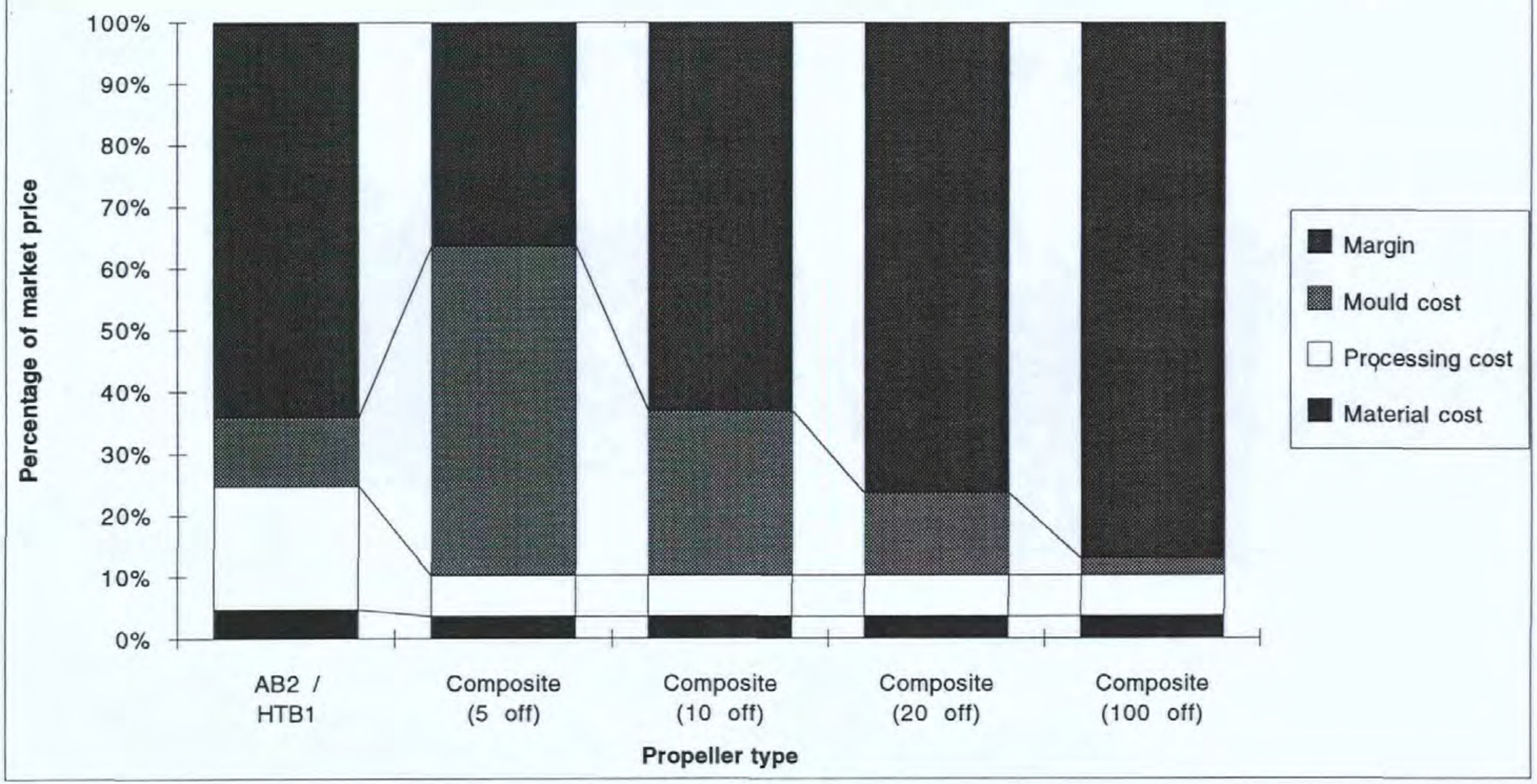
1. Time is cost at £30 per hour.
2. The present worth of any investment is not taken into account.
3. There is zero material waste and zero scrap. (waste metal can go back in the furnace, RTM wastes very little material).
4. Keyway and shaft taper machining is required for both props (although machining the small bush for the composite propeller is very much simpler than setting up an entire propeller).
5. Composite propeller is monolithic.
6. RTM tool faces are estimated at 40 hours work (@ £30 / hour).
7. The RTM tooling cost is divided between the number of propellers in table 3.4.
8. RTM equipment investment cost is low and not considered.
9. Manufacture of the bronze propeller is estimated at 3 hours (@ £30 / hour).
10. Manufacture of the composite propeller is estimated at 1 hour (@ £30 / hour).
11. Consumables for the bronze propeller are estimated at £20.

These figures can be modified. However considering these as typical figures, the cost break downs are shown in table 3.4 and figure 3.5. The profit margin shown for the metallic propeller is variable and probably not as optimistic as the one given. It is an estimation, as companies will not divulge commercially sensitive information of this nature.

Propeller type	**Material cost**	**Processing cost (labour cost for making the propeller)**	**Mould cost, labour and material (divided between the number of propellers produced)**	**Margin (profit)**
AB2 / HTB1	£ 21.00	£ 90.00	£ 50.00	£ 319.00
Composite (5 off)	£ 16.00	£ 30.00	£ 240.00	£ 204.00
Composite (10 off)	£ 16.00	£ 30.00	£ 120.00	£ 304.00
Composite (20 off)	£ 16.00	£ 30.00	£ 60.00	£ 354.00
Composite (100 off)	£ 16.00	£ 30.00	£ 12.00	£ 394.00

Table 3.4 Manufacturing cost breakdown.

Figure 3.5 Propeller manufacturing costs



3.4 Summary.

From the cost models presented:-

- An increase in the numbers of HTB1 or AB2 propellers will not yield a significant increase in profit margin, as the sand mould must be constructed for every propeller.
- Small numbers of composite propellers manufactured by RTM cannot increase the economic margin.
- For the numbers presented in this model, the indication is that the economic margin will become favourable when quantities of greater than about 15 propellers are achieved.

Thus, economically composite materials and associated manufacturing routes are likely to be viable when the manufacture of a relatively small number of like propellers is required. With greater maturity in RTM tooling techniques the process should become more and more cost effective.

Chapter Four

Manufacture of Marine Propellers by Resin Transfer Moulding.

4.1 Introduction.

4.1.1 Manufacture of Composite Components.

Metallic components are manufactured in two stages. Firstly the metal is manufactured from raw material with specific properties which are subject to modification with subsequent heat treatment. Then the component is manufactured from this material to the required shape. Composites differ because the raw materials of fibre and resin are brought together at the same time the component is manufactured. Thus the component is manufactured at the same time as the material. This fundamental difference allows:

- Net shape manufacture.
- Specific material property tailoring for the component.

In order to bring the fibre and resin together in the required geometry, an effective technique of manufacture is required. The manufacturing process must satisfy the following criteria:

- Cost appropriate to application.
- Allow the fibre and resin to be brought together in the correct ratio.
- Ensure correct fibre alignment.
- Resin must surround each fibre.
- Minimise foreign particles, defects and air voids.
- Accurately define the entire component geometry which is the requirement of the marine propeller.

Resin Transfer Moulding (RTM) enables these criteria to be achieved. Figure 4.1 shows the schematic arrangement of a RTM system. Dry fibres are placed in the mould tool in the designed directions, the resin is then injected either under pressure and/or drawn in with a vacuum into the closed mould cavity.

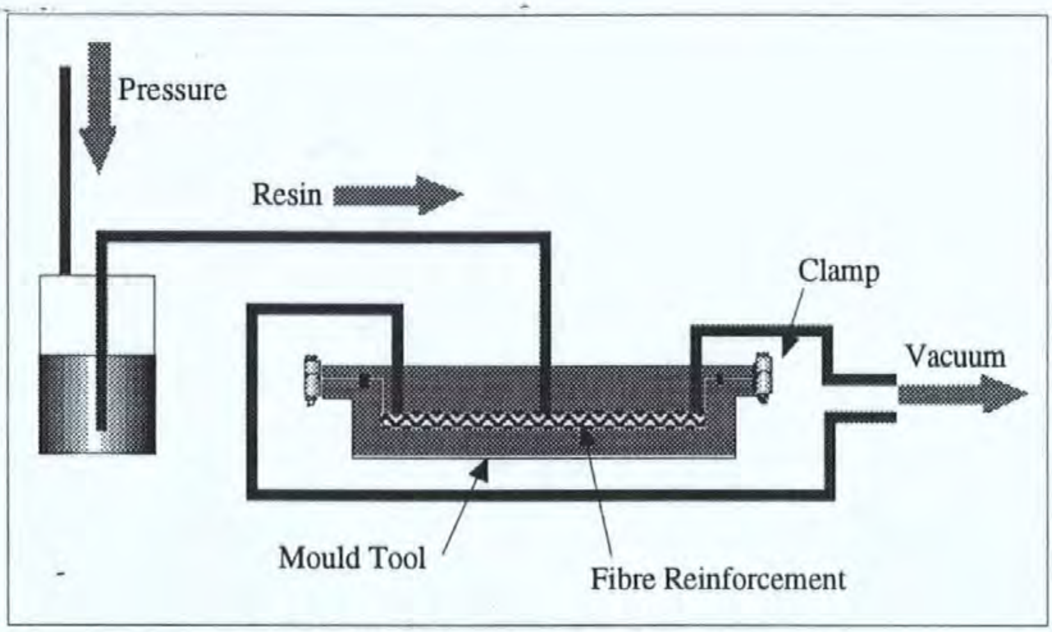


Figure 4.1 Resin transfer moulding schematic.

There are several alternative processes for the manufacture of FRP. However only one other option exists for propeller manufacture, because the moulding process for a propeller must define its entire geometry. Compression moulding can achieve this. Figure 4.2 shows this process schematically.

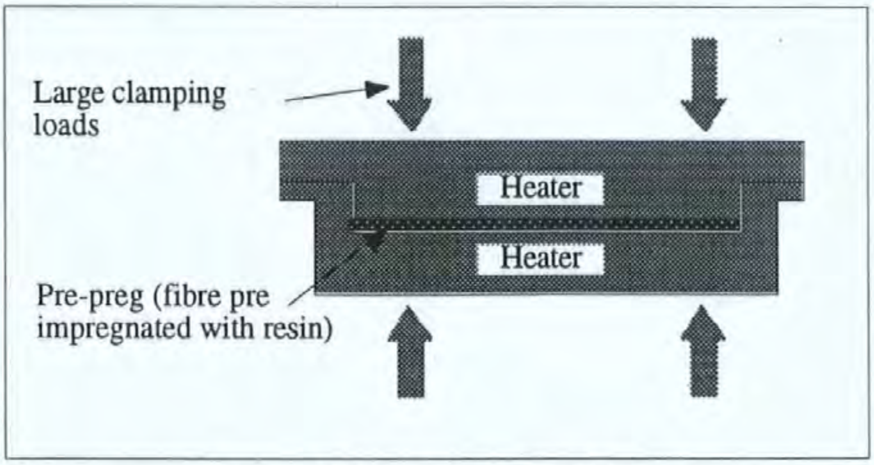


Figure 4.2 Compression moulding.

Fibre pre-impregnated with thermo setting resin that cures when heat is applied, is placed in a substantial tool. Closing the tool under a large load and heating to between 80°C and 160°C, depending on the resin system, cures the material in the desired shape. The disadvantage of this technique is that the mould tools are expensive. In order to withstand the high clamping forces and thermal loads, tooling must be substantial and consequently expensive. RTM does not necessarily require large variations in temperature to cure the resin, nor is it a process that requires strong tooling, as resin injection pressures are low, usually in the region of 1-5 bar. (Some compression moulding does not require high temperatures, but it is usually more effective when high temperatures are used). Generally speaking compression mould tools are required to be produced from metal, whereas RTM mould tools can be made from composite at a reduced cost. If the tolerances of the component or the size of the production run allow, then metal tooling, which is more durable is used for RTM. Thus the result is RTM can certainly be more cost effective at producing high quality, high fibre volume fraction and more complex parts than compression moulding. [Harper 1992].

In addition to cost there are other benefits of RTM which arise from tooling and processing, the following list shows some general advantages over other FRP manufacturing processes [Dean 1988].

- Low void content in laminate.
- Good control of mechanical properties.
- Repeatable process.
- Ability to mould complex shapes.
- Reduction in labour & material waste.
- Clean process, fibres are handled dry, (resin is only added after the tool is closed).
- Good for large production runs, as the process has a fast turn around time.
- Works well for large components.
- Minimal raw material storage problems (unlike pre-pregs that must be kept frozen).

4.1.2 Some Manufacturing Examples.

Industry and research establishments have exploited the clear benefits that RTM has to offer. Several examples in recent years owe much of their success to the flexibility that RTM allows.

The Advanced Composites Manufacturing Centre (ACMC) of the University of Plymouth has manufactured monolithic ballistic panels by RTM. The panels comprise a solid 60mm thick laminate of various different combinations of fibres in epoxy resin. Total weight of the finished test panels is in the order of 100kg. Due to the bulk of material, RTM was the most cost effective method of manufacture and possibly, with the exception of resin injection under a bag, the only method of consolidating this bulk of fibre and resin in a one hit moulding.

For 25 years, Dowty Aerospace have been developing RTM techniques for the manufacture of aircraft propeller blades plate 4.1. [McCarthy 1992]. The composite blades have several important advantages over those made from aluminium alloy.

- Weight saving of approximately 55kg for a 3.5 metre 4 blade propeller.
- Reduced pitch control moments.
- Not subject to fatigue cracks.
- Very tolerant to damage.
- Easily repaired.

The composite blade structure consists of 2 unidirectional carbon spars either side of a foam blade shaped blank. On top of this, ±45° glass and carbon fibres are braided, a process 10 times faster than filament winding. The fibres are run into an aluminium root attachment joint.

This whole assembly is then placed in a heated aluminium RTM tool at 80°C and low viscosity epoxy resin is fed in under precise pressure, with vacuum assistance. Typically one blade injection takes less than 20 minutes. RTM for this application offers the following advantages:

- Blades can be moulded in one hit incorporating the metal root structure.
- The constituent materials have a long shelf life at room temperature.
- Blade natural frequencies may be tuned by the addition or removal of material in the development stage with no modification to tooling.

Plate 4.1 Composite aircraft propeller
Blades manufactured by RTM. (After McCarthy 1992)

Concargo Ltd. have begun using RTM for the mass production of the roof for the Ford Transit Van [Sudol 1994]. The projected production run is estimated at 90 000 parts over 7 years from one nickel shell electro formed tool. This type of tooling is 40% cheaper than steel tooling, quicker to produce than steel and allows for a class A finish on the product. Production has been ramped up from concept to full production within 2 years.

The low volume fraction manufacturing process involves a gel coat sprayed into the tool, placement of precut fibre pack, closure of the mould and finally the resin injection. One port is used for the injection which takes just 6 minutes. The roof is de-moulded 26 minutes after the injection is first started. The goal of the company is to achieve an overall cycle time of 15 minutes.

Essentially, the process has enabled high quality, well finished components to be manufactured quickly with tooling that is significantly cheaper than steel RTM tools and cheaper than the tooling required for the production of metal parts.

4.1.3 Manufacturing Complexities.

These applications discussed and many other products manufactured by RTM can be categorised in terms of fibre to resin ratio. When the fibre content is low, approximately 20-30% by volume, the resin enters the mould, permeates the fibre structure and fills the mould cavity with relative ease. However, when higher mechanical performance is required, the proportion of fibre increases to approximately 50 - 60% and injecting the resin becomes progressively more difficult. The increase of fibre in the mould cavity not only slows the flow of resin into the mould but can often make the flow front of resin erratic and difficult to predict, the resin seeks out easy flow paths much more readily. This means in practice, for low fibre volume fraction components, processing parameters such as the resin viscosity and fibre weave architecture are not critical. As these and other parameters vary, so the moulding quality remains repeatable and consistent. However as the proportion of fibre starts to increase, it becomes increasingly important to control and maintain RTM process conditions.

Initial manufacturing of FRP propellers produced in the early stages of the study confirms this. In order to achieve the required mechanical properties to manufacture a propeller that is fit for purpose, fibre volume fractions of 50% are about the highest practical fibre volume fraction possible for the complex component shape. The fibre reinforcement is standard E–glass and the resin a slow curing epoxy. Plates 4.2 and 4.3 show the inconsistency of moulding quality realised for one design of experimental composite propeller. Variations occurred in different blades of the same propeller and in different propellers.

Plate 4.2 RTM processing variabilities.

Plate 4.3 RTM processing variabilities.

4.2 RTM - Some theoretical considerations.

4.2.1 Fluid flow through porous materials.

As much of this research is oriented towards manufacture, the following section examines some of the theoretical aspects of resin transfer moulding.

Many years ago a geological study was carried out to investigate the flow of fluid through porous rocks [Dalmont 1856]. Darcy reported in a later investigation that the rate at which a fluid flows through porous materials was found to be dependent on the following parameters:

- Pressure gradient.
- Porosity of the material in which the fluid is flowing.

Darcy worked with water so viscosity was not considered, however this must also be a consideration when alternative fluids are looked at.

Darcy's law is normally expressed in the following relationship, equation 4.1 described the volume of fluid able to move through a porous medium in a particular direction. [van Harten 1992]:

$$\boxed{q_x = - \frac{K}{\mu} \cdot \frac{dp}{dx}}$$

.............Equation 4.1

Where:

q_x Volume output in the x direction. *(This has the dimension of velocity, although not equal to the real fluid velocity).*

μ dynamic viscosity

K permeability

p pressure

K is the permeability of the porous material. It is the parameter that describes the ease with which a liquid can pass through a porous material. A number of complex mechanisms determine this value which are discussed later. It is not the same as porosity which only describes the space available for the liquid to flow and, in the case of a composite laminate, is simply expressed as the ratio of space to fibre, Thus a more complex expression is required to describe permeability, which includes porosity. Kozeny found permeability (*K*) to be given by equation 4.2 [Griffin 1995]:

$$\boxed{K = \frac{1}{C} \frac{\psi^3}{S^2 \ (1-\psi)^2}}$$

......Equation 4.2

Where:

K = permeability

C = dimensionless constant found by experiment

S = wetted surface area. *(= the total surface of the outside of the fibres per unit volume of the fibres).*

ψ = porosity

Carman found by experimentation that *C* should be about 5 for various grain-like media. The Darcy and Kozeny-Carman equations give the volume output of the liquid flowing through a porous media. This allows the velocity of the front of advancing liquid to be calculated. Since ψ is the space available for the liquid to occupy, then the actual liquid flow velocity is given by equation 4.3:

$$\boxed{V = \frac{q_x}{\psi}}$$

..........Equation 4.3

The permeability of a fibre pack can be measured experimentally. The time taken for resin to flow longitudinally through a mould containing a sample of the fabric used is measured, figure 4.3. There are problems with this approach, an "easy path" for the resin to flow occurs where the fibres meet the mould edge. To eliminate these edge effects, an improved approach is to use a mould where the resin is injected into the centre of the fibre pack and flows radially from this point, (figure 4.4). Each injection is viewed through a glass topped mould.

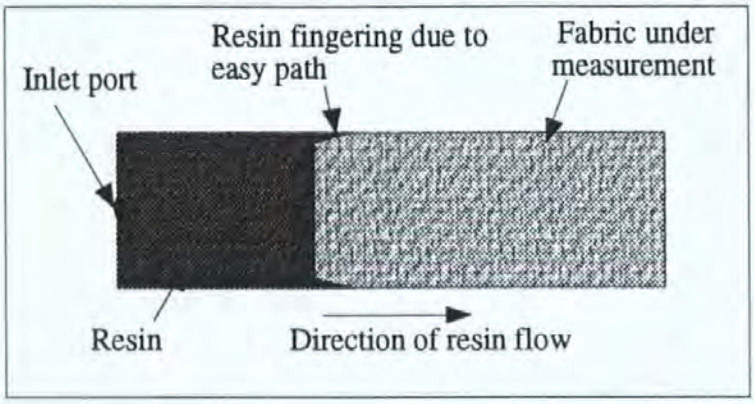


Figure 4.3 Longitudinal resin flow.

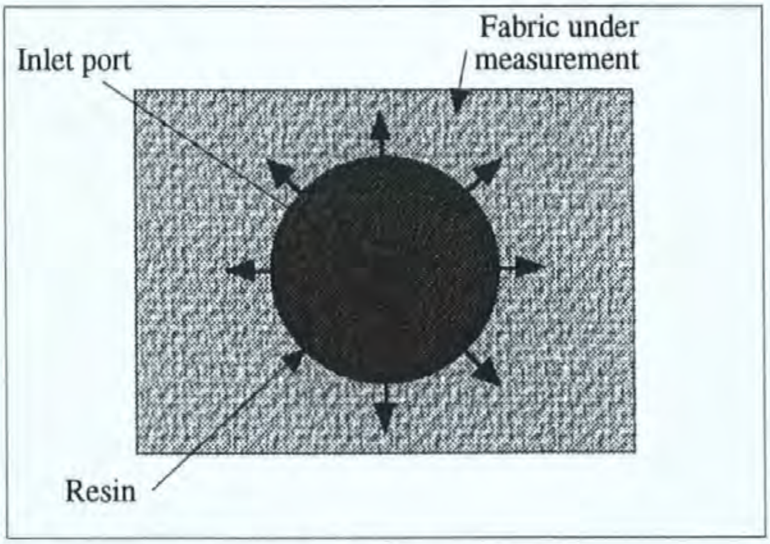


Figure 4.4 Radial resin flow.

The permeabilities, *K*, are found from equation 4.4 for longitudinal flow and 4.5 for radial flow [Griffin 1995].

$$\boxed{K = \frac{\mu L^2}{2\, P_o . T}}$$

..........*Equation 4.4*

$$\boxed{K = \frac{\mu}{P_o . T}\left[\left[\frac{r_o{}^2}{4}\right] + \frac{R^2}{4}\left[2\ ln\left[\frac{R}{r_o}\right] -1\right]\right]}$$

........*Equation 4.5*

Where: μ = dynamic viscosity (centipoise)

K = permeability (darcies)

P_o = inlet pressure (bar)

T = time (sec)

L = flow length (cm)

r_o = radius of inlet port (cm)

R = flow front radius (cm)

4.2.2 Fill mechanisms.

In composite manufacture by RTM, the porous material is the reinforcing fibre and liquid flowing in the pores is the resin. The porosity is determined by the volume of space between the fibres and the permeability describes the ease with which the resin can flow through these spaces. It is essential to understand the way in which each of these is influenced in a particular system by the fibre, resin and mould in order to get satisfactory moulding each and every time. Consideration of the fibre pack shows that there are two distinct sizes of porosity – large spaces between the tows of fibre and very much smaller spaces between fibres. For effective manufacture the resin must fill both spaces completely. Figure 4.5 shows the type of spaces the resin must occupy between the fibres.

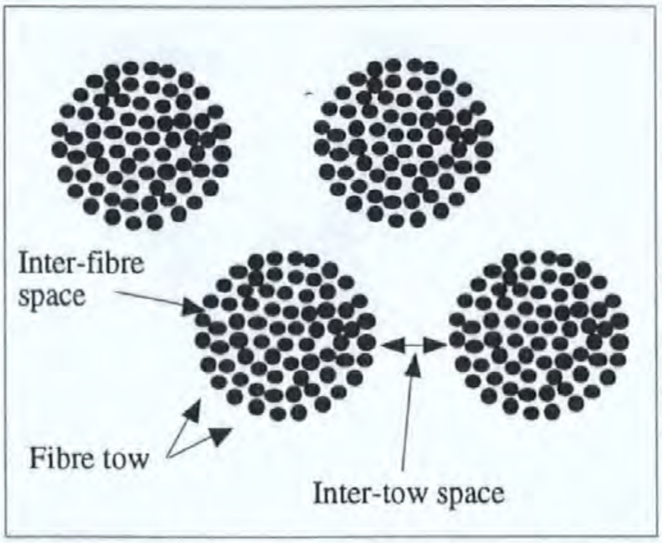


Figure 4.5 Space types the resin must fill.

The mechanism that drives the resin into the larger, inter-tow spaces is the injection pressure. The small inter–fibre spaces gives a significant capillary attraction [van Harten 1993]. As the resin is required to fill both space types to produce a void free laminate, both flow mechanisms are required. Thus the chemistry that defines the surface tension of the resin on the fibre interface is important. Considerable care must be taken in simulating RTM with fluids other than resin, this has been carried out on numerous occasions. The representation is questionable.

4.2.3 The influence of fabric architecture.

The key to allowing both space types to fill with resin, is the distribution of the space within the fabric. There should be good inter-tow spaces so that the bulk of the resin can move into the mould space, then the slower capillary action can take place to enable individual fibres to be wetted out. If no larger spaces exist, in other words the fibres are not arranged in bundles, then capillary filling will dominate and impregnation of the fibres will be slow. Figure 4.6 shows the former case where the fabric architecture is arranged in bundles or tows and both mechanisms can operate. "Fingering" of the resin flow front is caused by the lag in the fill of the fibre tows, capillary action allows gradual impregnation as the flow front progresses.

Allowing the resin to flow through the reinforcement fabric in this manner can significantly speed up the injection. A commonly held view is that as the injection pressure is increased, so the resin impregnation rate will increase. However while this is true to a point, if the pressure is too high, firstly the fibre pack may begin to move; this has been observed by the author to occur at pressures as low as 2.5 bar. Secondly, if the resin is driven in to the fibre pack too quickly, then the large spaces fill but the small inter-fibre spaces may not fill completely and the laminate quality will be poor. Thus the injection should occur at the natural soak rate of the fabric [McCarthy 1989]. The relationship between fibre architecture and the resin flow characteristics has not been established for the materials to be used for the propeller, thus in order to quantify this, a series of resin flow experiments were designed. These are reported in section 4.4.

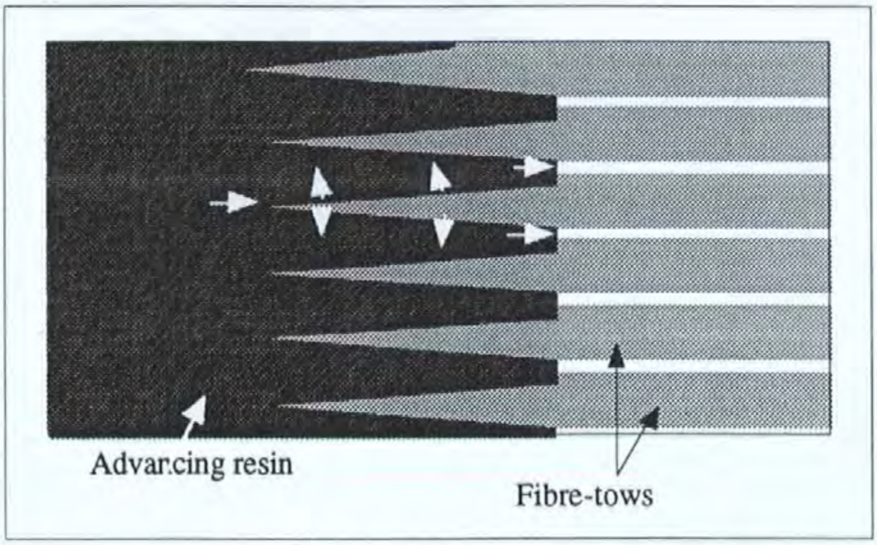


Figure 4.6 Fingering of resin flow.

4.3 Resin flow simulation.

4.3.1 Solutions to the RTM Processing Problem.

A significant body of research is growing in the area of RTM simulation. Several successful finite element models have been produced, the goal being to eliminate mouldings of sub standard quality. The modelling process enables the optimum placement of injection and outlet ports and thus the quickest and most reliable injection of resin when the mould tool is actually commissioned. However, expensive and sophisticated finite element prediction packages have come under criticism from some leading practitioners from within the RTM industry. A view often held is that experience in RTM mould tool design and application is cheaper and just as effective as time consuming software simulations. Three examples are given to show what can be done with computer modelling software.

Model simulations can be valuable in learning about, and visualising, how different fabric permeabilities affect the resin flow regime. Varying and investigating different parameters is possible without the expense of using a real mould and resin injection. A simulation model should take into account the geometry of the mould cavity, position of the resin inlet and outlet ports, the permeability of the fibre pack being modelled and any idiosyncrasies such as easy flow paths for the resin. The injection pressure is also a parameter to be included in the model.

4.3.2 Simulation of a flat plate containing mixed fabrics.

Figure 4.7 shows a number of different fabrics in the same tool and analysed together. The experiment reveals the expected complex flow front pattern from an injection in the bottom left of the laminate. The difference in fabric permeability is shown by the shape of the resin flow front. Figure 4.8 shows the computer simulation which correlates well with experiment. [Van Harten 1993].

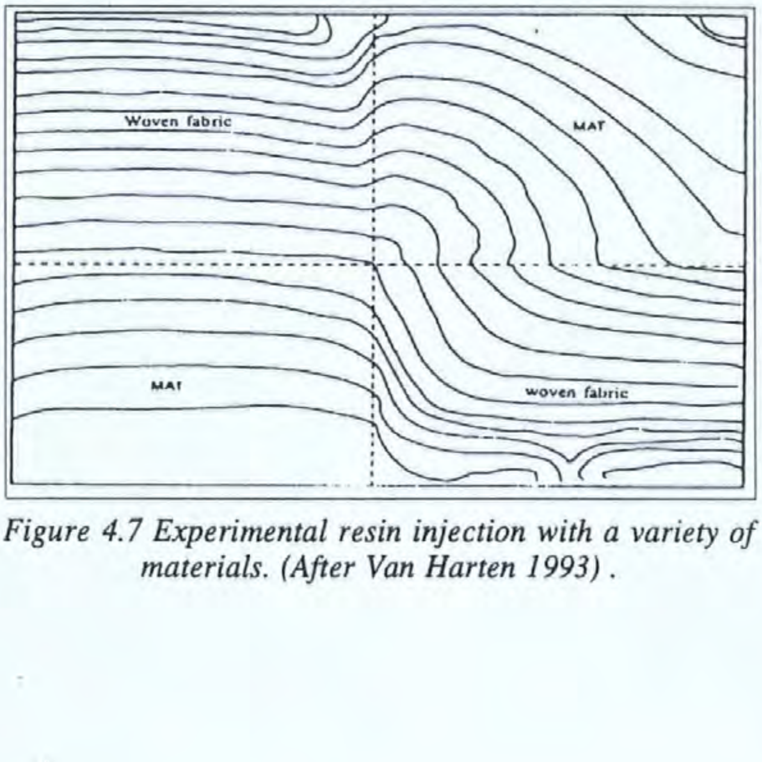


Figure 4.7 Experimental resin injection with a variety of materials. (After Van Harten 1993) .

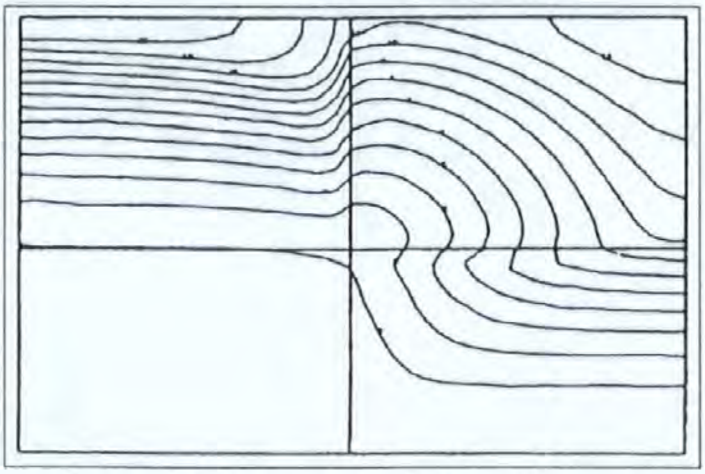


Figure 4.8 Computer simulation of the same material, (after van Harten 1993)

It can be seen that qualitatively the correlation between model and simulation is good. However it must be pointed out that this model does not take into consideration easy path effects, which have been illustrated classically in the bottom right hand corner area of the experiment, (figure 4.7). For many RTM applications this is a key issue. Its effect depends on the level of accuracy to which the fabric is cut and placed in the mould cavity. This parameter is operator dependent, variable and can thus only be modelled very tentatively.

4.3.3 RTM simulation at The University of Plymouth.

Work within this University (commercial in confidence) has demonstrated other effective simulations. Figure 4.9 shows the comparison between a model and an experiment for linear resin flow where a carbon laminate was manufactured. The carbon fabric was a 5 harness satin, with a plate thickness of 2.1mm at 55% volume fraction. The experiment was carried out in a mould approximately 1 metre by 0.3 metre.

In order that the correct fabric permeability could be used in the model, 2 experiments were performed to measure this. The fabric was arranged in a square mould and resin injected at the centre. Thus the resin flowed to form elliptical flow fronts, due to the anisotropy of the fabric. As this flow front progressed with time, so the fabric permeability could be calculated by the method shown in Section 4.2. Figure 4.10 shows the flow fronts as viewed from above the mould. The data was collected via a video camera and an image analysis computer package. It can be seen on flow fronts 2 and 3 a discontinuity in the isochrones. This was due to a lighting anomaly that reflected off the glass mould surface.

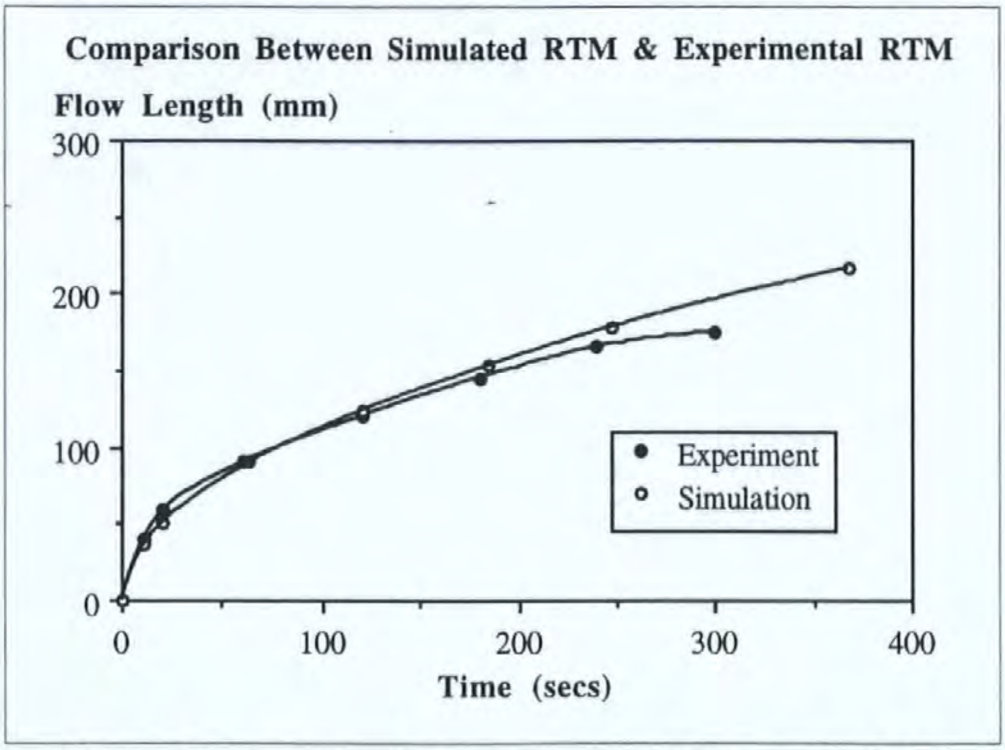


Figure 4.9 Comparison between experimental and simulated RTM.

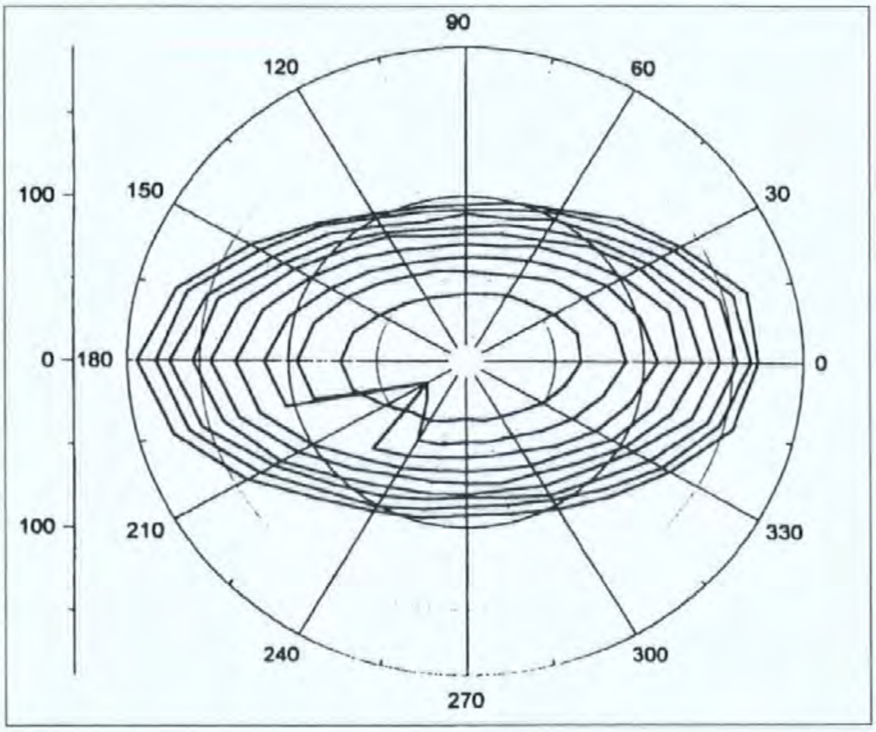


Figure 4.10 Flow fronts from which permeability was measured.

From figure 4.9 it can be seen how well the simulation correlated with the experimental data, the small divergence of the curves towards the end of the simulation is due to the resin in the experiment curing.

4.4 Experimentation to determine the most dominant RTM processing parameters.

4.4.1 Introduction.

In order to investigate resin flow as a function of fibre architecture, it was decided to carry out a series of experiments. These determined which parameters have a major effect on the end laminate quality and how the theory already discussed applies. In the light of previous practice of this research, the following were chosen for further study. These are considered to be the parameters that dominate the flow:-

- Effect of high volume fractions.
- Effect of reducing the resin viscosity.
- The effect of different fabric architectures.

The following secondary parameters were kept constant throughout each experiment:-

- Injection pressure 1 bar.
- Vacuum was not used.
- Resin and fibre type were fixed.
- Port position.
- Resin was not de-gased.

4.4.2 Experimental Procedure.

A mould tool was designed that enabled small wedge shaped test specimens to be produced. Figure 4.11 shows the details of the test coupons. This configuration was chosen because it allowed a specimen to be produced that had changing fibre volume fraction along its length. This was achieved by manufacturing each coupon with a consistent number of plies throughout. Thus the effect of different fibre volume fractions could be investigated in one experiment. Plate 4.4 shows the tool together with the temperature monitoring equipment[1]. Figure 4.12 shows the detail of the mould. The mould was substantially built so that any distortion of the mould during resin injection was insignificant. A straight edge was places across the top surface of the tool on a number of occasions and there was no detectable distortion.

---

[1] *Hot Bonder* from *Aeroform.*

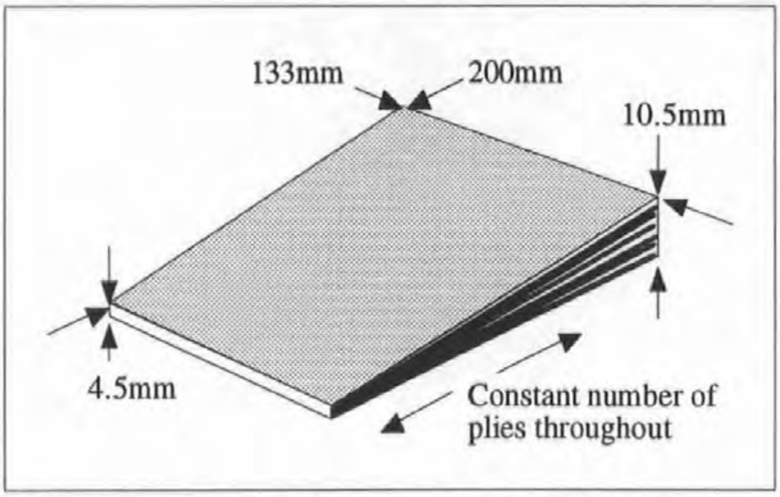


Figure 4.11 Composite test coupons showing dimensions.

The dimensions of the tool were chosen so that for the two different fabric types under consideration, of different aerial weights the same volume fractions could be achieved, table 4.1 shows the fabric properties. Plates 4.5 and 4.6 show the two fabric types under consideration.

Fabric	**Fibre Orientation**	**Aerial Weight**	**No. of Plies**	**Volume Fraction**	**Fibre Type**
Fabric A	0,90,+45,-45	2200	4	30-65%	E Glass
Fabric B	O,90	1458	6	30-65%	E/R Glass

Table 4.1 Fabrics used for the experimentation.

Plate 4.4 Experimental RTM mould (foreground)
& Hot Bonder (background) for recording temperature.

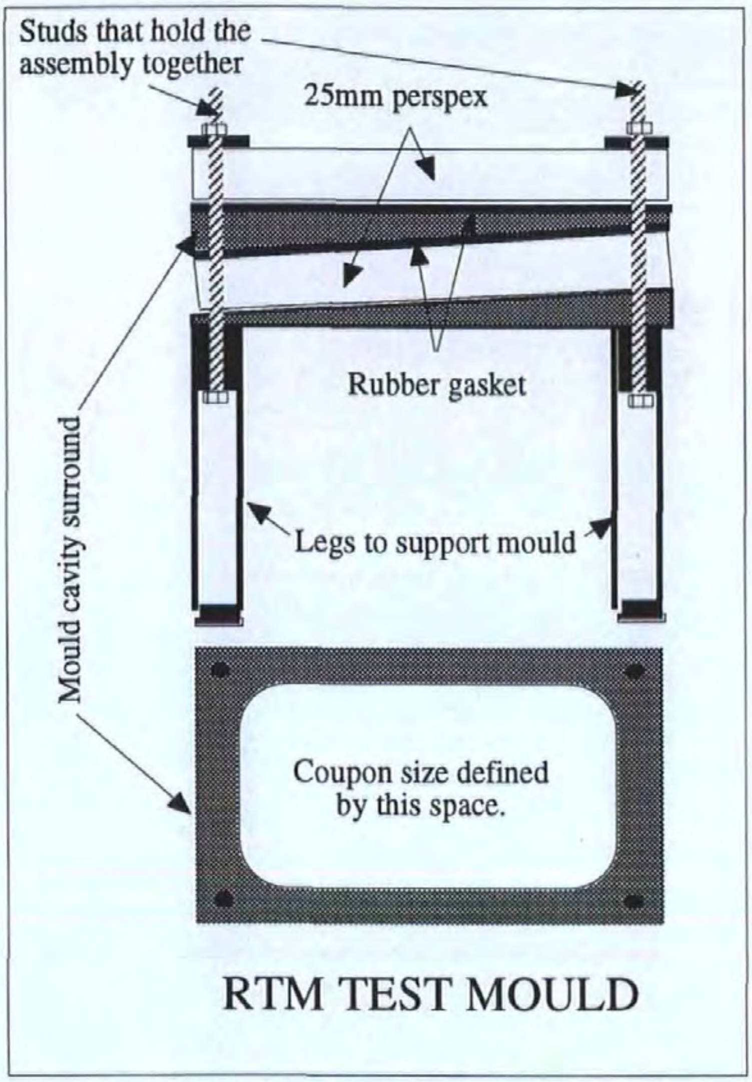


Figure 4.12 Mould for RTM test coupons of 200 mm in length.

Plate 4.5 Fabric A (0,90,+45,-45) E-glass 2200 g/m^2

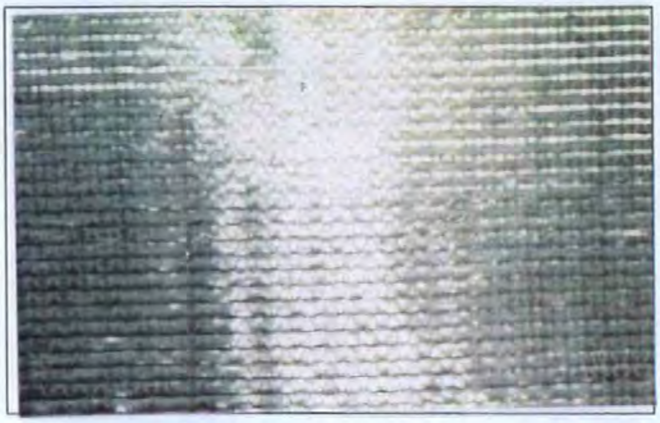


Plate 4.6 Fabric B (0,90) E/RH-glass 1458 g/m2

In order to collect the data, the following equipment was used:

- RS miniature 0–10 bar analogue pressure gauge (resin inlet pipe was kept the same length for each experiment in order that any losses in the pipe were consistent).
- J type thermocouples.
- Pressure vessel to inject resin.

4.4.3 Resin System

One resin system was used, Ciba Geigy LY 5052 epoxy. This resin has a long pot life when mixed with its slow hardener at room temperature. 34% hardener is used by weight to 100% resin, further data is included in appendix 4 of this thesis. Figure 4.13 shows the dynamic viscosity against temperature for this resin system, measured at the Department of Maths at the University of Plymouth. A *Carri–Med CS* rheometer was used from which the viscosity is found from shear rate divided by the shear stress found in the resin. Table 4.2 shows the viscosities in poise against resin temperature Appendix 3 includes the Newtonian characteristics obtained from this measurement.

Temperature (degrees C)	Viscosity (Poise)
20	10.01
30	4.6
40	2.5
50	1.6

Table 4.2 Resin viscosities.

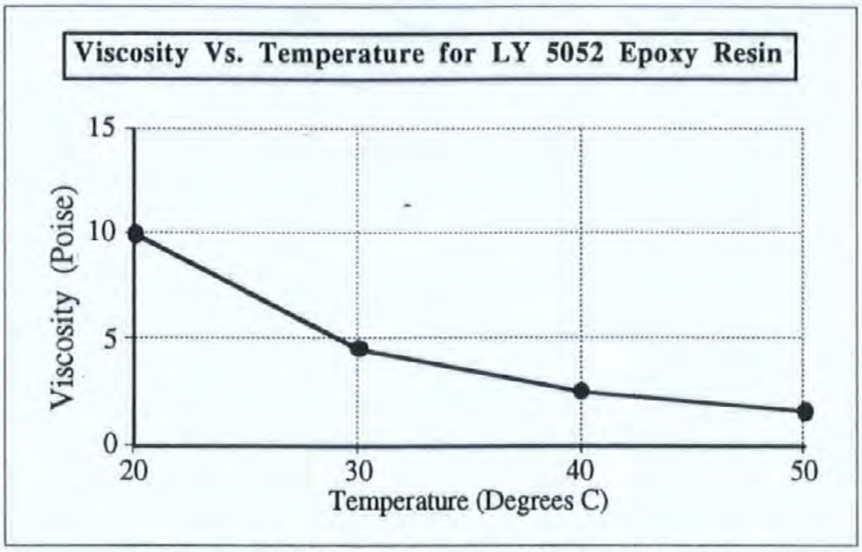


Figure 4.13 Resin viscosity (slow hardener)

4.4.4 Experiments.

The twelve experiments that were carried out are summarised in table 4.3. Eight of these were injected from the centre of the mould so that easy path effects from the mould edges could be eliminated. Four experiments, however were injected from the side of the tool. These were performed at the outset, it was then considered that an improvement would be to eliminate edge effects and inject from the centre.

In order to carry out the experiments at different temperatures and to study the effect of variable viscosity, the resin and hardener prior to mixing and the entire mould were placed in an oven. When they had reached the test temperature, they were removed from the oven and the resin and hardener mixed and injected in the mould cavity. The temperature of the mould and the resin were monitored as the resin was injected at the positions indicated in figure 4.14. One thermocouple was placed adjacent to the inlet port and one a little further inside the mould. Temperature plots are given in appendix 4a.

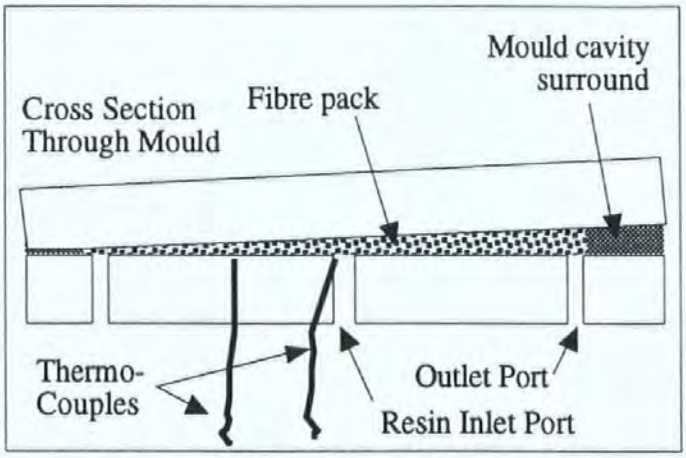


Figure 4.14 Thermocouple positions.

Exp. No	**Position of injection**	**Resin Type**	**Injection Pressure**	**Fibre Type**	**Temp.**	**Mould Fill Time**	**Fig.**
1	Side	LY 5052	1 bar	Fabric B	17°C	12 min	4.15
2	Side	LY 5052	1 bar	Fabric B	30°C	4 min	4.16
3	Side	LY 5052	1 bar	Fabric B	40°C	2.5 min	4.17
4	Side	LY 5052	1 bar	Fabric B	70°C	1 min	4.18
5	Centre	LY 5052	1 bar	Fabric A	14°C	40 min	4.19
6	Centre	LY 5052	1 bar	Fabric A	24°C	11 min	4.20
7	Centre	LY 5052	1 bar	Fabric A	24°C	10 min	4.21
8	Centre	LY 5052	1 bar	Fabric A	26°C	6 min	4.22
9	Centre	LY 5052	1 bar	Fabric B	14°C	5 min	4.23
10	Centre	LY 5052	1 bar	Fabric B	24°C	3 min	4.24
11	Centre	LY 5052	1 bar	Fabric B	25°C	3 min	4.25
12	Centre	LY 5052	1 bar	Fabric B	29°C	2 min	4.26

Table 4.3 Summary of experiments.

4.4.5 Results.

The resin flow fronts were recorded by tracing them at given time intervals onto acetate film with a fine permanent marker. The resin could easily be seen as it flowed through the fabric. The following assumptions were made:

- The mould was rigid and did not deflect as pressure was applied to inject the resin, this was confirmed by placing a straight edge across the perspex mould surfaces for visual observation.
- The areas traced out on the acetate were considered to represent the volume occupied by the resin.
- Injection pressures and pressure losses were the same for each experiment.

Having carried out the experiments already described, figures 4.15 to 4.26 show the resin flow together with the distribution of fibre volume fraction along the plate.

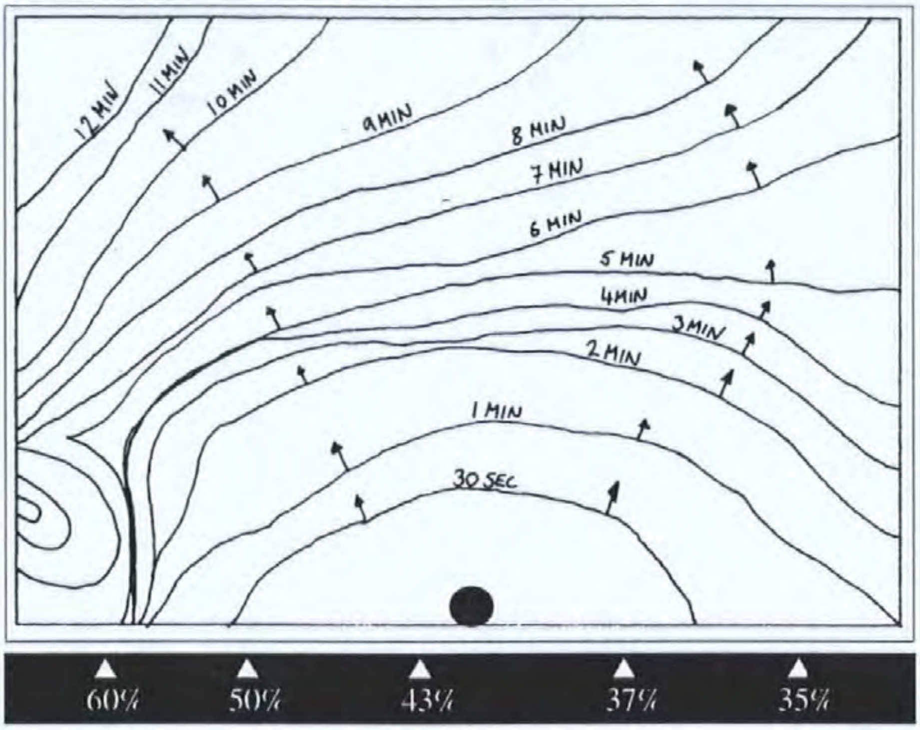


Figure 4.15 Resin flow coupon 1.

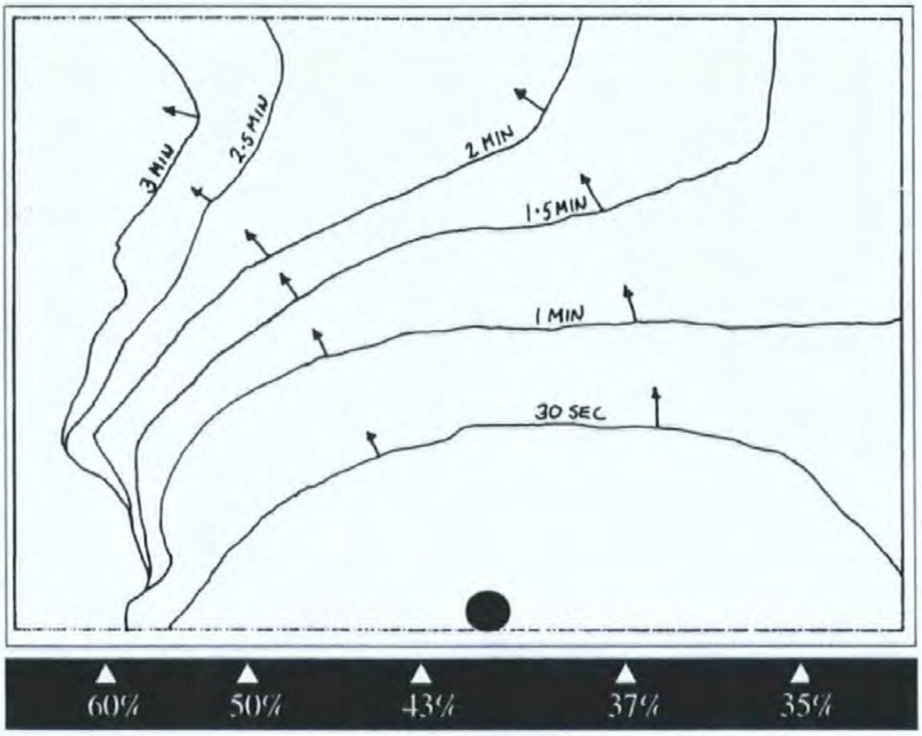


Figure 4.16 resin flow coupon 2.

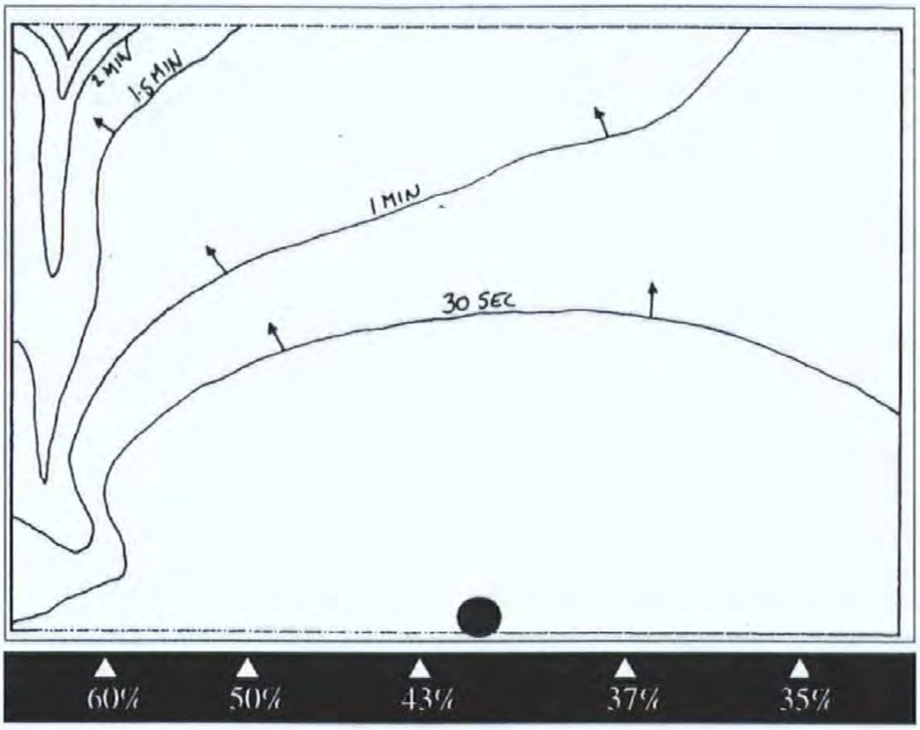


Figure 4.17 Resin flow coupon 3.

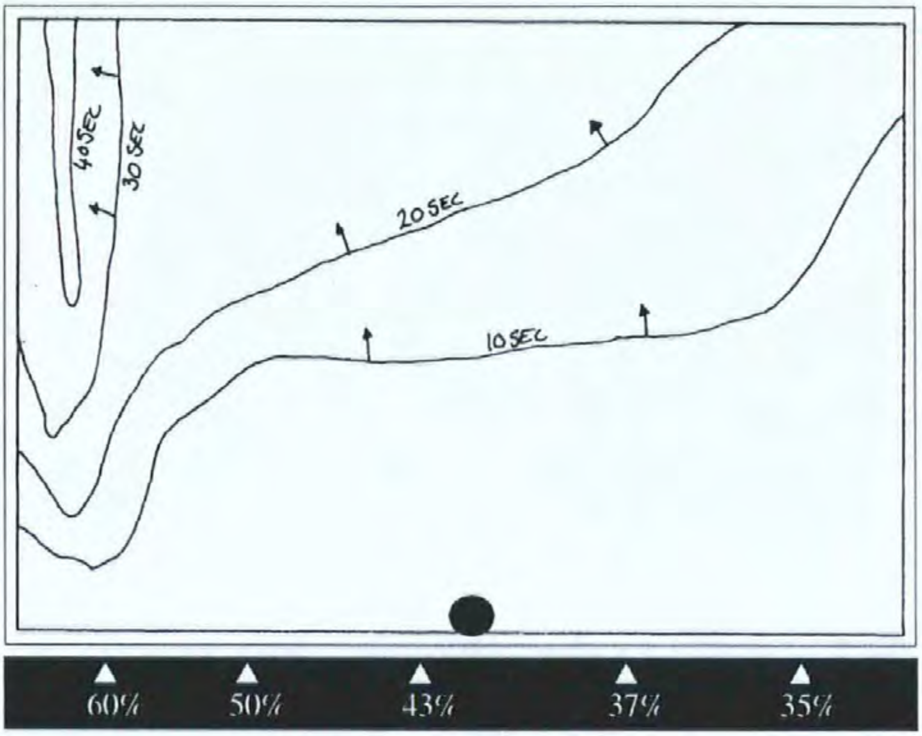


Figure 4.18 Resin flow coupon 4.

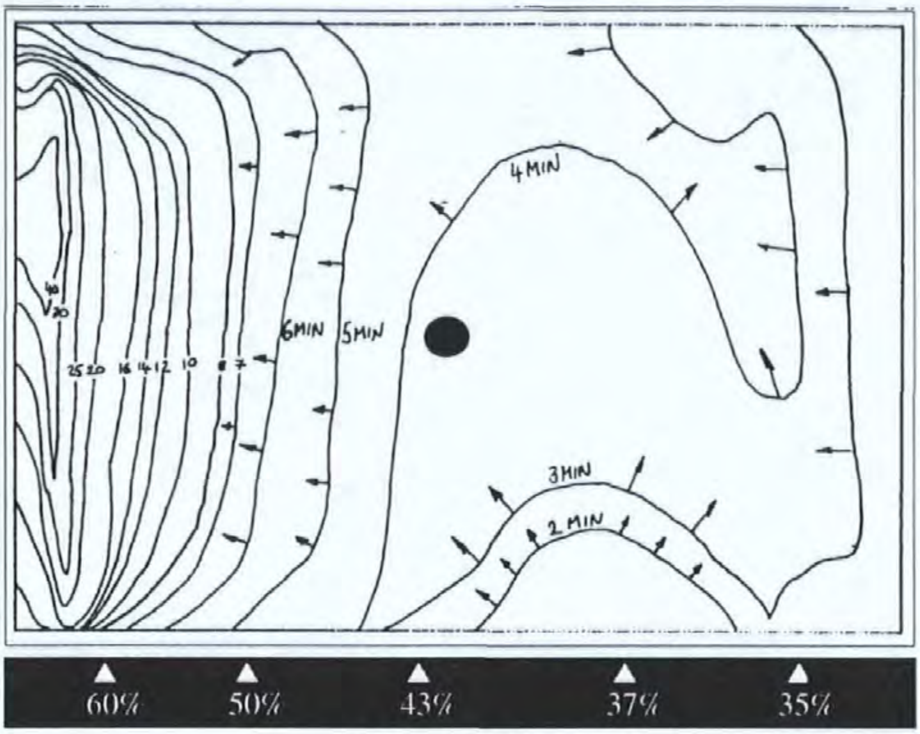


Figure 4.19 Resin flow coupon 5.

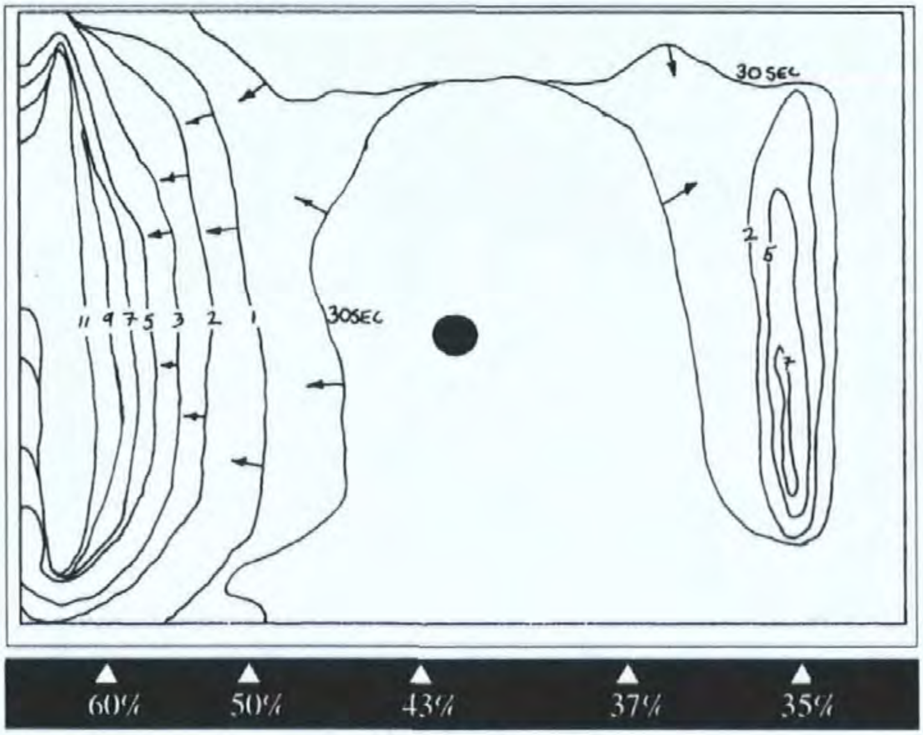


Figure 4.20 Resin flow coupon 6.

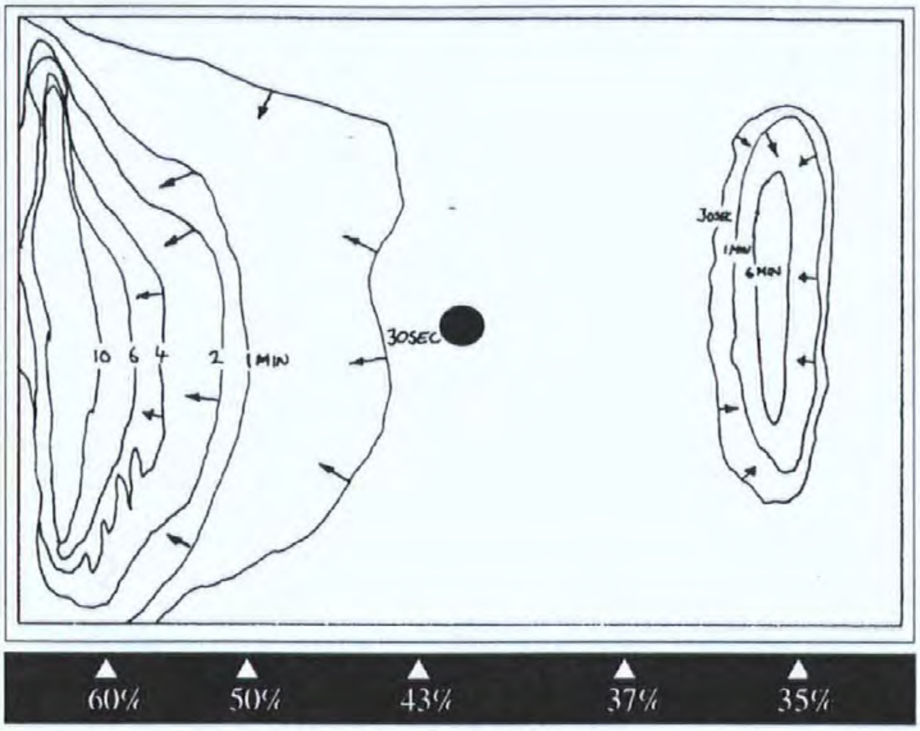


Figure 4.21 Resin flow coupon 7.

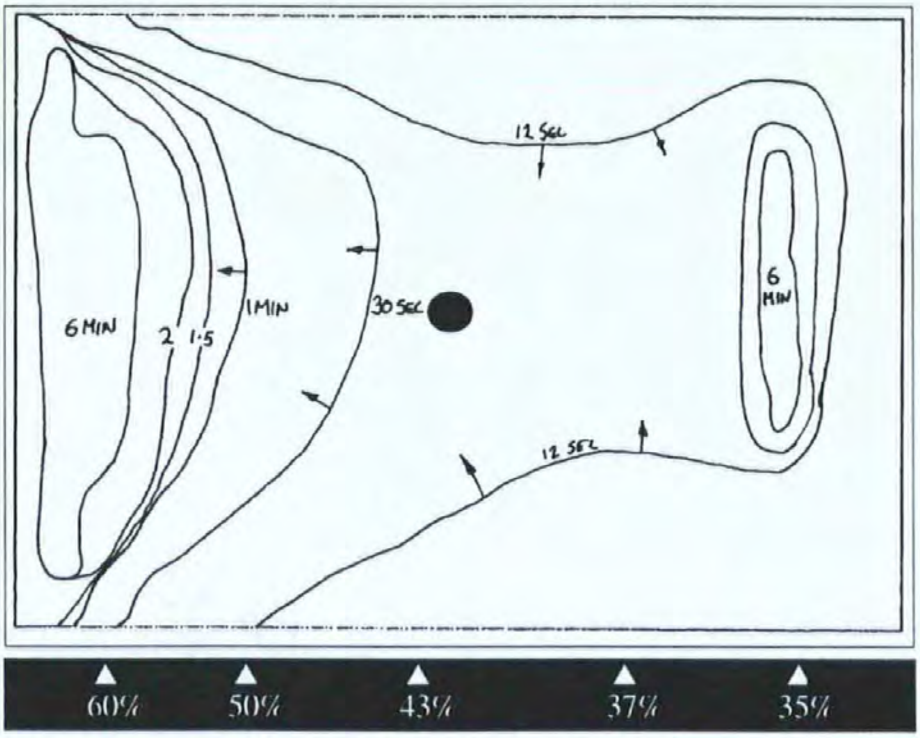


Figure 4.22 Resin flow coupon 8.

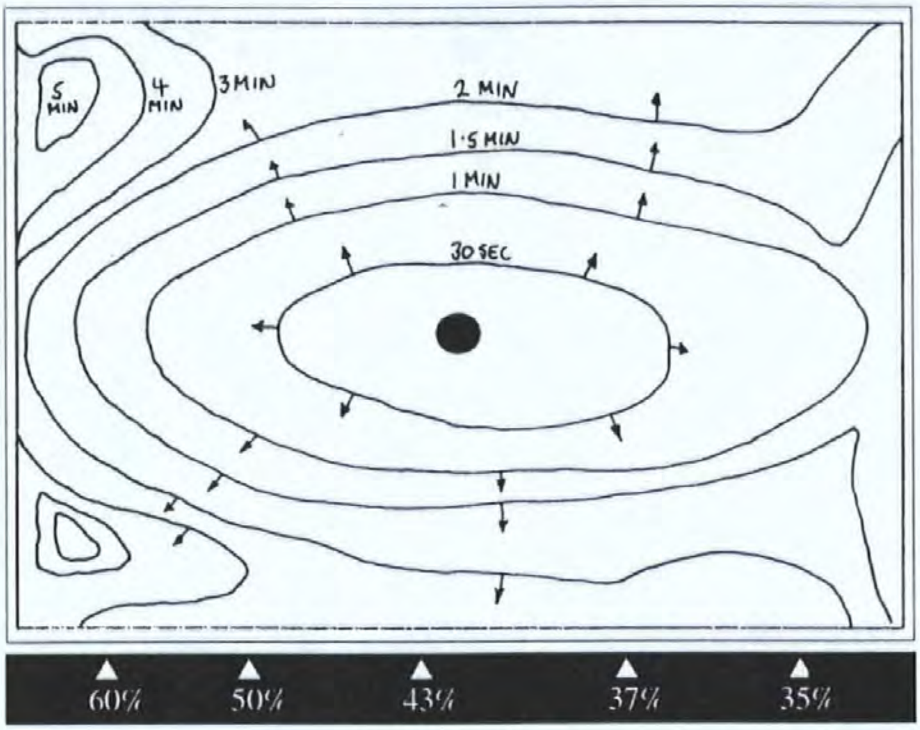


Figure 4.23 Resin flow coupon 9.

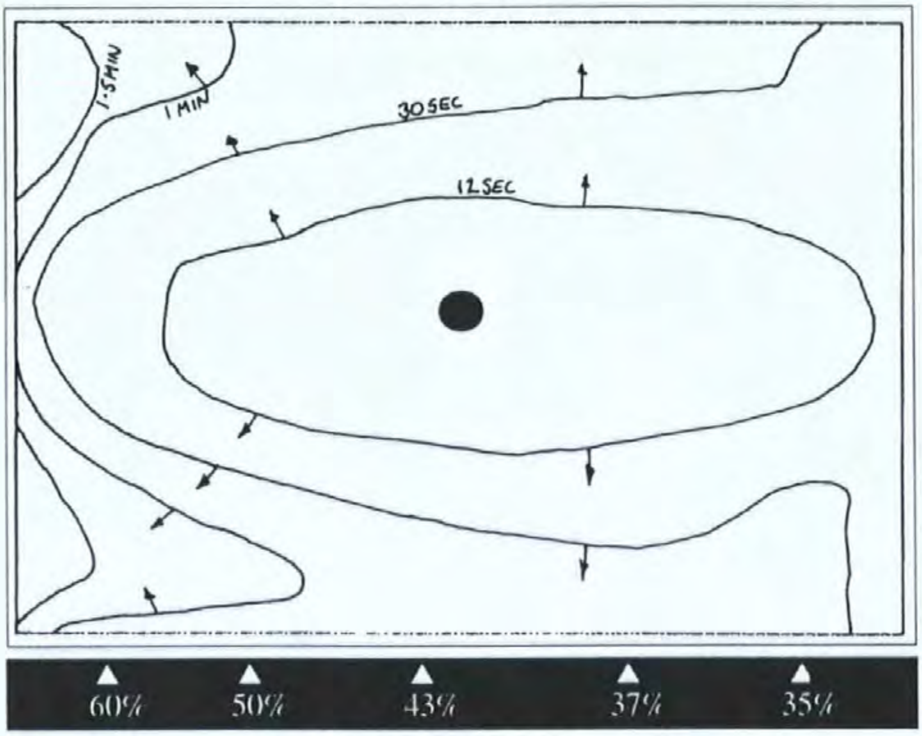


Figure 4.24 Resin flow coupon 10.

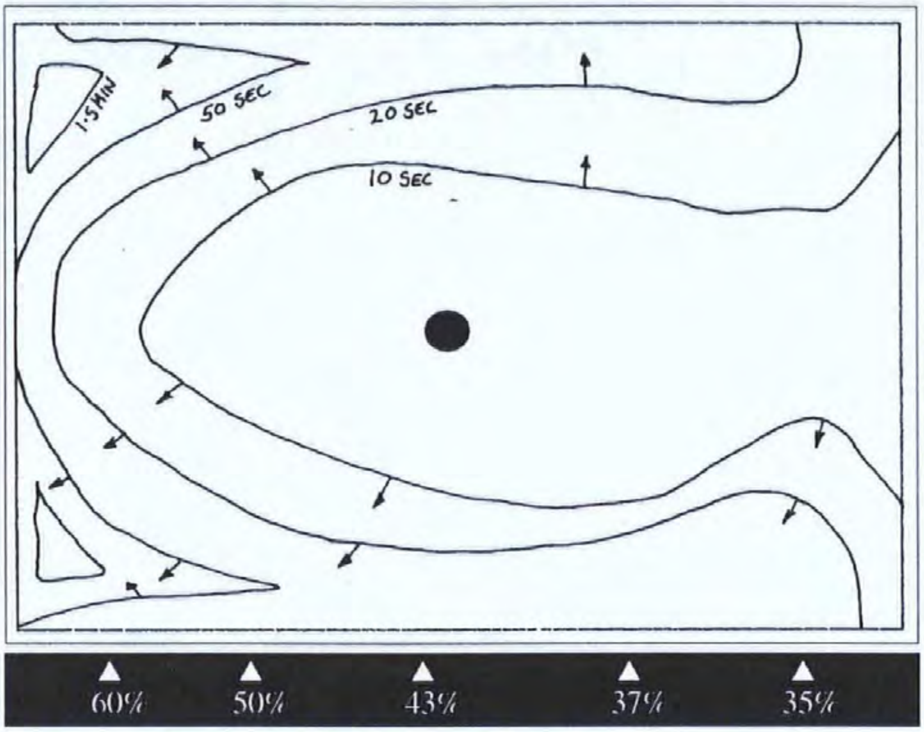


Figure 4.25 Resin flow coupon 11.

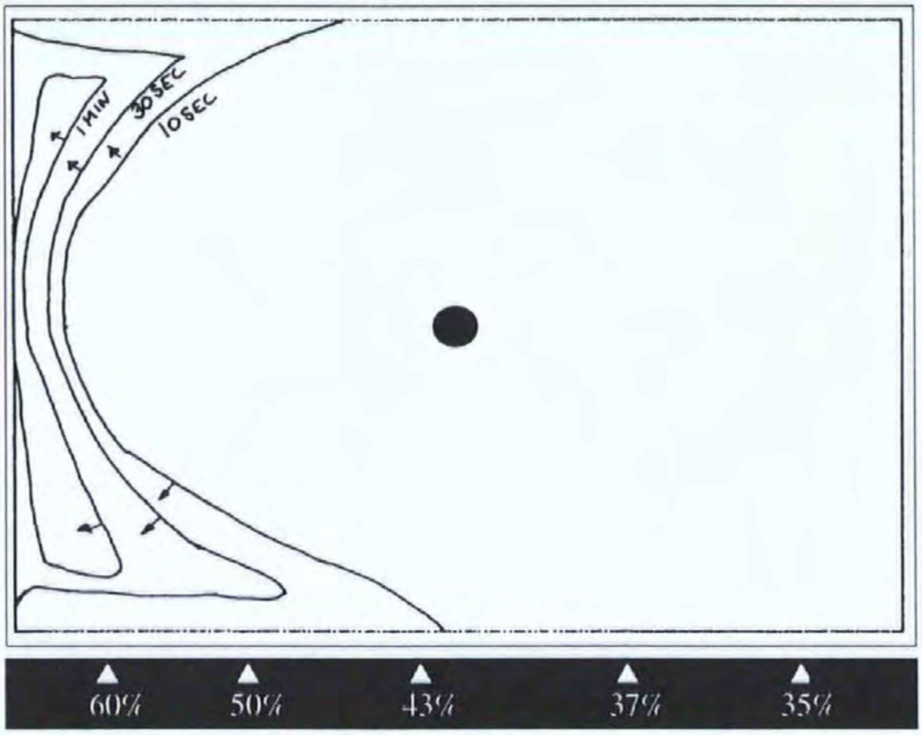


Figure 4.26 Resin flow coupon 12.

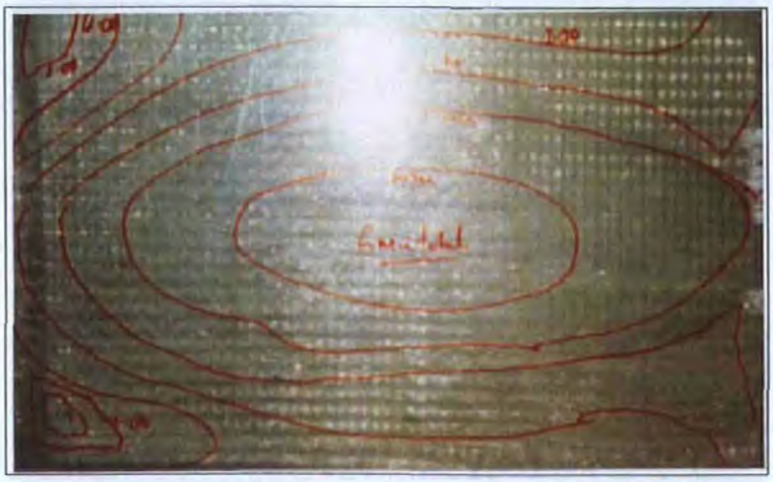


Plate 4.7 Coupon 9 after injection and subsequent removal from the mould.

4.4.6 Interpretation of the results.

Plate 4.7 shows a sample plate with its isochrones traced onto the acetate. In order to perform this analysis, the following graphs were derived from each experiment, as summarised in table 4.4.

Fig no	From which plates	Graph
4.27	(Side) 1,2,3,4	Total mould fill time vs. resin viscosity
4.28	(Side) 1,2,3,4	Total mould fill time vs. resin temperature
4.29	(Side) 1,2,3,4	% mould filled vs. time
4.30	(Centre) 5-12	% mould filled vs. time
4.36	(Centre) 5-12	Resin flow rate vs. fibre volume fraction

Table 4.4 Graphical analysis of data,
(numerical results are given in appendix 2).

4.4.6.1 Total mould fill time (side injection).

The total mould fill time has been plotted against the different resin viscosities in figure 4.27. Figure 4.28 shows how fill time varies with resin temperature. Since the relationship between temperature and viscosity is not linear, it can be seen that the most significant increases in injection time occur at the lower temperature. This has implications for production; as the required moulding temperature increases, so the cost of tooling and processing also increases. However, this experiment shows how, for example a rise from 20°C to 30°C speeds up injection significantly, however a rise from 40°C to 50°C has a smaller effect and may not be worth the extra cost. It can be seen that an increase in resin temperature from 17°C to 40°C results in a reduction in injection time of 75% from 10 minutes to 2.5 minutes.

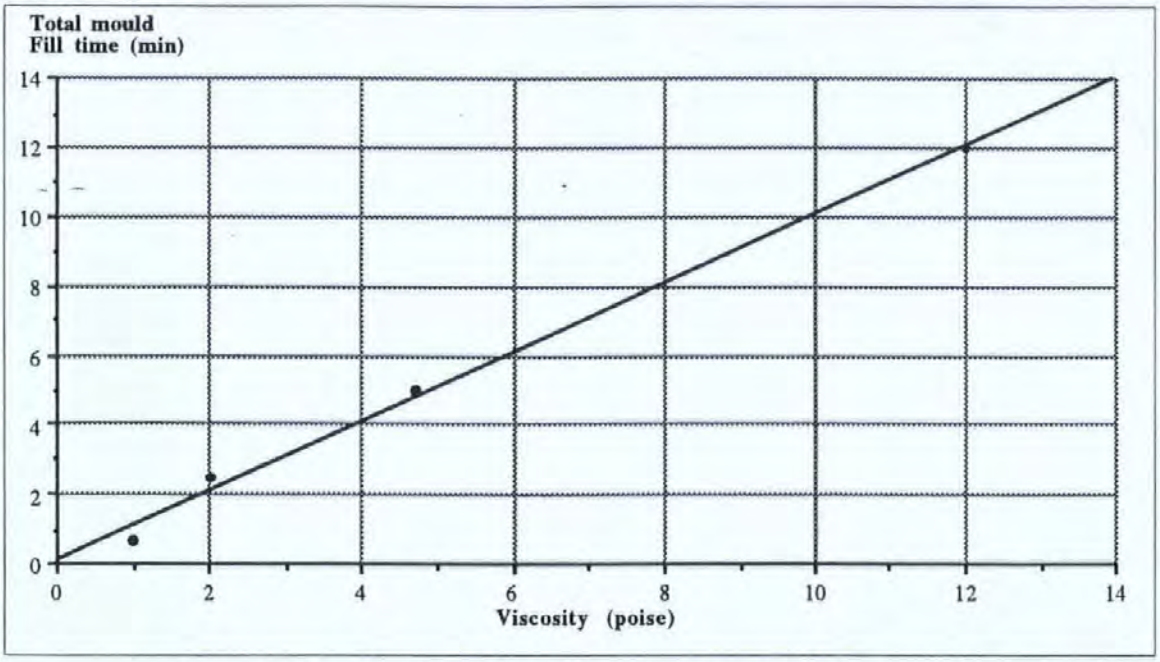


Figure 4.27 Mould fill time vs. resin viscosity (side injected).

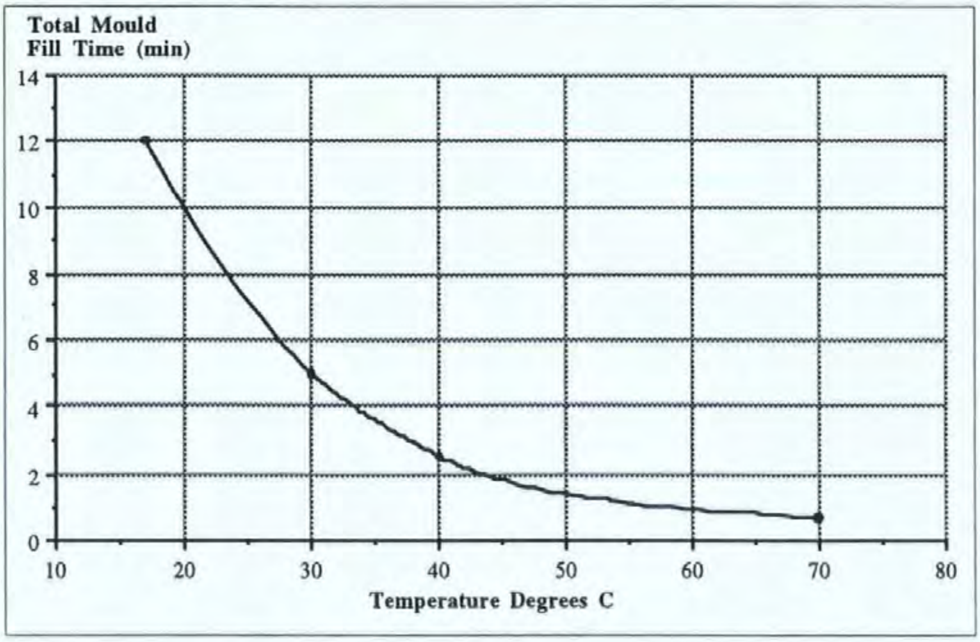


Figure 4.28 Mould fill time vs. resin temperature (side injected).

4.4.6.2 Percentage Mould Fill vs. Time.

In order to show how the resin injection progressed with time for each experiment, a planimeter was used to measure the areas enclosed by each isochrone. These areas were then plotted against time, the influence of temperature on fill rate is illustrated. Fill rates shown in figure 4.29, (side injection) show a clear relationship between temperature and thus viscosity and the rate at which the injection takes place. Figure 4.30 (central injection) shows a comparison of temperature and the influence of the two fabric architectures.

It can be seen that fabric B fills between 6 and 8 times faster than fabric A. At 14°C fabric B is filled in approximately 5 min and fabric A is filled in approximately 40 minutes, giving an 8 fold increase. At 24°C, fabric B is filled in approximately 2 minutes and fabric A in approximately 12 minutes, giving a 6 fold increase in fill time. Thus it can be seen how much more conducive to resin flow within the fibre pack the fibre architecture of fabric B is.

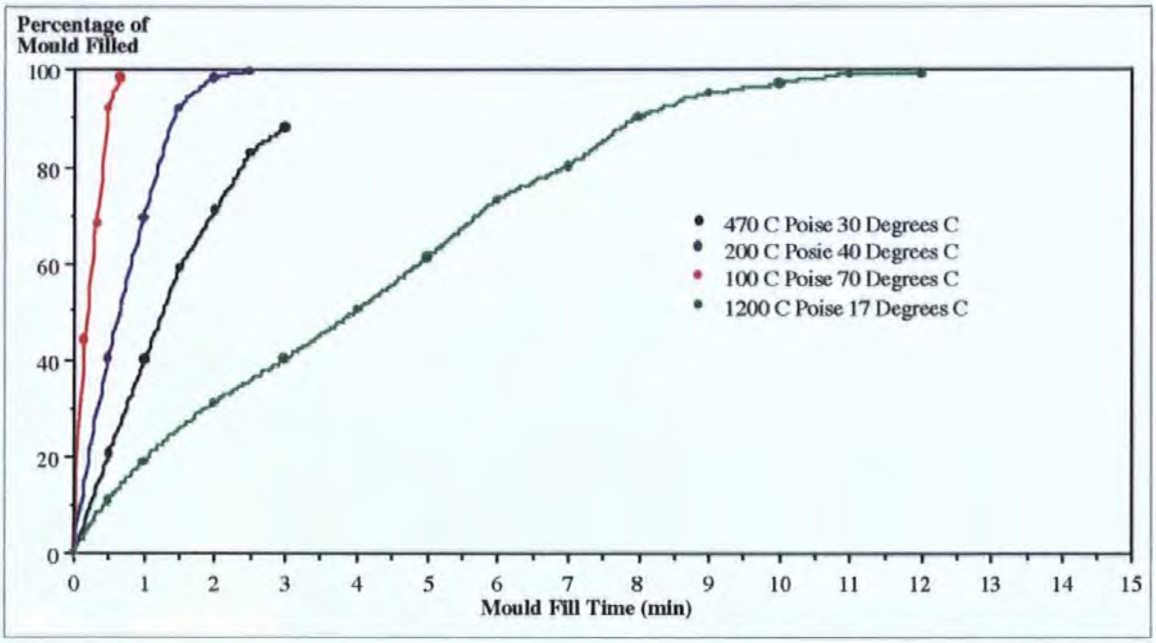


Figure 4.29 Percentage of mould filled vs. time (side injected).

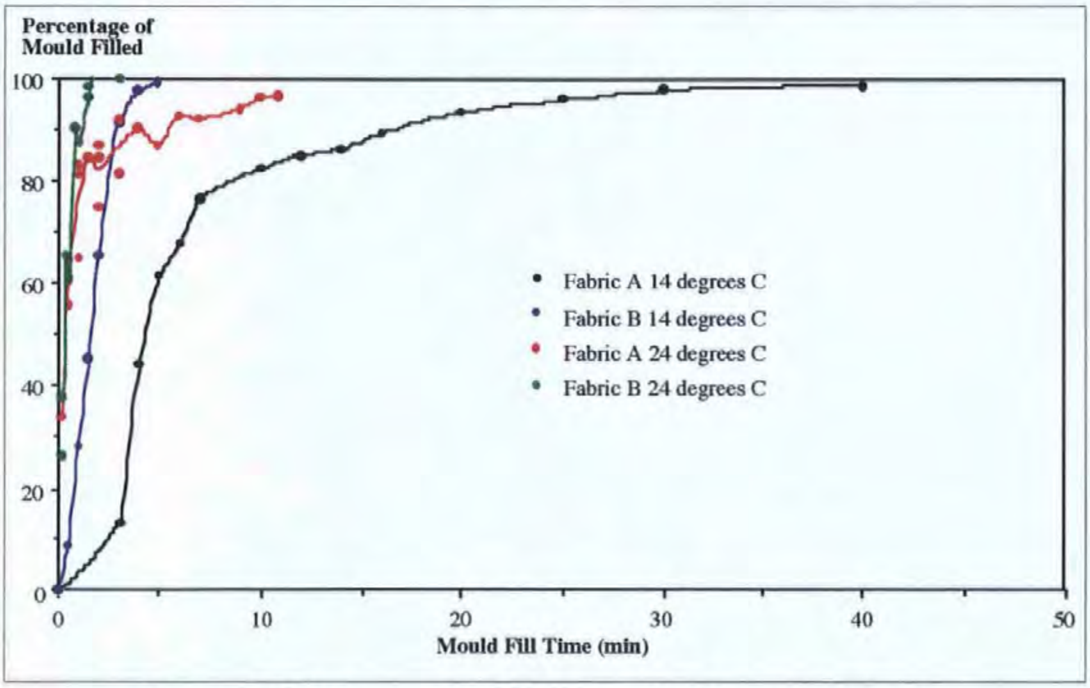


Figure 4.30 Fill rates for fabric types A & B (centre injection).

Fabric B is characterised by good inter-tow spacing, (figure 4.31) allowing both flow mechanisms to operate. These inter-tow spacings do reduce as the fabric is compressed in the mould, however although smaller spaces do remain. Generally the inter–tow spacing is approximately 10% of the tow diameter (uncompressed). Fabric A on the other hand is made up of 4 layers of fibre stacks each at 45 degrees to one another, (figure 4.32). Only one of these layers has good inter-tow spacing, thus the balance of resin flow mechanisms cannot operate and capillary flow dominates, which is only adequate to fill individual tows once the resin has arrived at that point. A by–product of the architecture of fabric B has been observed in that greater 3 dimensional resin flow is possible. This is also a contributory factor in enabling resin to fill the mould.

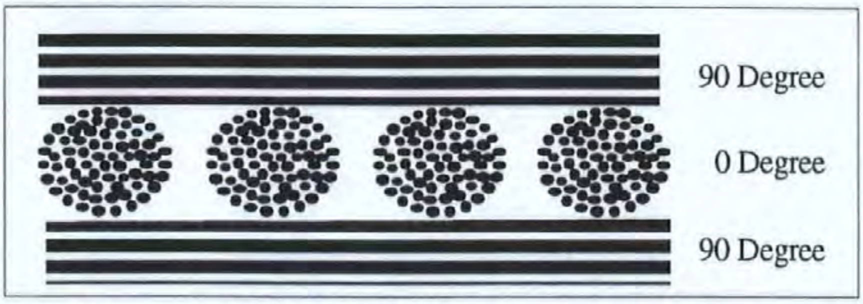


Figure 4.31 Fabric B showing good inter-tow spaces.

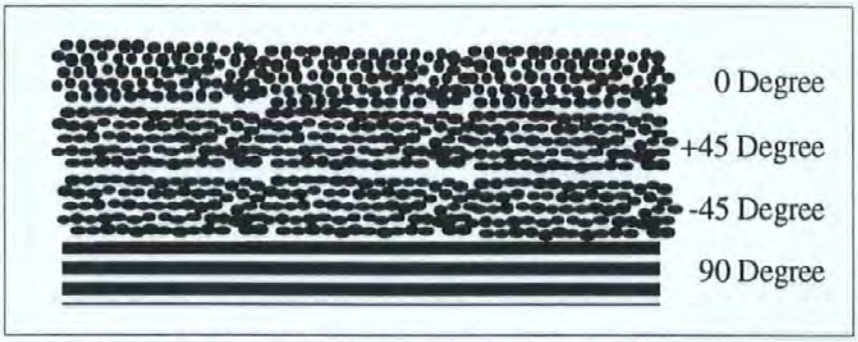


Figure 4.32 Fabric A showing poor inter-tow spacing.

The erratic nature of the the flow front patterns exhibited by fabric A can be seen in figure 4.19–4.22. This was mainly brought about because of the poor 3–dimensional flow properties of this material. However as soon as the injection was started with fabric B, resin flowed quickly through the thickness of the fibre pack, (figure 4.33). This was not the case with fabric A, where resin flowed around the edges first, (figure 4.34). This helps to explain why the fabric A at 24°C, (seen in figure 4.30 in red), initially fills faster than fabric B (in blue). The resin has initially quickly flowed around the edge of the mould, whereas the resin flowing through the biaxial cloth has been restricted to flowing through the material.

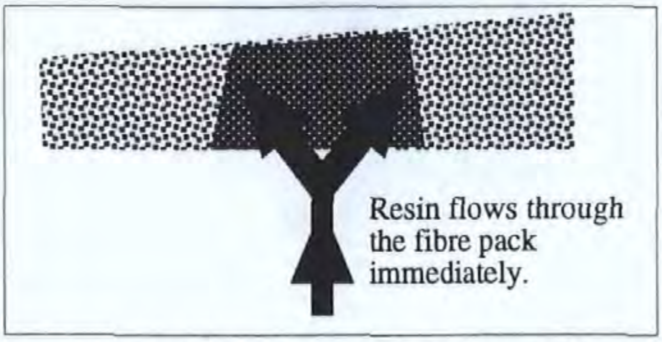


Figure 4.33 Initial resin flow (fabric B).

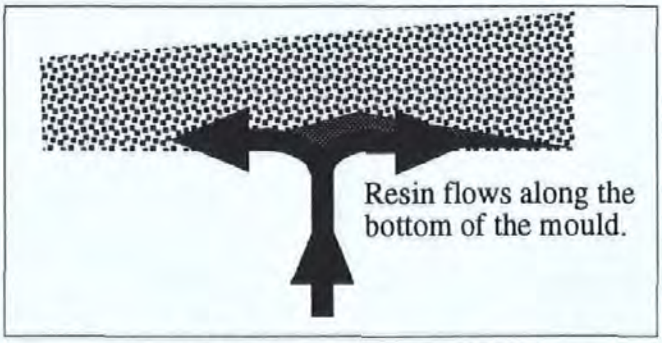


Figure 4.34 Initial resin flow (fabric A).

4.4.6.3 The effect of increased volume fraction on resin flow rate.

Because the samples produced had a variation in fibre volume fraction of between 35% and 65%, it was anticipated that if the resin flow rate in the direction of increasing fibre volume fraction was plotted against volume fraction, then it would be possible to determine if there was a critical point at which the resin flow was so slow as to be ineffective. The data was plotted in the manner shown in figure 4.35.

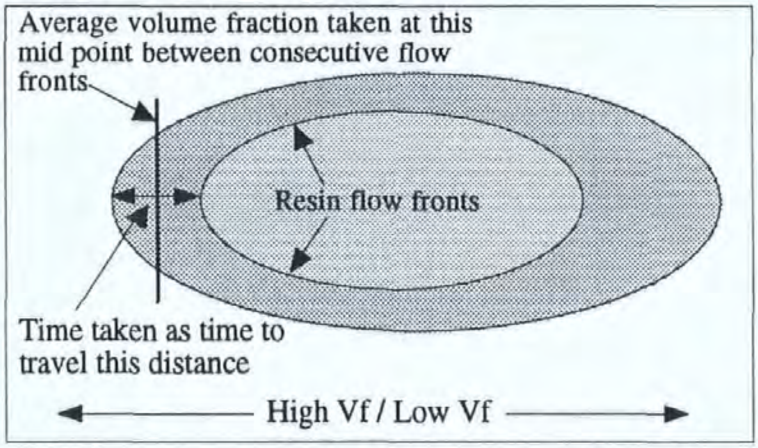


Figure 4.35 Measurement of flow velocity against fibre volume fraction.

The resin velocity was measured between isochrones and plotted against the average volume fraction (figure 4.36). Having plotted this data, various curve fits were attempted with only limited success because of the scatter of the data. The best fit was possible using a log curve. However, what is perhaps clearer without any attempt at introducing a curve, is that the data seems to settle out at very different points regardless of resin viscosity. Indicating the significant influence of fabric type.

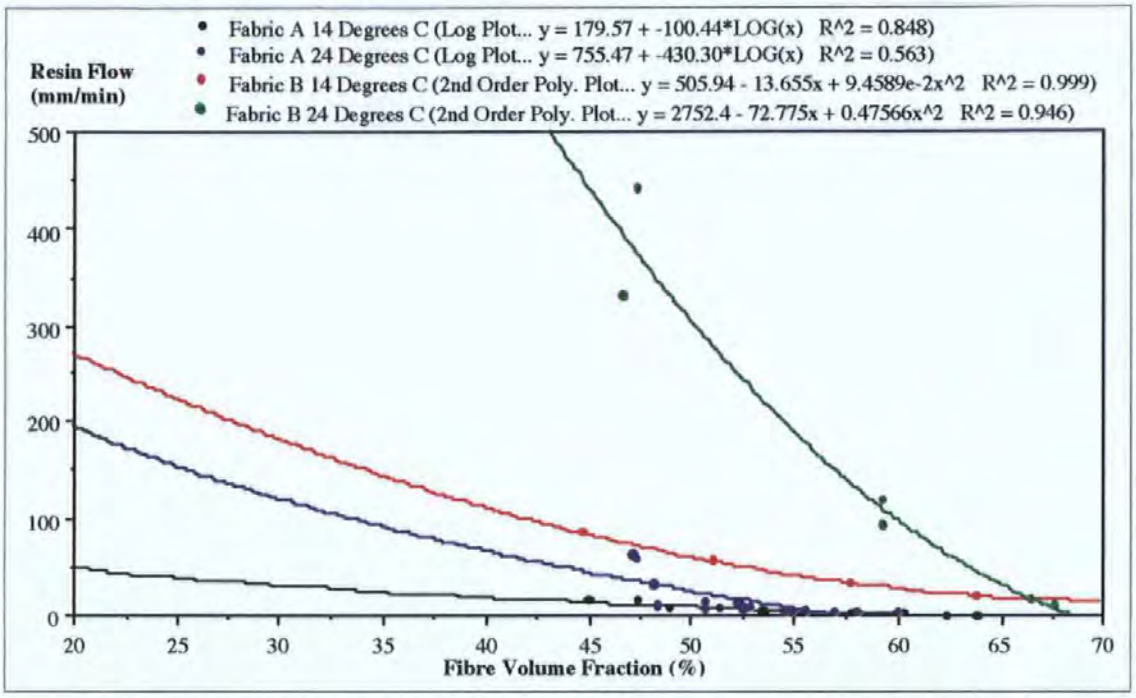


Figure 4.36 The influence of fibre volume fraction on resin flow velocity.

In summary, the following is observed; the resin flow velocity in fabric A at 45% fibre volume fraction is about the same as the resin flow velocity for fabric B at 65% fibre volume fraction. Also while the resin velocity for fabric A at about 60% fibre volume fraction seems to have almost stopped, the resin is still flowing in fabric B. Thus what is clear is the overriding effect of the fabric architecture. In addition the following must be noted; fabric orientation is not the cause of the small inter tow spacings in fabric A. These experiments have considered that the visible resin flow front is a good representation of the overall flow within the experimental plate. Whilst this is not absolutely the case, (for example look at the 2 min. flow isochrone in figure 4.19), it is considered that as the test plates are "thin," then the general picture generated of the resin flow is not in fact misleading. The central injection in the later experimental plates was carried out to minimise any edge effects.

4.5 Mathematical description of resin flow.

Having plotted the curves that show the experimental resin flow types, the analysis was taken a stage further. In order to obtain a generic mathematical description of the resin flow, the curves already plotted for the two different fabrics were idealised as exponential curves and the equations determined as a function of temperature. Thus for a given resin temperature the rate of resin flow could be predicted for both fabric types. Thus a more general picture was created that enabled consideration of a variety of different resin temperatures.

So that this can be carried out, certain assumptions were necessary. In examining the curves in figure 4.30, it can be seen from inspection that curves follow an exponential type function of the form:

$$\boxed{\%\ mould\ filled = 100\ (\ 1\text{-}exp^{(-Kt\ )})} \qquad \text{....Equation 4.6}$$

Where: t = time in seconds

K = index to be determined

This function can be seen to be approximately correct from figure 4.37 where the natural log is taken from each data point. Straight lines are fitted to these points and the correlation is shown. Several attempts were made to achieve better correlation, particularly with respect to the curve represented in red which has a correlation function of only 0.737. There is considerable scatter associated with this set of data points. Care was taken to ignore any erroneous data, however the gradient of the line was not altered significantly. Therefore it was considered for completeness to include all the data.

What is needed now, is to determine the index *K* . The index t is known because this is the time taken for the resin to fill a given area. When the log of % mould fill is plotted against time, (figure 4.37) then the gradient of a straight line curve fit equates the value *-K*.

Rewriting equation 4.7...

$$\boxed{(100\ \text{-}\ \%\ fill\ )/\ 100\ =\ exp^{(-Kt\ )}} \qquad \text{Equation 4.7}$$

$$\boxed{y = exp^{(-Kt\ )}} \qquad \text{Equation 4.8}$$

$$\boxed{ln\ y = \ -Kt} \qquad \text{Equation 4.9}$$

$$\boxed{ln\ y\ /\ t\ = -K} \qquad \text{Equation 4.10}$$

The data for this calculation is given in appendix 2. Figure 4.37 shows the plot, together with the equations for the straight line fit and correlation coefficients. The gradients for each line are held within these equations. These are given in table 4.5.

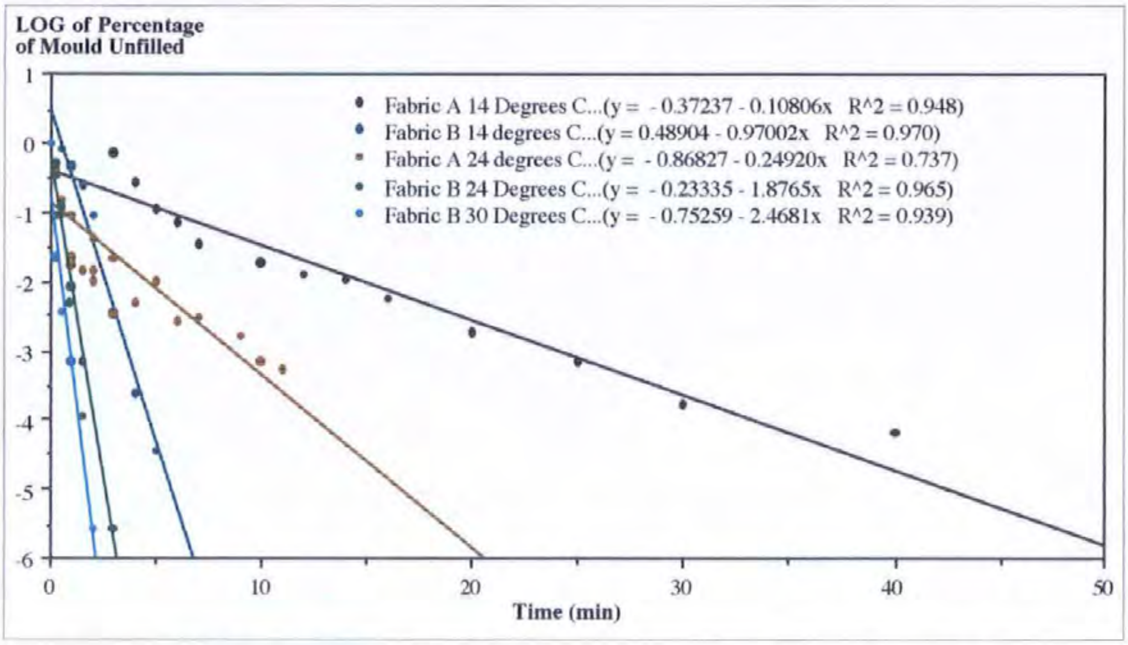


Figure 4.37 Log plot of unfilled mould space vs. time with straight line fits.

Temperature	Fabric A	Fabric B
14	-0.10806	-0.97002
24	-0.2492	-1.8765
30		-2.4681

Table 4.5 Gradients from figure 4.37.

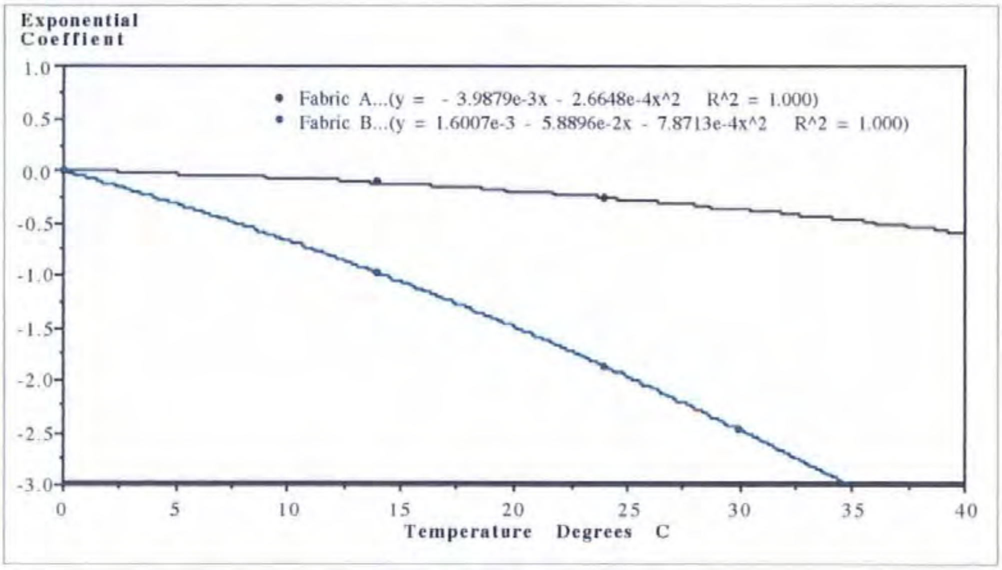


Figure 4.38 Exponential coefficient vs.temperature (derived from gradients table 4.5).

Software was used to fit the straight lines and from these calculate the gradients. Having determined the gradients and therefore *K*, these values were plotted against temperature. This gave a function that for a given temperature and the index *K* could be found from the line equation given in the software. Figure 4.38 gives these plots for both fabric A and fabric B and the respective functions. 2nd order polynomial curve fits were used for these graphs and the respective functions generated from these curves. The final form of the equations to predict the mould fill rate at different temperatures *(T)* are:

Fabric A $\boxed{\% \mathit{fill} = 100(1 - exp((-0.0040 * T) - (0.00027 * T\wedge 2)) * t}$

......Equation 4.11

Fabric B $\boxed{\% \mathit{fill} = 100(1 - exp((0.0016 - 0.059 * T) - (0.00079 * T\wedge 2)) * t}$

......Equation 4.12

These functions are plotted against the actual fill times for 14°C and 24°C, figures 4.39 and 4.40.

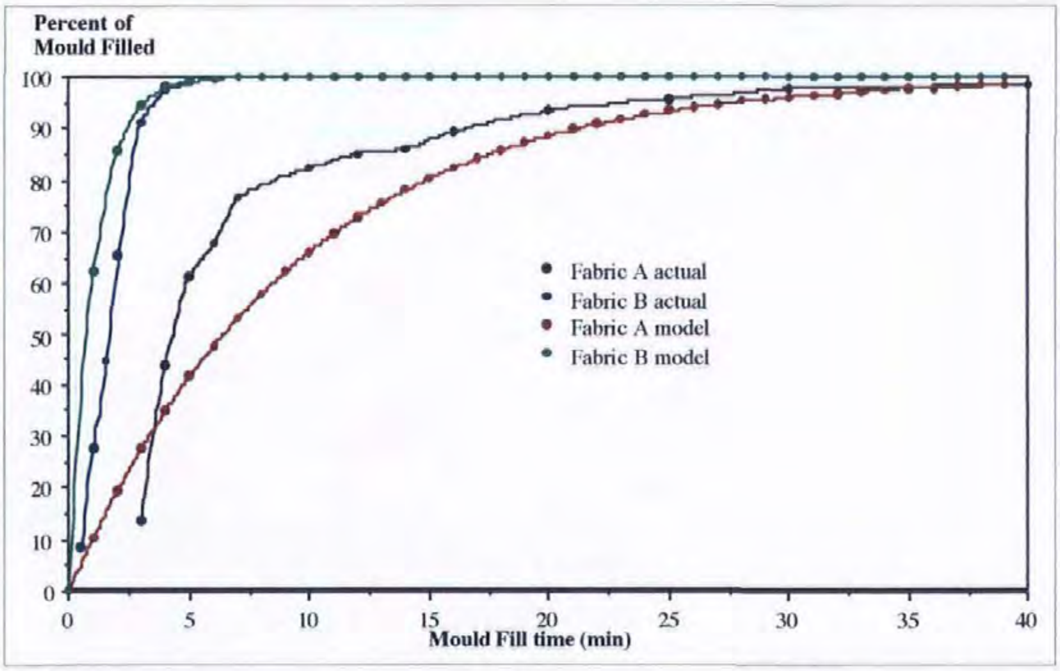


Figure 4.39 Comparison of actual fill times and modelled fill times at 14°C.

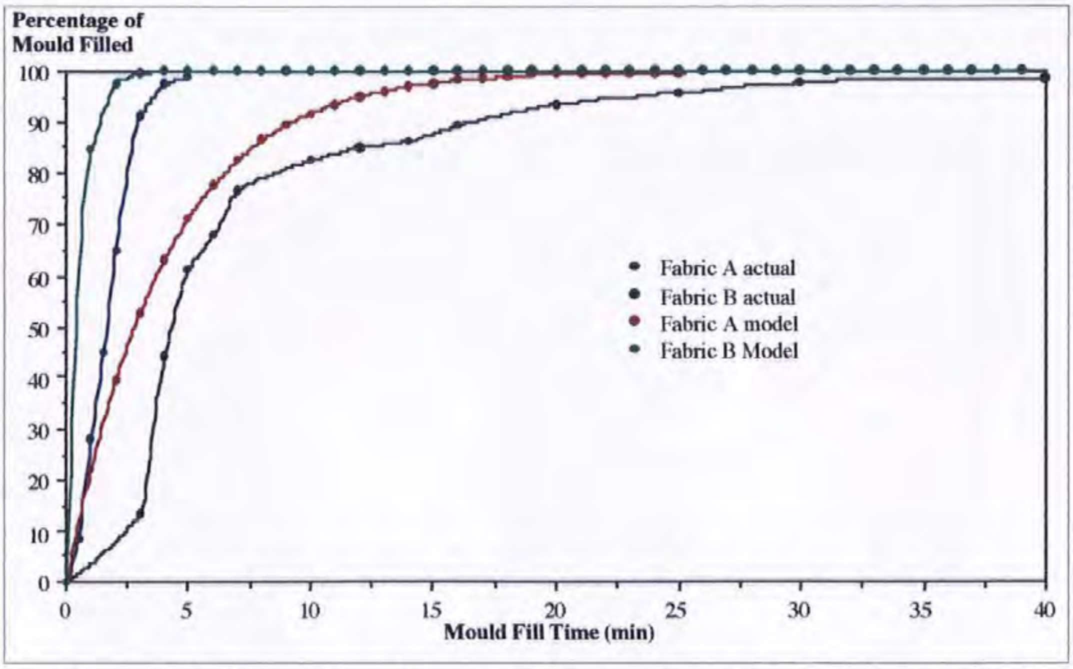


Figure 4.40 Comparison of actual fill times and modelled fill times at 24°C.

Modelling like this has the benefit of being derived directly from real data. With some adaptation this type of model should be useful in a production context. For significant production runs, the manufacturing parameters can be monitored, compared to what should actually be happening and any discrepancy fed back to the operator. Whilst this does not have the generic flexibility of finite element analysis, models such as this might form a crucial part of an RTM process monitoring system. The crucial benefit of this approach is the assessability of simple interpolations based on real data, which is easily derived and applied to the production monitoring of a real component. Statistical process controls such as these will be compared with dielectric cure monitoring during production, thereby giving the operative more information on manufacturing parameters than would otherwise be available.

4.6 Propeller Manufacture.

4.6.1 Initial manufacturing improvements.

As indicated earlier, the first attempts at propeller manufacture by RTM were of limited success. The quality of fibre wet out was poor, dry patches were often present, the injection times were long, (up to an hour) and there was a general inconsistency about the process.

However, in the light of these experiments, certain changes were brought about in order to improve the quality of manufacture.

- Resin and the entire propeller mould were heated to 35° C, thus achieving and maintaining a resin viscosity of around 4 poise.
- Fabric B was used instead of fabric A at a fibre volume fraction of 50%.

The fibre volume fraction of the propeller laminates before and after the changes was kept at 50%. The first major effect of changing these parameters was the difference in injection time. This reduced from between 45 to 60 minutes, to between 6 to 10 minutes. The second difference was in the quality of the laminate. Plates 4.8 and 4.9 show clearly the difference. Under careful visual scrutiny, few voids were noticed. The goal of improved moulding quality has been achieved.

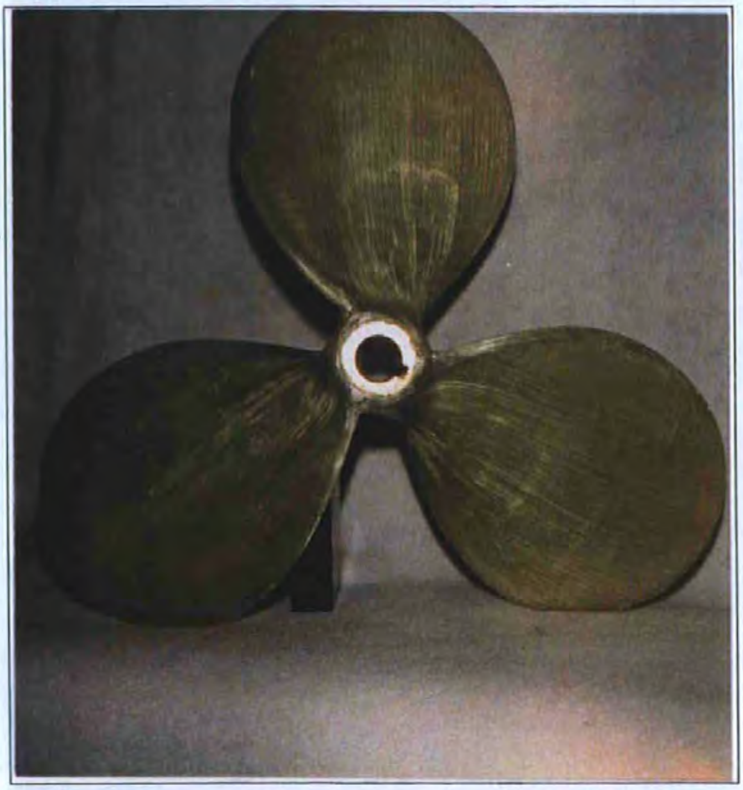


Plate 4.8 Propeller manufacture after improvements.

Plate 4.9 Propeller prior to improvements.

Successful manufacture of larger propellers for the vessel *Aquatay* were made possible by employing fabric architectures that were known to allow consistent and quick resin flow. The propeller for *Aquatay* is 26 inches in diameter, this is shown in plate 4.10.

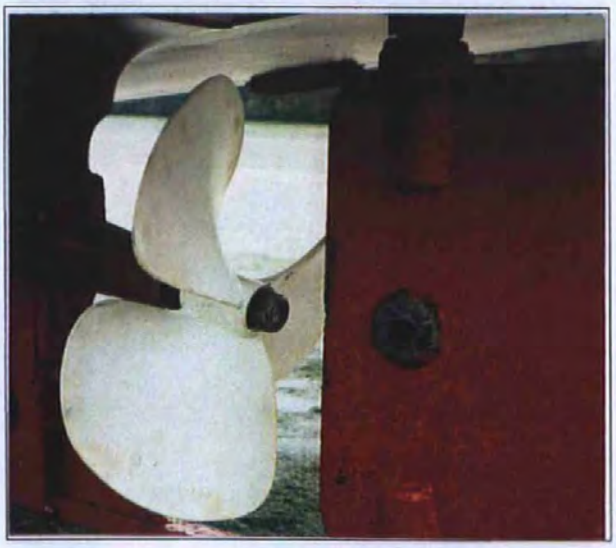


Plate 4.10 Successful manufacture of the propeller for the vessel Aquatay.

4.6.2 Further propeller manufacture.

Before and after the experimentation a total of four different propeller designs have been manufactured together with the associated RTM tooling. Throughout the duration of this research programme, it was intended to maintain a manufacturing capability for the propellers under consideration. This has enabled sufficient propellers to be produced for comprehensive experimental evaluation. It has been possible to extend practical experience by putting into service a range of different composite propellers. This section summarises some of the practical manufacturing issues that have been solved. Trials on three different vessels together with open water tests carried out at the Royal Naval Engineering College, Manadon, and at the University of Newcastle upon Tyne, are reported in chapter 5.

Each of the four composite propellers was made as a geometrically identical retro–fit replacement of the metallic propeller already in service. This enabled straight forward installation on the vessel. Table 4.5 shows the major dimensions and features of each propeller.

Originating Vessel	Diameter [in]	Pitch [in]	No. Blades	DAR	Power [hp]	No. Manufactured
n/a	12	14	3	0.5	10 – 20	10
Pandora	20	12	3	0.5	38	7
40hp Suzuki outboard	12	13	3	0.5	40	2
Aquatay	26	21	3	0.7	220	4

Table 4.5 Details of composite propellers manufactured.

The objectives sought from manufacturing these propellers in a composite material were initially to produce a range of composite propellers that are:

- Strong enough.
- Stiff enough to maintain hydrodynamic performance.
- Damage tolerance to withstand light impacts and dockside handling.
- Resistance to sea water degradation.
- Faithful geometric reproduction of the original metal propellers.
- A retro fit for the vessel for which the original metal design was intended.
- Moulded to produce a net shaped product with a high quality surface finish.

In order to achieve those in the above list and to put into practice the RTM principles established now established, a RTM mould was manufactured for each propeller.

The manufacture of the first composite propeller and associated tooling is outlined by the earlier report "A Viability Study into Fibre Composite Marine Propellers" [Searle 1991]. The production of the three subsequent propeller types built on the experience obtained in the initial viability study. The selection of propellers manufactured was chosen for their suitability for use on the University owned vessels. Three different University owned power boats were selected, the respective propellers then used as patterns for the RTM tooling. It is not the purpose of this chapter to expound on the subject of RTM tooling manufacture, however the following section describes some essential aspects.

4.6.2.1 Soft RTM tooling.

Soft composite tooling was chosen for the manufacture of each tool. This is an inherently quick and cost effective route to producing RTM tooling, compared to metal or electro–form nickel, since lead times are minimised and no specialised equipment is required.

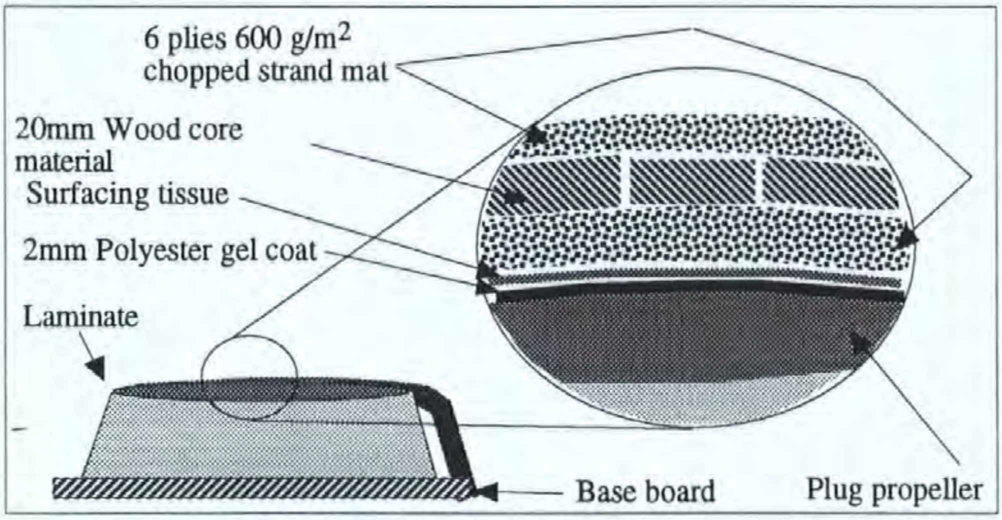


Figure 4.41 RTM soft tooling lay up.

Polyester resin[1] and 600 g/m^2 chopped strand mat (CSM) formed the basis for the mould construction. Each mould was made in two halves using the existing metal propeller as the plug. Figure 4.41 show the generalised laminating schedule. A future improvement on these materials would have been to use a tougher resin system such as an epoxy or vinylester. This produces a laminate where the surface is less prone to cracking. On completion a steel backing structure is built around the tool, see plates 4.11 to 4.14.

4.6.2.2 Porting.

It has been found experimentally that the most effective port position for injecting the resin is in the boss region of the propeller and to vent at the blade tip. At the resin inlet and venting locations brass connectors were used; these were inserted in the appropriate location after the mould had been laminated. 8mm plastic vent pipes were inserted into these brass connectors. The pipes were clamped off when the resin reached them, and replaced after each injection. (Figure 4.42).

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[1] Cristic Resin A from Scott Bader.

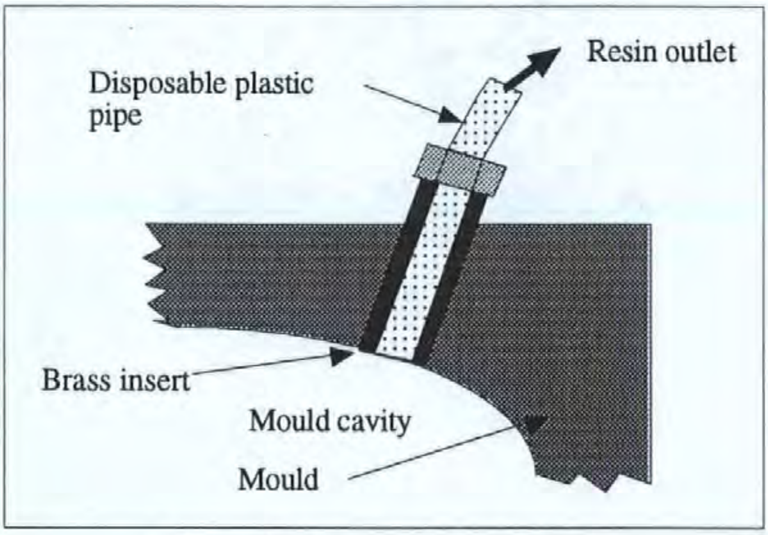

Figure 4.42 Porting arrangements.

4.6.2.3 Sealing and clamping.

In order to produce good quality moulding by RTM, it is essential that the mould halves seal to maintain a vacuum–tight mould cavity. This requires accurate, repeatable locations of the mould halves. In practice this is achieved by using a 5mm x 10mm silicon seal located in an 8mm channel. The mould is held accurately shut against the seal by either a hydraulic press, pneumatic air bag or a series of dowels and bolts at the periphery of the mould. For this research, the moulds for the *Pandora* propeller and the 0.305m propeller used the hydraulic press to close the mould. The moulds for the outboard propeller and the propeller for Aquatay used dowels and bolts which are preferable. Figure 4.43 shows the silicon seal compressed from 10 mm in height to 8mm thus providing an effective vacuum tight seal.

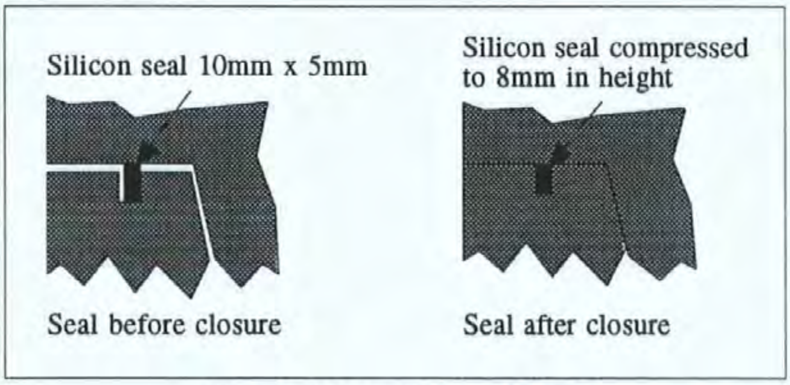

Figure 4.43 RTM mould seal.

4.6.2.4 Developments in tool configuration.

Certain changes to the mould configuration have been introduced since the moulds for the 0.305m propeller and the *Pandora* propeller were built. Figure 4.44 shows how the initial tooling consisted of two virtually identical mould halves. It has been shown in practice that this arrangement leads to difficulty in loading the fibres which tend to slip out of the mould cavity during mould closure. The fibres are in close proximity to the seal and can protrude across the sealing surfaces. Also the silicone seal has to contour around complex curve and its effectiveness is compromised.

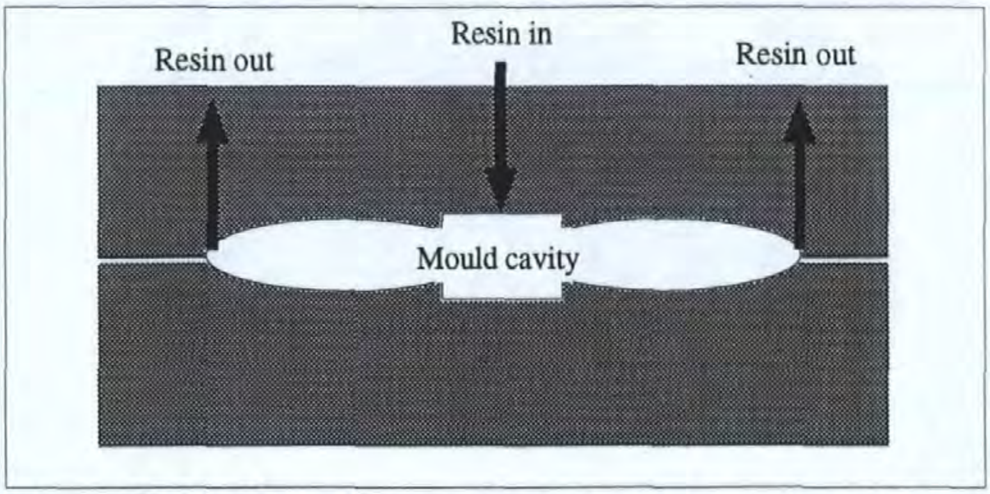

Figure 4.44 Mould arrangement with two virtually identical mould halves.

The alternative configuration solves these issues by using a deeper cavity so that the mould has lead in, shown in figure 4.45. This enables the fibres to be loaded with greater accuracy at the blade tips, without fear of moving on mould closure and a high fibre volume fraction can be maintained in these critical areas. Moulds for outboard propeller and the *Aquatay* propeller, use this type of configuration.

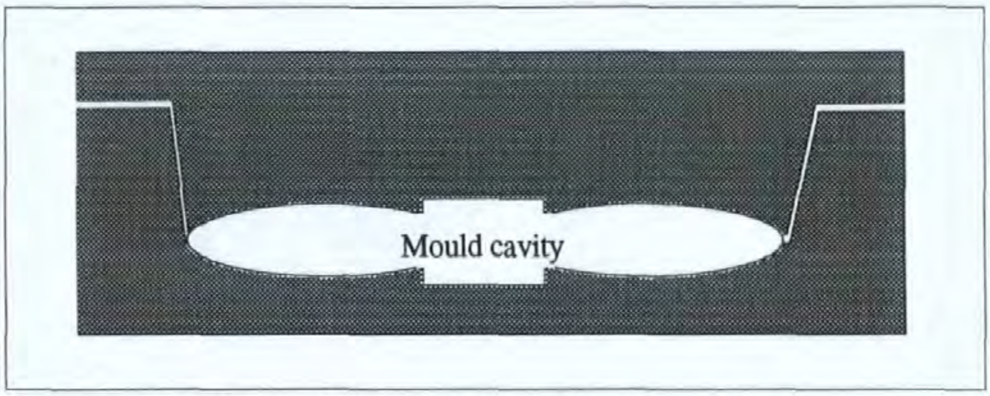

Figure 4.45 Improved mould configuration.

A general view is given of each of the four propeller moulds in plates 4.11 to 4.14.

Plate 4.11 The initial mould for the 12 inch Teignbridge propeller.

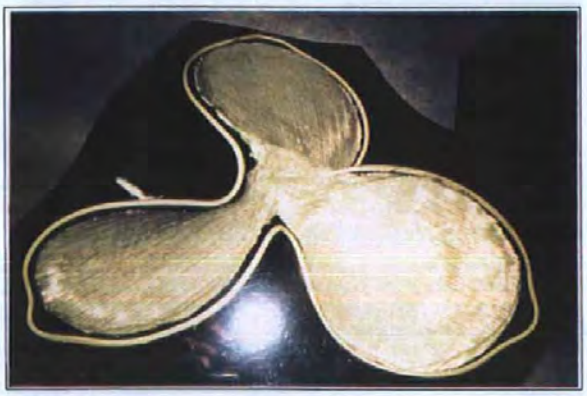

Plate 4.12 The mould for the propeller for the vessel "Pandora".

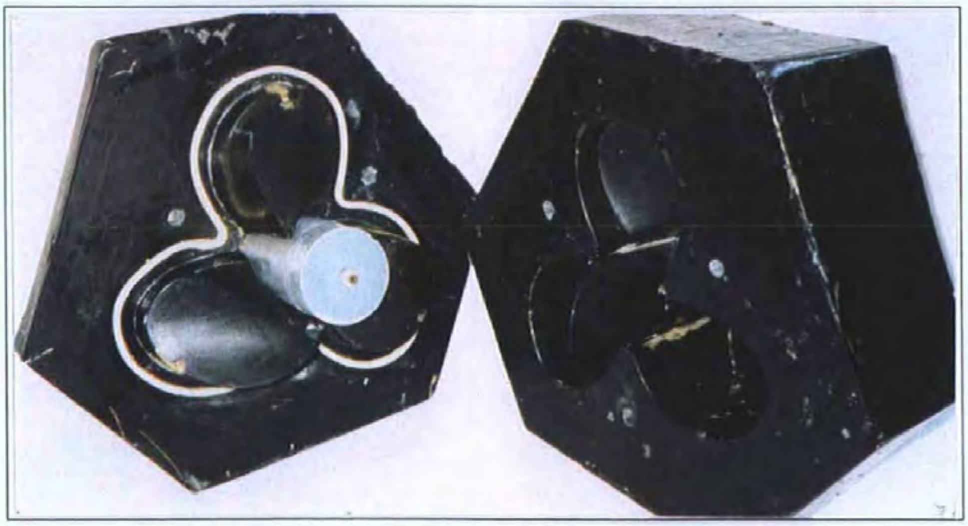

Plate 4.13 The mould for the outboard motor propeller.

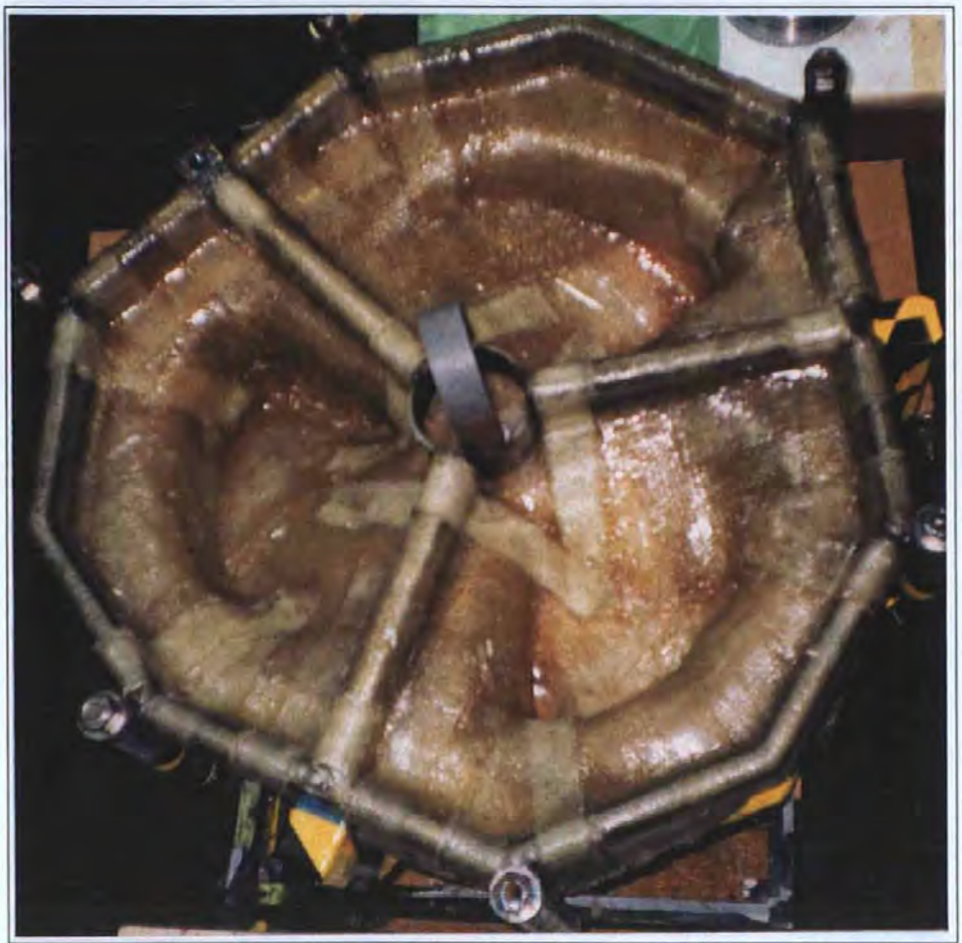

Plate 4.14 The mould for the propeller for the vessel "Aquatay" showing the deep cavity.

4.6.3 Injection port and shaft attachment interface.

So that each propeller could be fitted to the existing shaft, the traditional taper keyway shaft attachment was maintained. A manganese bronze (HTB1) boss insert was moulded with each propeller for *Pandora* and *Aquatay*. This proved an effective shaft attachment method and presented no drive problems. The insert provided a convenient resin injection point. Figure 4.16 shows the generalised arrangement, plate 4.15 shows the boss prior to moulding.

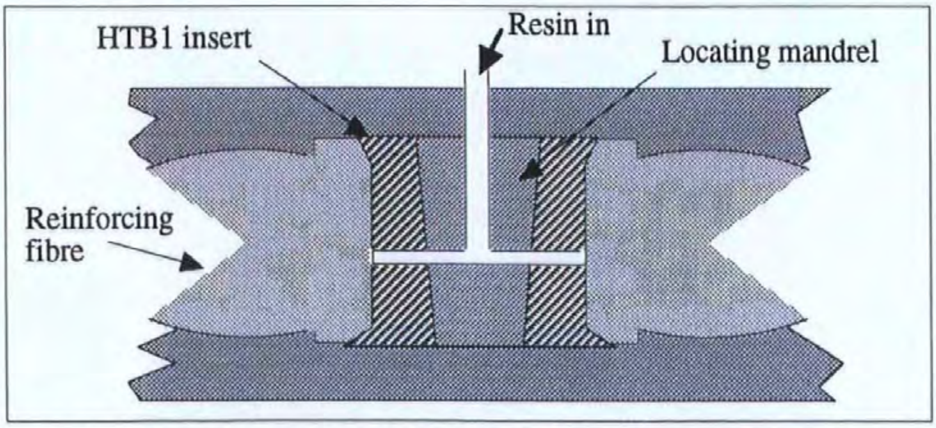

Figure 4.46 The arrangement of the boss insert showing resin injection port.

Plate 4.15 HTB1 boss insert in place on a propeller for "Pandora" and the boss prior to moulding.

4.6.3.1 Resin injection equipment.

Resin injection was carried out with the use of a simple low cost pressure pot, (figure 4.47).

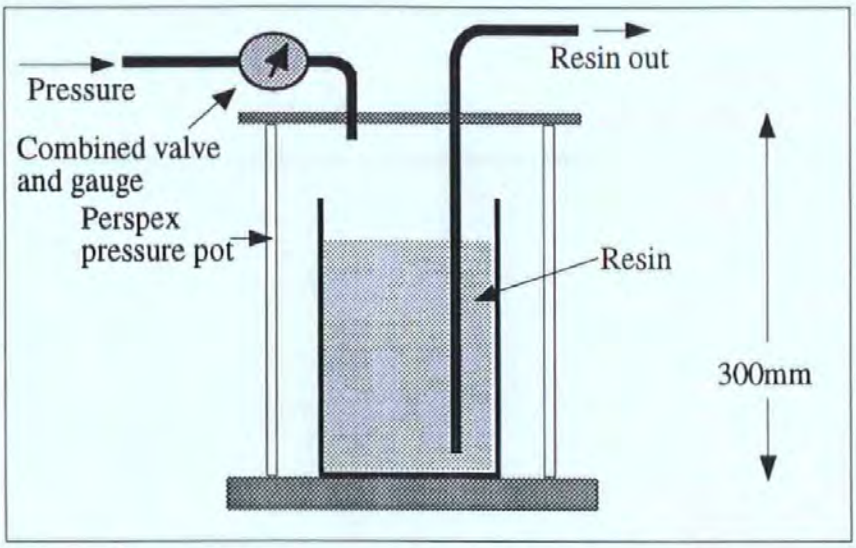

Figure 4.47 Pressure pot used for resin injection.

4.6.3.2 Surface Finish

A variety of surface finishes have been used, these include the following:

- Acrylic paint.
- 2 part polyurethane varnish.
- Epoxy gel coat.
- Silicon carbide gel coat.

The acrylic paint finishes were used on the 0.305m propeller shown in plate 4.16 in order to achieve a smooth finish for the open water testing. As these were the first propellers to be made by RTM as part of this research programme, the moulded surfaces had some minor defects. Later propellers were moulded with high quality finishes and had no retrospective surface finishing. The benefit of closed tooling is that only minimal finishing is required. One propeller for *Pandora* was treated with a 2 part polyurethane varnish, only because the initial moulding was sub standard and required some extra finishing. The epoxy gel coat provided pleasing aesthetics and a relatively void free surface finish.

4.6.3.3 Fibre Loading.

Successful production RTM depends on the loading of the fibre reinforcement accurately into the mould cavity. The first difficulty was the large volume fraction of fibre required to give the mechanical strength. The second was geometric, I.E. the precise alignment of the fibres and position and quantity of ply drop–offs. The third was the practical difficulty of fraying of the fibres from mats. In order to load the high proportion of fibre into mould cavity it was decided to manufacture a dry pre–form. The most effective method was to stitch the plies of fibre together with a tow of glass fibres. This was quick and held each ply in the correct position. This enabled a high volume fraction of fibre to be maintained right at the blade tips also. The bronze boss was also stitched in place and the whole preformed item simply placed with accuracy into the mould cavity. Figure 4.48 shows the arrangement of the stitched pre–form.

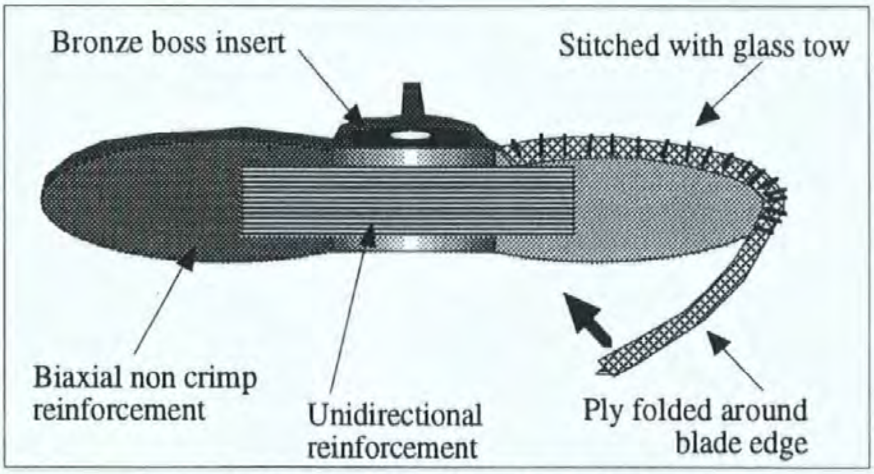

Figure 4.48 Preforming the fibre reinforcement.

4.7 Examples of each design.

The materials used for each propeller were E–glass fibre reinforcement and room temperature curing epoxy[2] as the matrix material. E–glass was chosen for its low cost in relation to other fibre types and for its low modulus. The low modulus fibre used in the composite for these marine propellers is to allow the investigation of the engineered hydro–elastic tailoring, since a lower modulus material allows greater deflection for the same load. Epoxy resin was used for its long pot life, ease of controlling its viscosity and superior structural properties over polyester and vinylester resin systems outlined.

After bringing together the practical elements discussed in this chapter, successful manufacture was possible for all four propeller designs. Plates 4.16–4.19 show examples of each design made in composite.

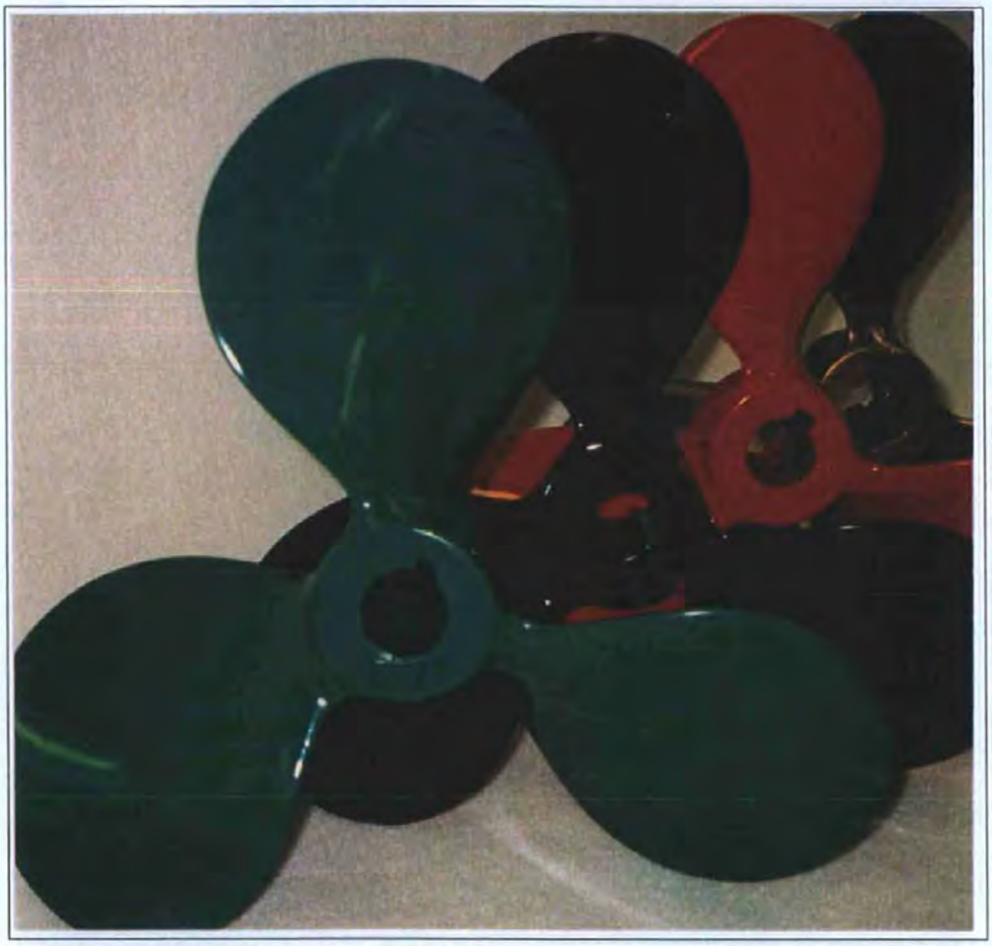

Plate 4.16 12in propellers painted in preparation for open water testing.

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[2] Either Ciba Giegy 5052, or SP Ampreg 20

Plate 4.17 The propeller installed on the vessel "Pandora".

Plate 4.18 Outboard motor propeller.

Plate 4.19 Propeller installed on the vessel "Aquatay".

4.8 Summary.

4.8.1 RTM.

The benefits of RTM have been shown previously, together with some well established and successful applications. The process is cost effective and good for producing high quality, high performance parts. It does seem however that the process is actually underutilised. Certain sectors of the composites manufacturing industry are still investing huge sums of money in metallic compression moulding tools, to the point where some companies can only trade their products at a loss, such are the costs of their tooling investments. RTM is a highly effective process for producing quality composite parts at moderate prices, it is, however sensitive to process parameters.

4.8.2 Experimentation.

This research was embarked upon with little knowledge of the major parameters that influence the success of RTM processing. It soon became apparent that if the manufacture of propellers was to be successful by this method, information relating to the processing must be uncovered. In the absence of experience and with a dearth of pragmatic literature, the best way forward was experimentation. This enabled a number of things to be highlighted. In particular;

Resin Viscosity

- Reducing the resin viscosity can speed up the injection process dramatically.
- An increase from 17 to 40° C gave a 75% reduction in injection time, for the resin used in the experiment.

Fabric Architecture.

- Fabric architecture is a critical parameter that should be optimised, if not, slow, inconsistent and erratic resin flow will result.
- For the experimental mould, a 8-9 fold reduction in injection time was achieved between 2 different cloth types, all other parameters equal.

Fibre Volume Fraction.

- It was shown that for one cloth type, resin flow was virtually stopped at 55% volume fraction, whereas the other fabric exhibited significant resin flow at 67% volume fraction.

In order to improve on the information that has been presented from this experimentation, a number of points should be considered to enhance the data.

- Greater number of experiments
- Greater variety of temperatures
- Other fabrics should be tested, especially enhanced flow cloths.
- A variety of different injection pressures should be used.
- Image analysis should be used to collect and analyse the flow front data.
- Microscopy of samples manufactured during experimentation.

Enhancement of this information would be to the advantage of this project, however great improvements have already been made in the manufacturing of propellers to this point.

4.8.3 Propeller manufacture.

The tool manufacture and production of a range of propellers was carried out successfully without great expense. The manufacturing technology demonstrated is accessible and mature enough to implement into a production environment.

Chapter Five

Testing Carried out on a Range of Composite Propellers.

5.1 Introduction.

The following preliminary tests were carried out to study the performance of composite propellers.

- Speed and bollard pull measurements on the vessel *Pandora*.
- Longevity tests on the vessel *Pandora*.
- Sea trials with the outboard motor propeller.
- Open water towing tank measurements.
- Cavitation tunnel measurements.
- Sea trials on the vessel *Aquatay*.

Earlier parts of this thesis have looked at the economic and manufacturing issues pertaining to the composite propeller, the prime concern of this chapter is to begin the investigation as to the fitness for purpose of composite materials for marine propellers.

5.2 Boat trials.

5.2.1 Performance measurements on the vessel *Pandora*.

The University's vessel *Pandora* is a 7m (23') GRP work boat powered by a 23kw (31hp) continuous or 28kw (38hp) intermittent diesel engine. The maximum engine speed is 1700 RPM with a gearbox reduction of 1.85 to 1. The main purpose of the boat is safety cover for student recreation. It can carry up to 12 people plus diving equipment. Plate 5.1 shows the vessel.

Plate 5.1 "Pandora".

The purposes of testing the propellers on *Pandora* were:

- To establish the effectiveness of the boss attachment to the conventional shaft.
- To evaluate the structural integrity of the propeller under working conditions.
- To measure and compare the thrust as measured in the bollard pull condition for the composite and bronze propellers.
- To measure and compare the speed vs engine RPM of the boat using the composite and bronze propellers.
- To commence life trials for the composite propeller under working conditions.

A composite propeller was installed early in 1994; since that time the propeller has remained immersed in the water and has been used regularly. Three weeks after installation, experiments were performed to measure the bollard pull and the speed/engine RPM characteristics of both the composite and bronze propeller. The results are shown in figures 5.1 and 5.2.

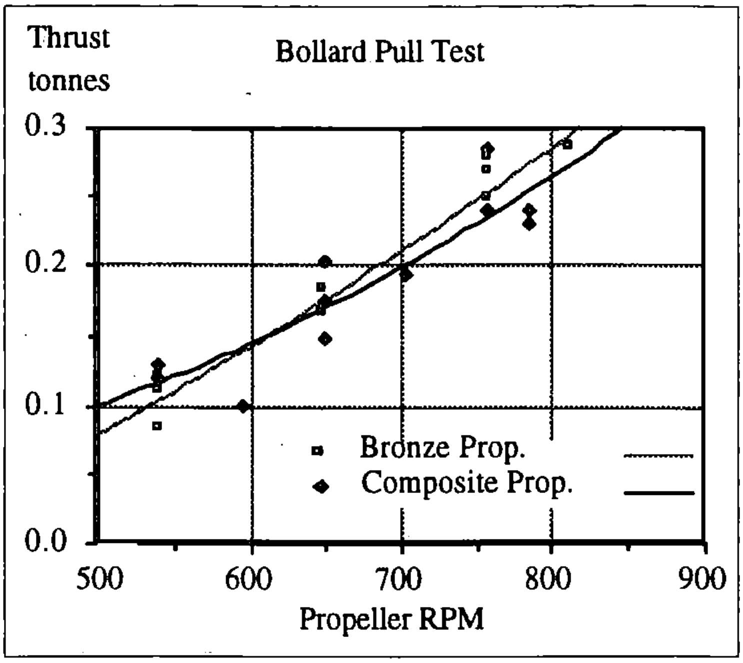

Figure 5.1 Bollard pull test results.

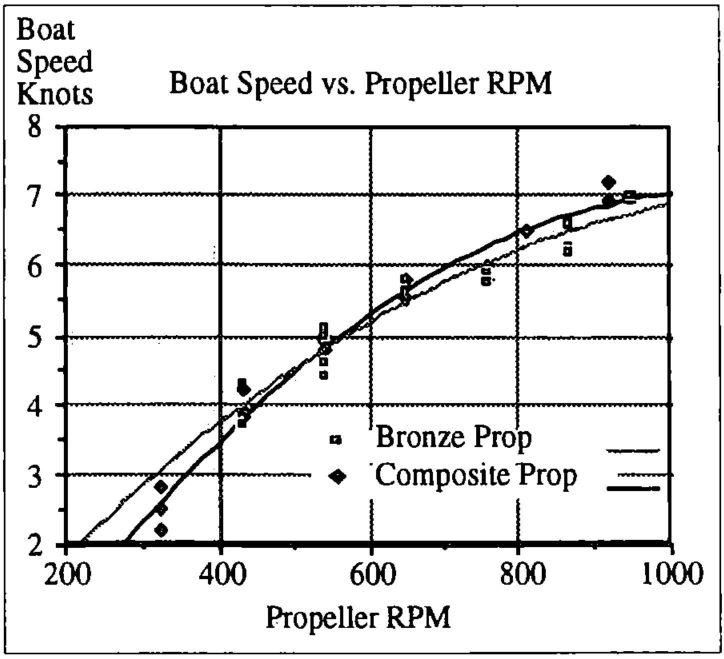

Figure 5.2 Speed test results.

After these tests were performed and three weeks of general boat duties the propeller was removed for inspection:

- The boss joint showed no signs of degradation.
- During this period of immersion no marine growth occurred.
- One of the leading blade edges had been slightly scuffed, this was probably due to an impact with an underwater object.

From these test results the main conclusion was that the performance of both propellers were comparable. This is to be expected as both propellers had identical geometries, although their respective elastic properties were different.

5.2.2 Longevity trials on the vessel *Pandora*.

After these trials, the propeller was left on the vessel so that an assessment of the long term behaviour of the propeller during everyday use could be made. Inspections were made of the propeller by slipping the vessel at regular intervals. The history of this appraisal is recorded in table 5.1. "Hours use" indicate the hours of engine running time as recorded on the engine log. All the vessel operations were carried out in Plymouth Sound and the surrounding waterways.

Date	Hours use	Comments
25/4/94		Prop 1 installed
25/5/94	n/a	Prop removed, all blades lost after hitting a mystery under water object. No damage to shaft gearbox or engine
9/6/94	0 hours	New propeller installed
28/6/94	30 hours	
13/7/94	62 hours	Slight marine growth, composite in the boss area worn slightly where rope had been entangled
25/8/94	117 hours	3mm radius size chip on 2 blades caused by 1m of thick electrical wire wrapped around prop
7/9/94	119 hours	•
3/11/94	159 hours	•
9/11/94	165 hours	•
1/12/94	n/a	Prop removed after shedding 2 blades on impact with a significant piece of wood which could not be recovered, no damage to gearbox or transmission system.

Table 5.1 Propeller use history.

Plate 5.2 The propeller before failure.

During the period of service there were two propeller failures. These were catastrophic and occurred without prior warning or change in performance. No visible material degradation had taken place and the failures were symptomatic of hitting a submerged object. No damage was sustained by the shaft, gearbox or engine which is seldom the case with metal propeller systems. Plates 5.2 and 5.3 show the first propeller before and after the failures.

Plate 5.3 The propeller having lost all three blades.

5.2.3 Sea trials of the outboard motor propeller.

A full description of this project is given by Bucknol [1993]. The propeller was tested on a 13 foot Dory class power boat with a 40hp engine. Only subjective assessment was possible from those responsible for the full time usage of the boat. The subjective performance of the composite propeller was comparable with the aluminium propeller.

This view is significant, as the same cannot be said of commercially available short fibre, thermo plastic propellers recently introduced to the market. Experience on University boats has shown that under similar loading conditions these propellers can not absorb the same power as the aluminium and still drive the boat as effectively. This view is explained by the low modulus of the short fibre themoplastic. The blades bend under load more than either the aluminium or the glass epoxy composite. From the experience gained from testing the composite blades thoroughly, they would seem a viable alternative to the aluminium blades. Their introduction would be particularly advantageous when considered as a low cost replacement. The composite propeller tested in this case used the boss from an Aluminium propeller with composite blades fitted onto this component by interference fit and a resin keyway. As the blades can be made quickly from low cost materials, they should make effective replacements should the aluminium blades get damaged, (figure 5.3).

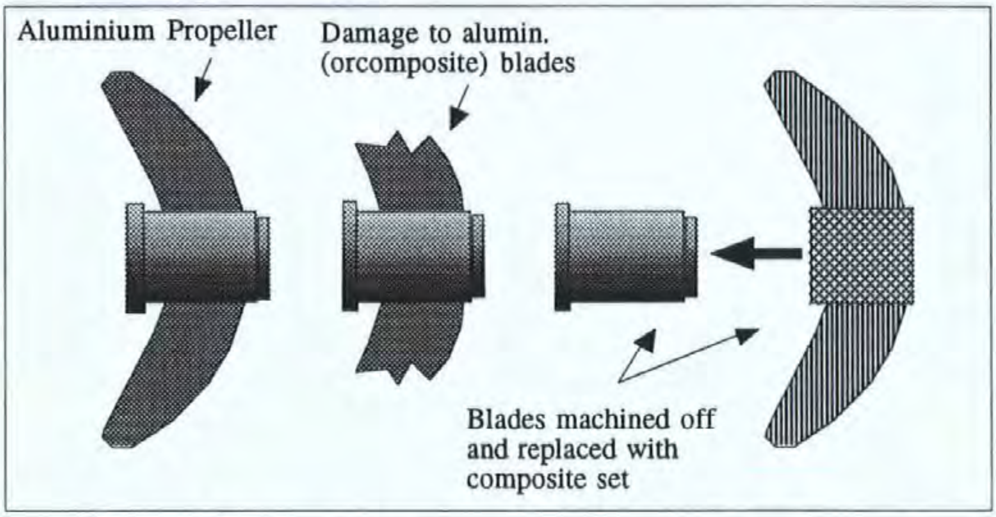

Figure 5.3 Composite outboard motor propeller as an effective replacement for damaged blades

5.3 Open water testing.

5.3.1 Towing tank measurements.

Although work to design a working hydroelastic propeller is still in early stages, a number of designs have been successfully tank tested to assess the potential of the concept.

Five of the 12in propellers, each having different elastic properties, were used in an open water towing tank test. Each propeller was tested at a range of different advance coefficients (J) to determine the thrust coefficients (K_T) and torque coefficients (K_Q) and hence the open water efficiency (η_o).

Because the composite propellers were taken from a tool that had been made using the bronze propeller as a pattern, the geometries of the bronze and composite were identical. The manufacturing inaccuracies in the bronze propeller between different blades were greater than any differences between individual propellers. Five propellers were tested, each with different material properties, summarised in table 5.2, (these properties were calculated with conventional laminate analysis software[1]. Figure 5.4 defines the angles of reference for the different moduli.

Prop.	Resin	Fibre	Fibre Volume	Modulus 0 deg.	Modulus 90 deg.	Modulus +45 deg.	Modulus -45 deg.
(1) Bronze	•	•	•	120 GPa	120 GPa	120 GPa	120 GPa
(2) Green	Epoxy	E Glass	41%	29 GPa	29 GPa	29 GPa	29 GPa
(3) Red	Epoxy	E Glass	35%	5.5 GPa	5.5 GPa	38 GPa	2.2 GPa
(4) Blue	Polyester	E Glass	20%	8 GPa	8 GPa	8 GPa	8 GPa
(5) Foam	Epoxy	E Glass	40%	•	•	•	•

Table 5.2 Elastic properties of propellers used in the experiment.

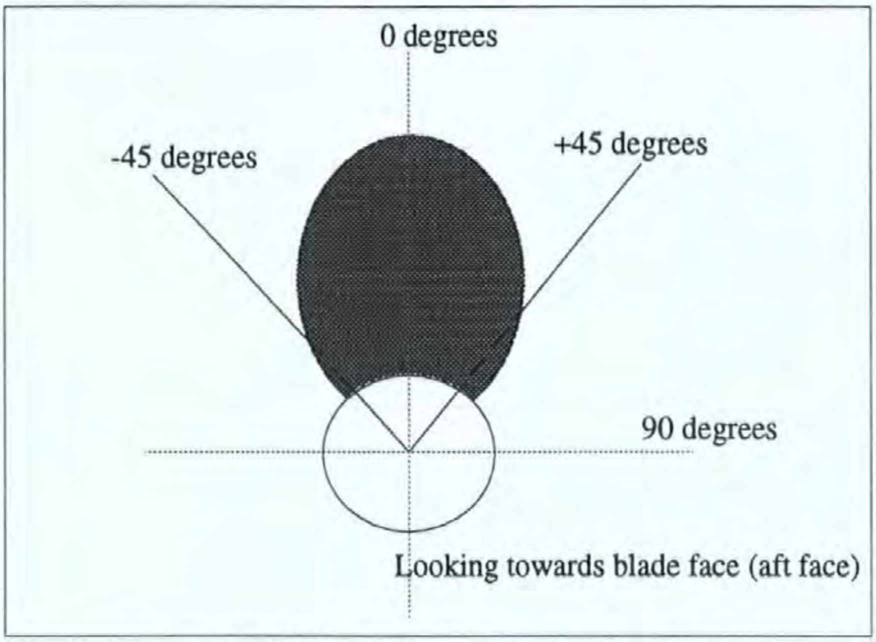

Figure 5.4 Definition of directional moduli.

- The bronze propeller is included as a control by which to compare the composite propellers.
- Propellers 2 & 4 are not tailored to any particular bending characteristic, however they were not as stiff as the bronze propeller.
- Propeller 5 was made with a foam core so that it was potentially more elastic than propeller 3, although both 3 & 5 were designed with fibre alignment so that as load is developed, the blade twists as it is coupled to the bending and causes the pitch to change.

The aim of the open water test was to conduct a tentative investigation into the effect of different blade elasticities. The initial measure of this was the shape of the propeller efficiency envelope. Plate 5.4 shows one of the propellers in the towing tank.

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[1] "Genlam" from Think Composites.

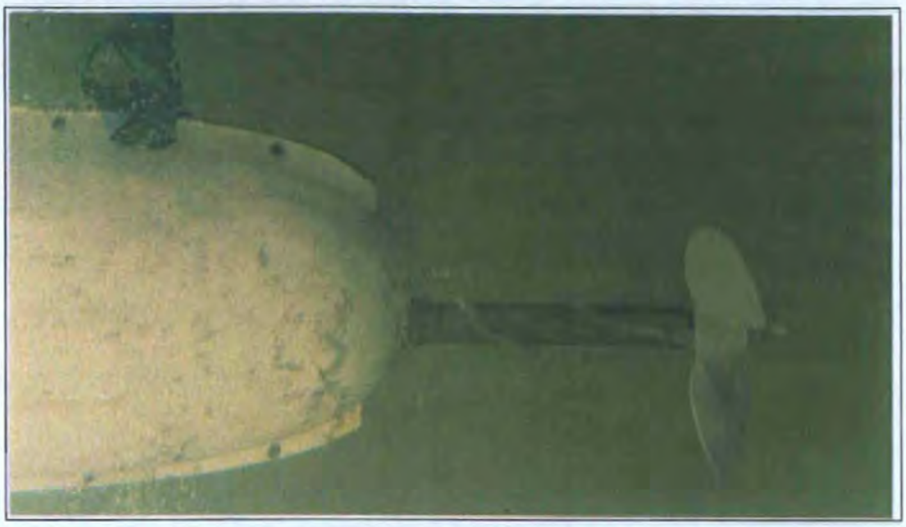


Plate 5.4 A composite propeller in the towing tank.

Figures 5.5–5.4 show the results of the open water test, each compared to the bronze control, plotted separately for clarity. The open water efficiencies have been calculated from the thrust and torque coefficients in the usual manner. (Equations 5.1–5.3).

J = Advance coefficient.
n = Revolutions per second.
D = Propeller diameter.
K_T = Thrust coefficient.
K_Q = Torque coefficient.
η_o = Open water efficiency.
Q = Torque.
T = Thrust.
V_A = Advance velocity (water velocity at the propeller).
ρ = Density of water.

$$\boxed{K_Q = \frac{Q}{\rho n^2 D^5}}$$

..............*Equation 5.1*

$$\boxed{K_T = \frac{T}{\rho n^2 D^4}}$$

...................*Equation 5.2*

$$\eta_o = \frac{K_T J}{K_Q 2\pi}$$

..........Equation 5.3

$$J = \frac{V_A}{n D}$$

................Equation 5.4

With the exception of the foam sandwich propeller, the composite propellers are all more efficient than the bronze at lower J values and less efficient at the optimum J value. The reverse is true for the foam sandwich propeller which has a smaller width to the efficiency curve.

These results should be taken within the context of their preliminary nature and the scatter on the graphs. However, whilst not conclusive in absolute terms, the indications are, firstly that the composite propellers are as efficient as their manganese bronze counterparts. Secondly, it may be possible to change the shape of the efficiency envelope by altering the elasticity of the propeller material.

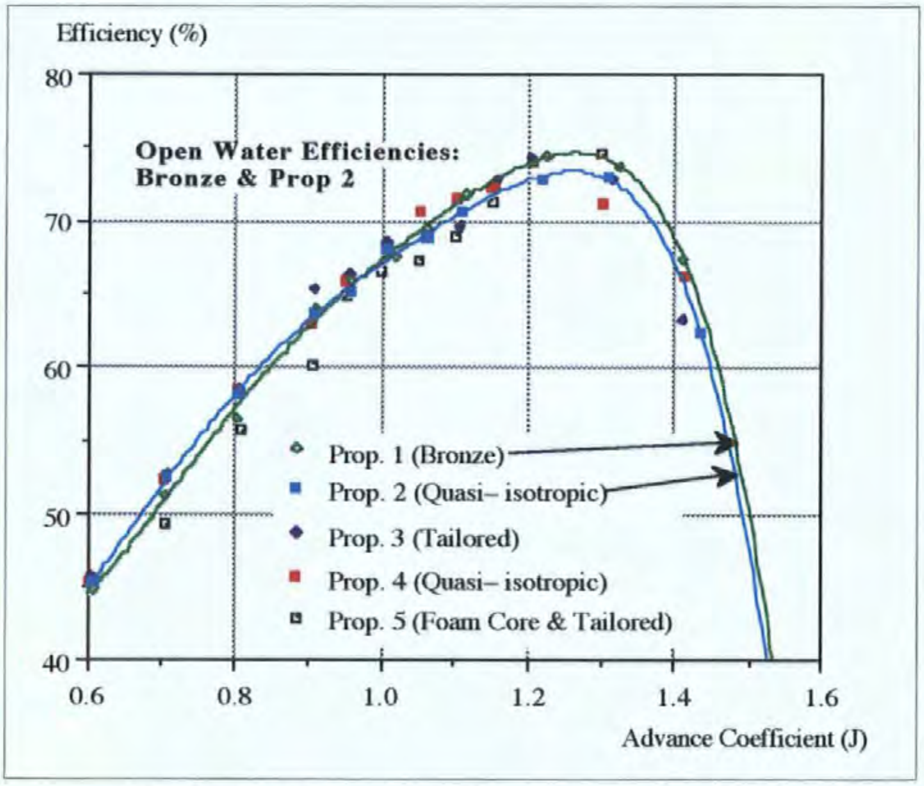


Figure 5.5 Open water efficiency bronze and propeller 2.

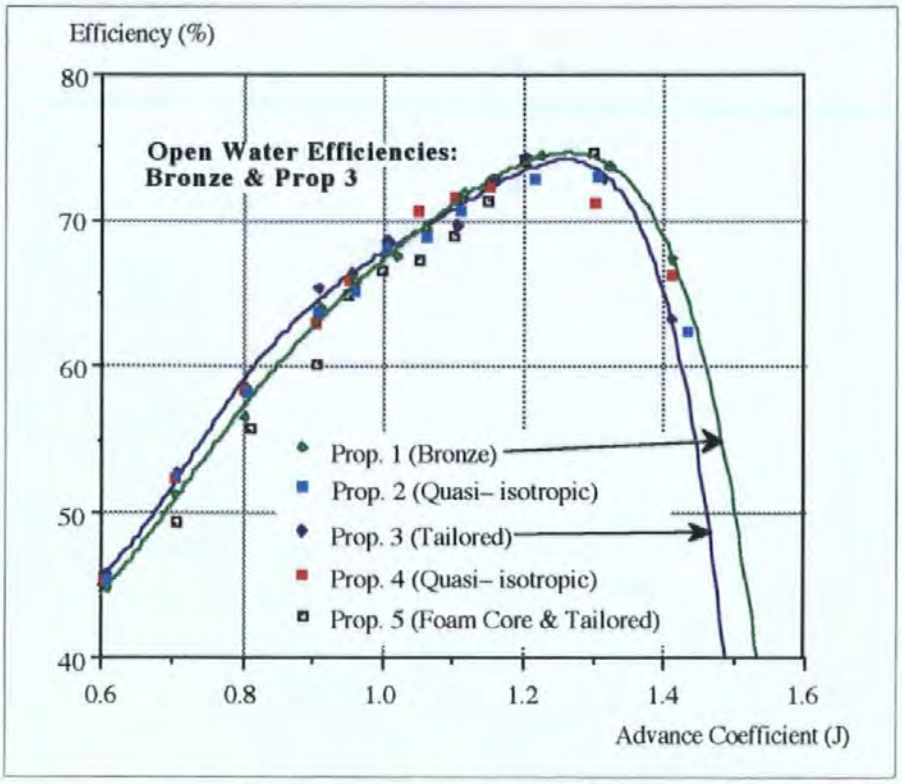


Figure 5.6 Open water efficiency bronze and propeller 3.

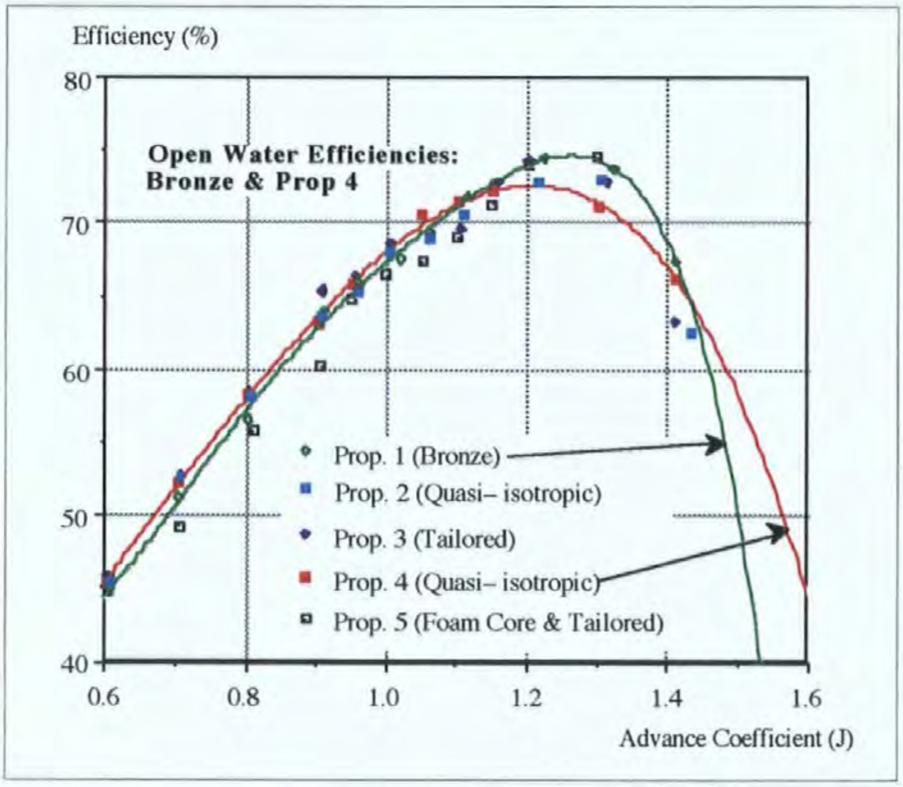


Figure 5.7 Open water efficiency bronze and propeller 4.

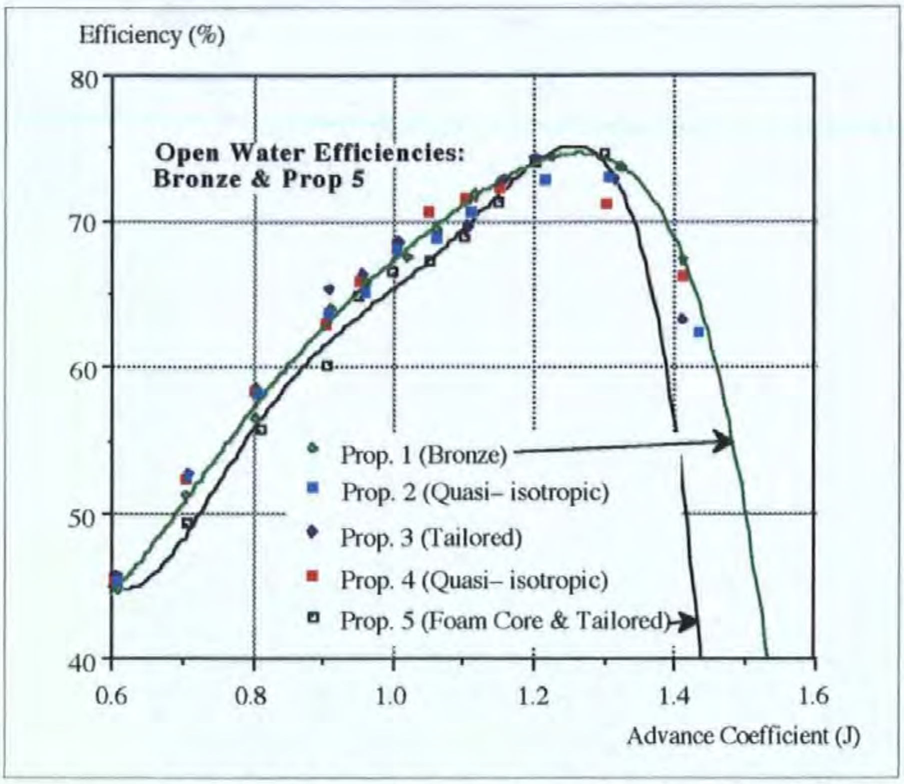


Figure 5.8 Open water efficiency bronze and propeller 5.

5 .3.2 Cavitation tunnel testing.

The open water tank testing experiments yielded some useful results in terms of producing a series of K_T K_Q charts. A similar set of experiments were performed in the cavitation tunnel at Newcastle University. A full report on the experimentation is given by MacLeod [1995]. The following section summarises the key points of the experiment in which, a number of crucial benefits were realised over the work in the towing tank. Table 5.3 compares the major experimental equipment parameters for the towing tank and the cavitation tunnel.

- The propeller could be observed easily during the experiment
- Experimental parameters could be controlled more precisely
- Thrust and torque dynamometers had greater ranges
- Propeller driving motor had more power

	Towing Tank	**Cavitation Tunnel**
Torque Dynamometer	15Nm	150Nm
Thrust Dynamometer	400N	3000N
Max. Velocity of Advance (Va)	3m/s	> 4m/s
Max. RPM	700	3000
Motor Power	1.5 kw	≈ 50 kw

Table 5.3 Experimental parameters.

5.3.2.1 Experimental Observation.

This was greatly enhanced as the cavitation tunnel has viewing windows immediately adjacent to the turning propeller. The towing tank clearly does not permit the propeller to be viewed in the same way. Close inspection of the propeller during the experiment allows the onset of cavitation and the deformation of the blades under load to be observed.

5.3.2.2 Experimental Parameters.

It is important that good control of the experimental parameters is possible. Many of the experiments that are performed in cavitation tunnels involve scaled down model propellers. In order to model cavitation successfully, the model should be run at the same cavitation number as the full size propeller. The best method of ensuring this happens, is to vary the water pressure in the tunnel. This can be done in the Newcastle cavitation tunnel.

5.3.2.3 Dynamometer Range.

It can be seen from table 5.3, that the dynamometers for thrust and torque can measure significantly greater loads than those in the towing tank. Although the precise figure is not available, it can be inferred from this that the motor turning the propeller in the tunnel has a significantly higher power than the one used in the towing tank. This has important implications for the cavitation study. It has already been stated that there was no evidence for any cavitation taking place in the towing tank experiment. Cavitation occurs as the cavitation number (σ) becomes smaller, as given by equation 5.5.

$$\boxed{\sigma = \frac{p - p_v}{1/2\ \rho\ V^2_A}}$$

..........................*Equation 5.5*

Where:

σ = Cavitation number
p = Local absolute pressure
p_V = Vapour pressure of fluid
ρ = Fluid density
V_A = Velocity of advance

It can be seen from equation 5.5 that in order for the cavitation number to be small, the velocity of advance must be large. Because the propeller must operate at the correct advance coefficient (J), to compensate for the increase in the velocity of advance, the RPM must increase. This requires more torque and therefore more power from the driving motor.

The cavitation tunnel enabled the propellers under test to operate in cavitating conditions. A second important consideration, resulting from more power being absorbed by the test propeller, is that each blade is subjected to a greater bending moment. Thus the blades will deform to a larger extent under the bigger load and any change in performance shall be more measurable.

5.3.2.4 Experimental Aims.

These were to produce a set of K_T K_Q curves for one composite and one bronze propeller and observe both propellers in the cavitation condition. From these observations it would be possible to determine if one propeller had a different efficiency envelope from the other, and how a propeller with significantly different elastic properties affects the onset of cavitation.

5.3.2.5 Methodology.

Two propellers were selected for the experimentation from the five possibilities used in the towing tank. The bronze propeller and one tailored (red) propeller were used. The red tailored propeller has anisotropic elastic properties that allow the pitch to back off (decrease) as a bending load is developed upon it.

Having installed each propeller in turn into the cavitation tunnel, the thrust and torque coefficients were measured under the following conditions:

- The speed of the water within the tunnel was maintained as high as possible in order to keep the Reynold's number high and avoid detrimental effects on accuracy caused by skin friction.
- The propeller was run at the correct advance coefficient which is most easily obtained by setting the water speed, then adjusting the RPM to suit.
- The pressure in the tunnel was lowered to produce the correct cavitation number at the propeller axis.
- Each experiment was performed at an advance velocity of 3 to 4 m/s.

The observations of cavitation onset are significant as both propellers performed differently. Table 5.4 summarises the cavitation performance, figures 5.9 and 5.10 give the efficiency and the K_T K_Q curves respectively.

	Bronze Prop.	**Composite Prop.**
Onset of Cavitation (RPM)	830–980 RPM	875–1050 RPM
Advance Velocity	4 m/s	4 m/s
Comment	Large amount of unsteady cavitation, significant formation of cloud cavitation	Higher proportion of steady cavitation, tip vortex cleaner

Table 5.4 Cavitation performance.

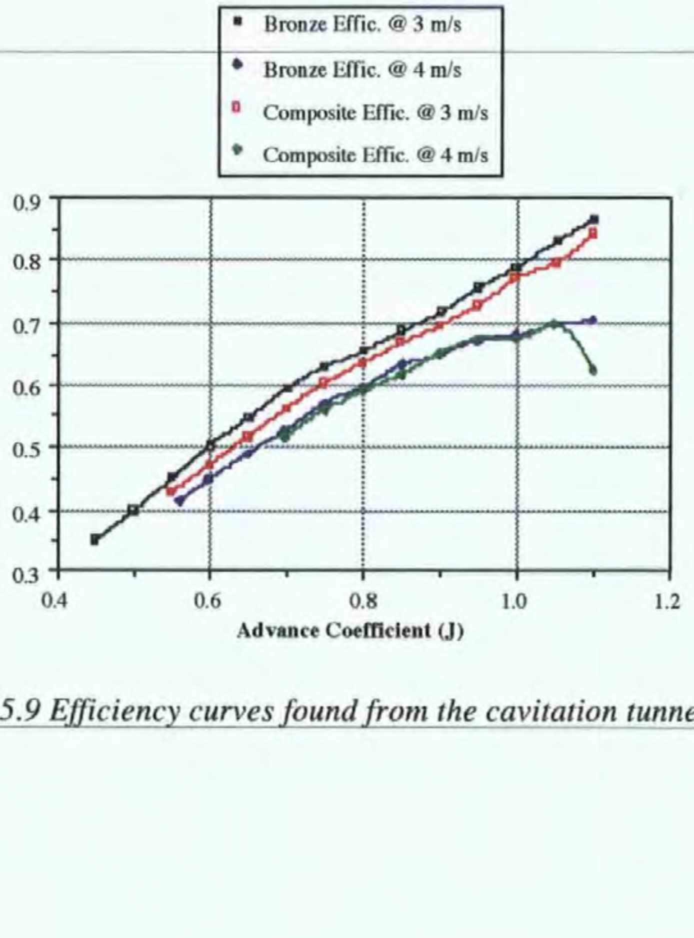


Figure 5.9 Efficiency curves found from the cavitation tunnel measurements.

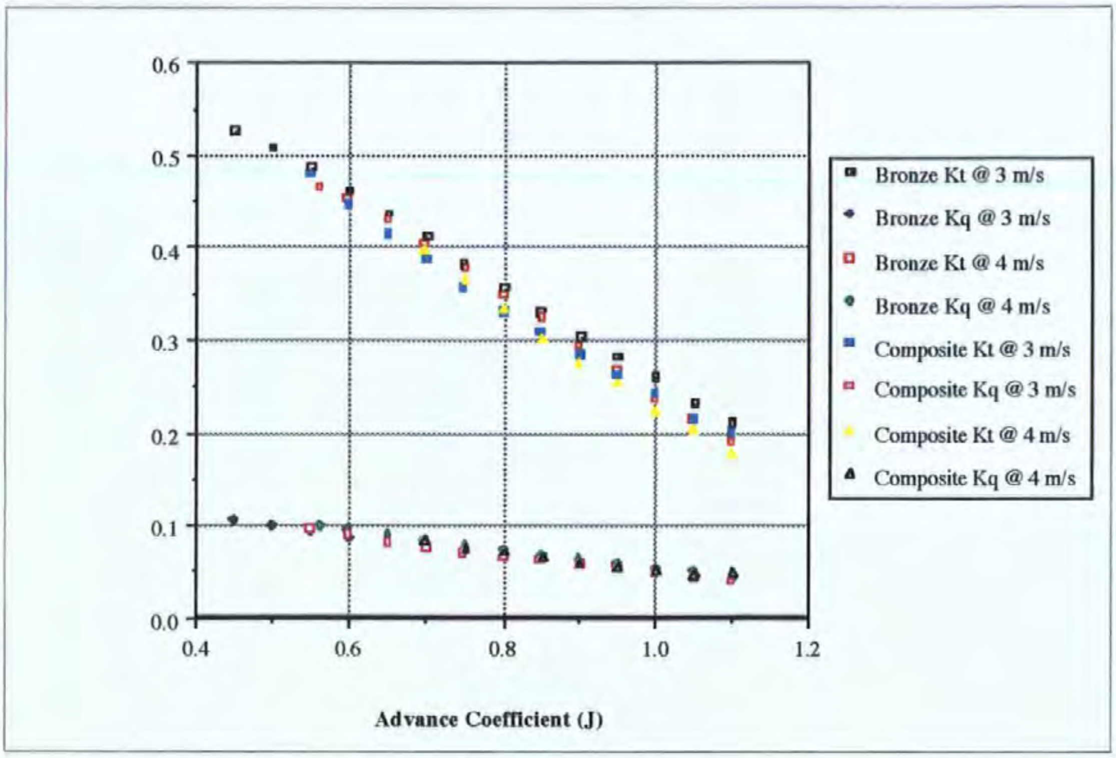


Figure 5.10 K_T K_Q curves *found from the cavitation tunnel measurements.*

5.3.2.6 Conclusions from the cavitation tunnel work.

The following point were raised by the experimentation in the cavitation tunnel:

1. The different elastic moduli of the two propellers certainly affected the onset of cavitation.
2. The lower stiffness of the composite propeller delayed cavitation onset.
3. The efficiency curves do show a shift that given the similarity in propeller geometry must be caused by the flexibility of the propeller.
4. The efficiencies are all very high at 3 m/s water speed (around 85%, theoretical maximum is 76%), some measurements must be brought into question.
5. More time in the cavitation tunnel would substantiate the drop in efficiency of the composite propeller at 1.1 J at 4 m/s water speed.

5.4 Summary.

Tentative conclusions can now be drawn from the towing tank work and the cavitation tunnel work. It is not valid to attempt to compare the data from each experiment as the experimental conditions are different. However the hydroelastic tailoring of composite propellers has been seen to offer some potential. The experiments described should be considered a platform from which to launch further work.

A significant enhancement to the cavitation work would have been to use image analysis techniques to help visualise the blade tip deflections under load. Such a system would comprise of a video image of the deforming propeller blade, viewed under strobed lighting, and computer software to determine and present the data pertaining to these deformations. This information coupled to the structural analysis software would provide an invaluable tool for the future composite propeller designer.

The greatest future benefit from hydroelastically tailoring the type of propeller used in the experimentation described, may be the ability to have greater control of the onset of cavitation because of the geometry change under load. This would reduce cavitation erosion damage, cavitation induced noise and other inefficiencies that may not be directly evident in the K_T K_Q and η_o plots. This benefit is worth pursuing in its own right, even if it is not possible to radically alter the shape of the efficiency envelope by material selection.

The development of a suitable model to help analyse these series of benefits is the key to maximising the potential. This is discussed in Chapter 6.

A variety of experience has now been gained with respect to the use in service of a number of composite propellers. In any of the cases described, there was no evidence of any in service cavitation damage. However a great deal more experience is required before any confidence can be placed in the fitness for purpose of composites for marine propellers. A catalogue of many more accidents and mis–use incidents is also needed, although the experience to date is useful. 165 running hours on the vessel "Pandora" over a period of approximately 6 months where the propeller was submerged in sea water almost continually, has gone some way to validate the structural design for "normal" use. Two important questions remain. Firstly, how will the propeller fare over a much longer period of time? More service running time will help answer this. A programme of laboratory accelerated fatigue testing in sea water would allow greater control of environmental parameters and yield more reliable data. Secondly the question of the propeller's ability to withstand impacts is possibly the biggest issue to address. Two propellers on "Pandora" were destroyed by impact damage.

It can not be said for certain that the first propeller was damaged by the impact with an object. Nothing was observed in the vicinity of the propeller at the time the damage took place. Damage to the second propeller was certainly caused by a large piece of wood. This was not recovered. These incidents must be put into context by considering the following points.

- Material flaws existed in some of the early composite propellers. As described in Chapter 3 these have largely been eliminated.
- Regular inspection up to the time of each incident revealed no visual degradation of the propeller material.
- The vessel "Pandora" has a robust guard that fits closely around the propeller. If a solid object enters the propeller disc, something must fail regardless of the propeller material.

- Small and non catastrophic damage generally requires less skill to repair in composite than in bronze alloys where often a foundry is required.
- Impacts occurring to metal propellers that may be more robust than composite for this type of loading can often lead to extensive damage to other parts of the propulsion system if the propeller stays intact. There is a significant body of anecdotal evidence supporting this.
- Damage to metal propellers often results in all or the majority of the blades being bent, and rendering the unit ineffective for propulsion. Composites, however,do not fail plastically.The impact energy is absorbed by many small cracks at the fibre resin interfaces. Thus, if the composite is correctly engineered, moderate impacts may weaken the structure but not alter the overall geometry. So, albeit at lower power, propulsion can still take place.

Sea trials on the vessel "Aquatay" showed a marked increase in the vessel's top speed, from 16 knots with the bronze propeller to 18.5 knots with the composite propeller. As only one day was available to trial the propeller for this boat further investigations were not possible.

Chapter Six

Prediction of the Hydrodynamic Performance Advantages for Elastically Tailored Composite Propellers.

6.1 Introduction.

This chapter examines the potential of anisotropic material properties for the design of the propeller. The observations from the towing tank work in chapter 5 suggest that the possibility exists to improve the hydrodynamic performance of the propeller by designing specific elasticity into the structure of the blade. Of the propellers tested in the towing tank, 3 composite propellers exhibited marginally higher efficiencies over the bronze propeller at advance coefficients less than the design point, that is, at higher thrust coefficients. At the design point for any propeller, the maximum efficiency is achieved by using the correct propeller geometry. Any elasticity that permits a pitch change will not add to this maximum possible efficiency. However, any elastic property that allows a pitch change in response to different operating conditions will lead to greater efficiencies in off design conditions at greater thrust coefficients. This has been tentatively shown by the experimental work in the towing tank.

In order to investigate and optimise the advantage of building a propeller in an anisotropic material that has a particular elastic response, additional investigation was carried out. The scatter shown in the tank testing results meant that further study was required.

6.1.1. Elastic tailoring of anisotropic composites.

Composites offer design variables not possible with isotropic materials. Two composite structures can be produced of the same weight, geometry and the same material, however their elastic properties can be different. Figure 6.1 and plate 6.1 show how the distribution of elastic modulus affects a cantilever beam as bending is coupled to twist under load. The bending stiffness of a beam like this can also be tailored, whilst keeping the in plane tensile properties the same. This uniqueness of composites is useful for many structures, not least propellers. This property of hydroelastic tailoring may allow a composite propeller blade to deform to advantage during use.

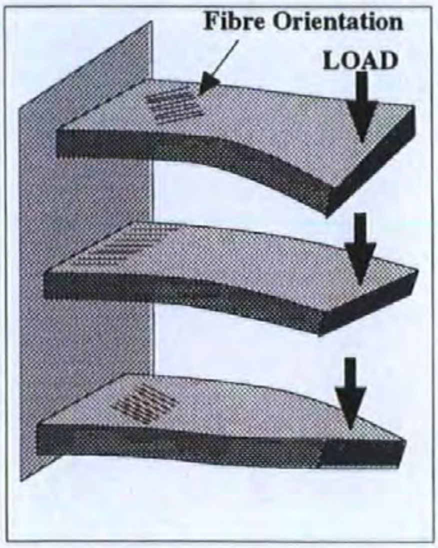


Figure 6.1 Different fibre orientations that give a different elastic response under the same load.

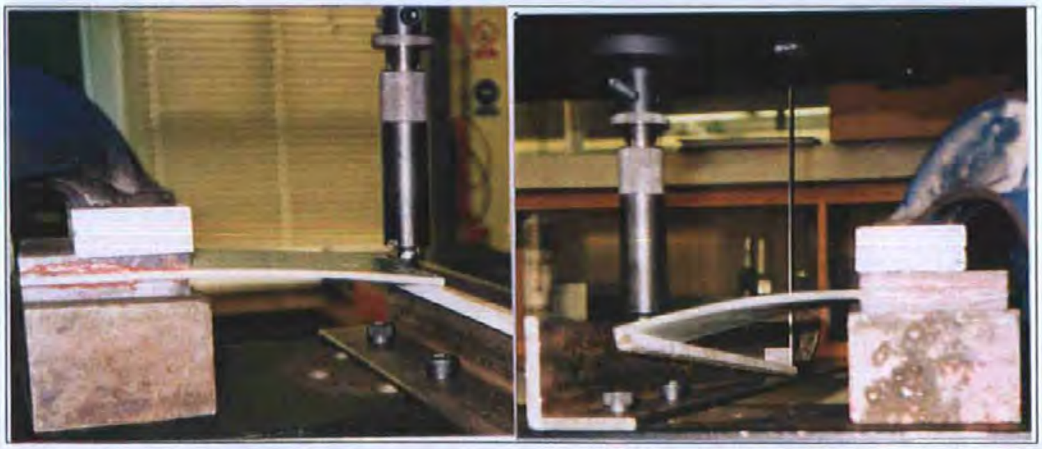


Plate 6.1 Two uni-directional glass/epoxy cantilever specimens. One with fibre aligned longitudinally showing no twist. The other with fibre aligned at 30° to the longitudinal axis, showing bend/twist coupling under load.

A number of applications have employed this characteristic to advantage. Notably, helicopter blades, where bend/twist coupling is achieved by appropriately angled fibre architecture. This aeroelastic tailoring is used to control blade flutter. [Garfinkle 94].

6.1.2 Mechanical self pitching propellers.

Mechanical controllable pitch propellers exhibit significantly different thrust coefficients, torque coefficients and efficiencies over fixed pitch propellers. The benefit is seen to be most effective for a vessel that operates at a number of different conditions. For example, fishing vessels, motor sailers or cargo vessels. The "AutoProp" from Bruntons Propellers is a self pitching propeller where the blades align themselves automatically to assume an optimum pitch for the current operating conditions. This propeller is shown in plate 6.2. The unique hydrodynamic characteristics are seen in figure 6.2.

Plate 6.2 The Brunton's "AutoProp" [Company literature]

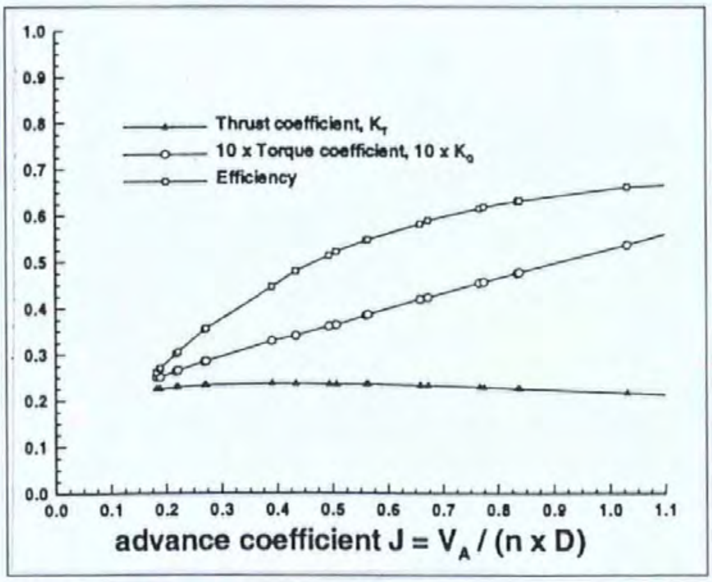


Figure 6.2 Thrust, torque coefficients and efficiency for the "AutoProp" [after Lurie 1995]

This benefit does however come at a significant extra cost for the added mechanical complexity. A cost increase of 400–500% over conventional propellers is typical.

6.1.3 The hydrodynamic benefit.

As the hydrodynamic load (thrust coefficient) increases, the blade angle of attack can:

- Remain the same.
- Increase.
- Decrease.

The greatest benefit will come about by *maximising the pitch change* for a given propeller.

There are two important ways of showing the efficiency of propellers with different characteristics:-

- The K_t K_q, efficiency chart; this deals with the propeller in isolation.
- The engine diagram, which deals with the propeller, engine and hull as an entire system.

6.2.4.1 The K_t K_q, efficiency chart.

A generalised K_t K_q, efficiency chart, is shown in figure 6.3. The diagram shows propeller efficiency plotted against the advance coefficient *(J)*. For fixed pitch propellers an optimum efficiency is shown, at a particular set of operating conditions. However, the shape of this efficiency envelope can be altered significantly for a variable pitch propeller. This has been previously illustrated in figure 6.2. The grey shading in figure 6.3 indicates the improved efficiency from a propeller that has a variable pitch.

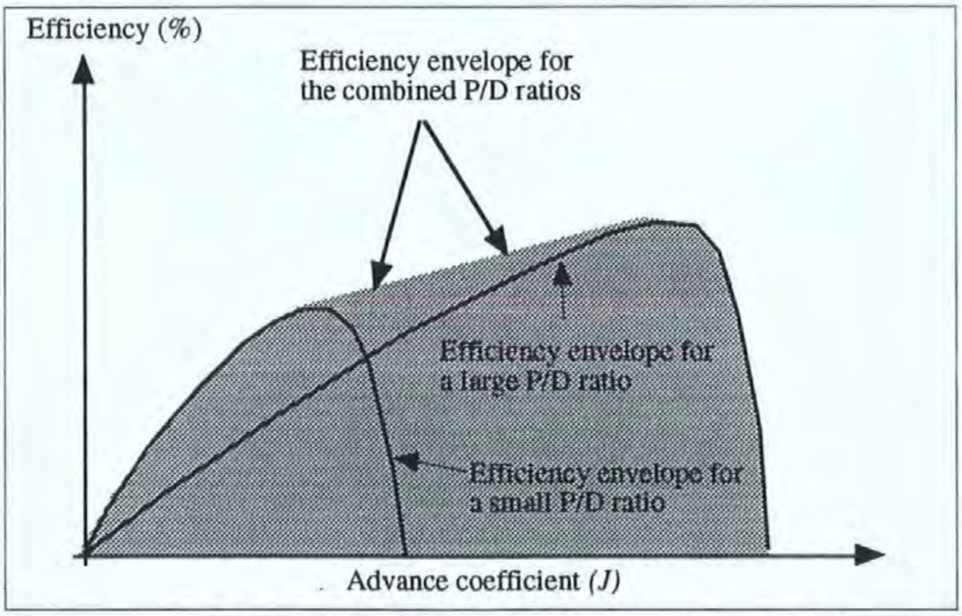


Figure 6.3 Generalised efficiency advantage for a variable pitch propeller .

6.2.4.2 The engine diagram.

For many applications the acceleration performance of a marine vehicle is important. A race boat that can accelerate away from the start line faster than its competitors is at a clear advantage. A vessel that has to manoeuvre accurately and change speed rapidly to achieve this, will gain from more effective acceleration brought about by a propeller that allows this. To explain this fully, a generic engine diagram is given in figure 6.4.

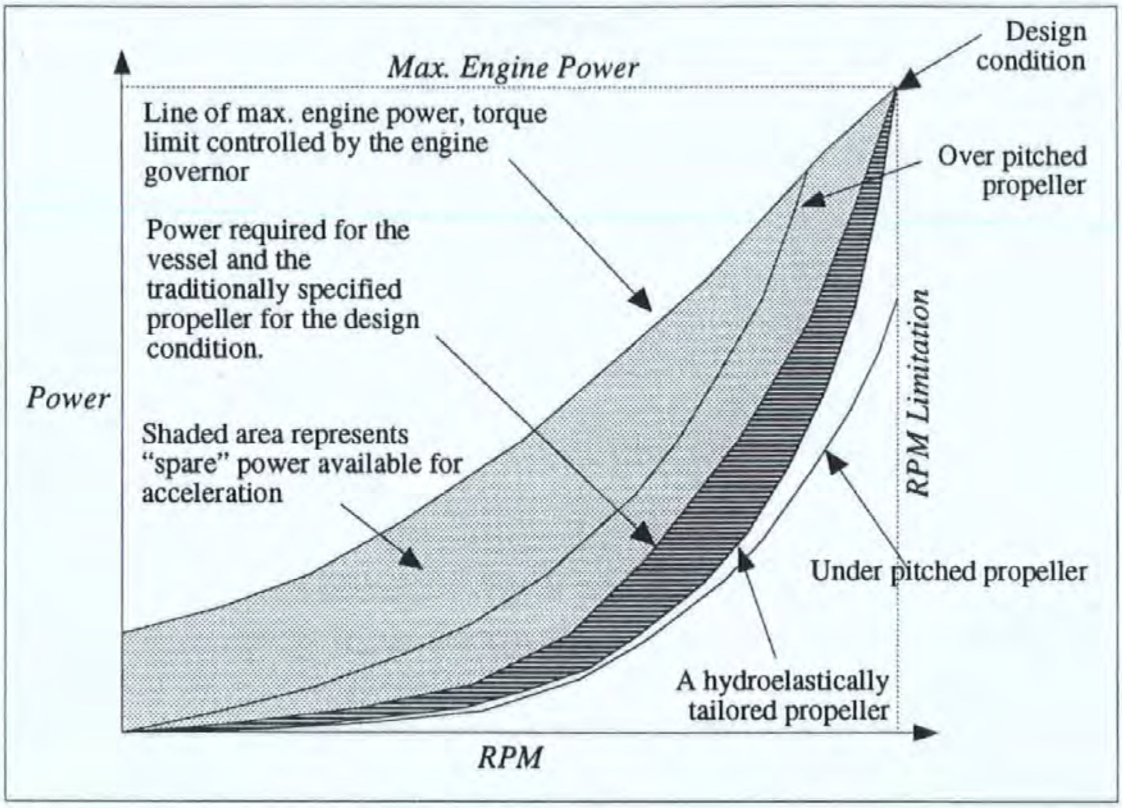


Figure 6.4 Generic engine diagram (after Bate 1995).

This shows some fundamentally important points:

- The design condition for which the traditional propeller, engine and vessel combination have been chosen is shown at the top right of the diagram.

- The over pitched propeller is shown, maximum RPM is not reached as the torque limit is reached first.

- Maximum RPM for the under–pitched propeller but at a lower torque and thus less power.

- The curve for a propeller that is initially under–pitched is shown. As power is developed, the pitch increases so the design point is reached. The advantage is that for conditions below maximum power but at higher thrust coefficients and RPM, less power is required as shown by the extra shaded area. This means that either greater power is available to accelerate the vessel, or less power is used and fuel conserved.

For most applications the propeller that has a pitch that increases as the engine power increases should be more efficient during transient conditions and operating below the maximum power condition. This is analogous to the gear box of a car. Many vessels do have to operate in conditions below the maximum power conditions, where it is important that efficiency is still achieved. Fishing vessels that trawl for their catch have two distinct operating conditions. They may travel to the fishing grounds at speeds in excess of 10 knots, whilst the trawling may take place at 3 to 4 knots. During mine hunting operations, the vessel is required to locate within a "hover box" of typically 20m by 20m, [Vosper Thonycroft 1996]. In order to do this, the mine hunter uses the main propeller to stem the wind/tide vector thus maintaining station. The vessel is operating below maximum power where savings can be made with a carefully designed deformable propeller.

Thus the broad goals have been identified in the light of these hydrodynamic perspectives.

- The blade design that gives the maximum possible pitch change.
- The pitch should reduce for high propeller loading (increased thrust coefficient), and increase towards the matching point where the load is smaller.

6.3 The Modelling Strategy.

Having identified firstly the elastic possibilities with composites and secondly the hydrodynamic implications, a model to generically predict the elastic deformations of a composite propeller blade was required. Thus a pitch change would be determined and the hydrodynamic benefit predicted.

The most appropriate modelling route was to use a finite element analysis (FEA) software package. This enabled the deformations under load of the propeller with a variety of material configurations to be determined. The FEA software used was PAFEC–PC, this was familiar to the author and able to handle anisotropic materials. The flow chart in figure 6.5 shows the strategy that was adopted.

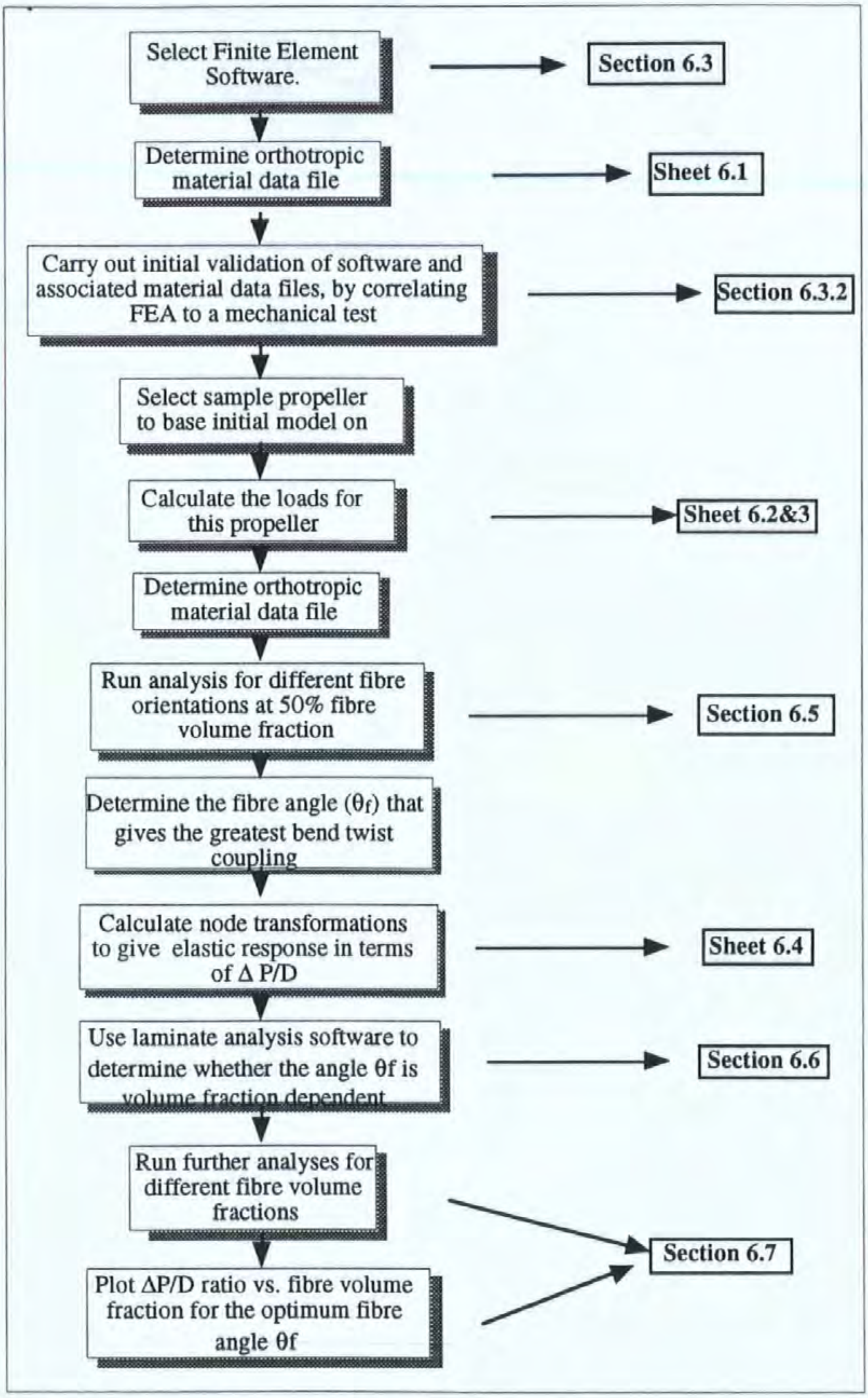
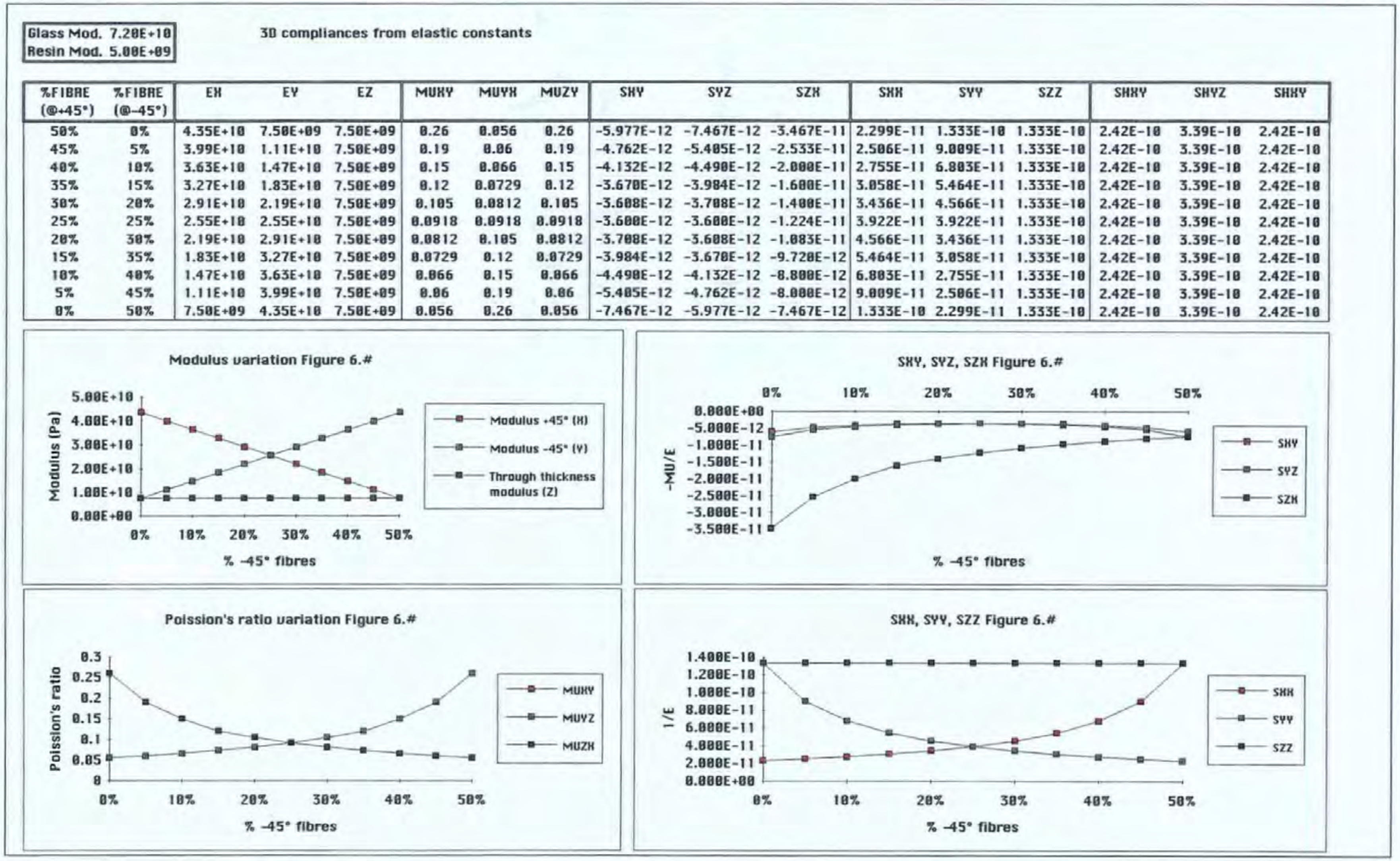


Figure 6.5 The adopted modelling strategy.

The first task was to create the material data file. The data required to run PAFEC is calculated in spreadsheet 6.1. and shown graphically for visual inspection of their consistency. Poisson's ratios were calculated by laminate analysis software, (these values



Glass Mod. 7.20E+10
Resin Mod. 5.00E+09

3D compliances from elastic constants

%FIBRE (@+45°)	%FIBRE (@-45°)	EX	EY	EZ	MUXY	MUYX	MUZY	SXY	SYZ	SZX	SXX	SYY	SZZ	SHXY	SHYZ	SHXY
50%	0%	4.35E+10	7.50E+09	7.50E+09	0.26	0.056	0.26	-5.977E-12	-7.467E-12	-3.467E-11	2.299E-11	1.333E-10	1.333E-10	2.42E-10	3.39E-10	2.42E-10
45%	5%	3.99E+10	1.11E+10	7.50E+09	0.19	0.06	0.19	-4.762E-12	-5.405E-12	-2.533E-11	2.506E-11	9.009E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
40%	10%	3.63E+10	1.47E+10	7.50E+09	0.15	0.066	0.15	-4.132E-12	-4.490E-12	-2.000E-11	2.755E-11	6.803E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
35%	15%	3.27E+10	1.83E+10	7.50E+09	0.12	0.0729	0.12	-3.670E-12	-3.984E-12	-1.600E-11	3.058E-11	5.464E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
30%	20%	2.91E+10	2.19E+10	7.50E+09	0.105	0.0812	0.105	-3.608E-12	-3.708E-12	-1.400E-11	3.436E-11	4.566E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
25%	25%	2.55E+10	2.55E+10	7.50E+09	0.0918	0.0918	0.0918	-3.600E-12	-3.600E-12	-1.224E-11	3.922E-11	3.922E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
20%	30%	2.19E+10	2.91E+10	7.50E+09	0.0812	0.105	0.0812	-3.708E-12	-3.608E-12	-1.083E-11	4.566E-11	3.436E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
15%	35%	1.83E+10	3.27E+10	7.50E+09	0.0729	0.12	0.0729	-3.984E-12	-3.670E-12	-9.720E-12	5.464E-11	3.058E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
10%	40%	1.47E+10	3.63E+10	7.50E+09	0.066	0.15	0.066	-4.490E-12	-4.132E-12	-8.800E-12	6.803E-11	2.755E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
5%	45%	1.11E+10	3.99E+10	7.50E+09	0.06	0.19	0.06	-5.405E-12	-4.762E-12	-8.000E-12	9.009E-11	2.506E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10
0%	50%	7.50E+09	4.35E+10	7.50E+09	0.056	0.26	0.056	-7.467E-12	-5.977E-12	-7.467E-12	1.333E-10	2.299E-11	1.333E-10	2.42E-10	3.39E-10	2.42E-10

Modulus variation Figure 6.#

SXY, SYZ, SZX Figure 6.#

Poission's ratio variation Figure 6.#

SXX, SYY, SZZ Figure 6.#

Spreadsheet 6.1 Calculation of anisotropic material compliances.

(Source the author)

can not simply be ratioed by a rule of mixtures approach which only moderately considers the effect of properties in other directions). The laminate chosen for initial analysis purposes was a uni–directional, E–glass laminate at 50% volume fraction. Glass was chosen as it has a low modulus compared to either carbon or aramid. The volume fraction of 50% was used as an initial baseline, representing a good compromise between achieving good mechanical properties and what can be realised by RTM manufacture. However later models investigated reduced volume fractions.

6.3.2 Finite element validation.

An important first task was to gain confidence in the output from the software. Care was taken to calculate accurately the material properties, then validate these and the PAFEC software by a simple experiment. The results yielded the following data:

- The confidence that could be placed in the software.
- The sensitivity to element type.
- The sensitivity to the elastic moduli data.

PAFEC FEA gives a linear model of the structure under analysis. Since polymer composites are linearly elastic to failure, this is satisfactory. In order to carry out the validation under the above headings, two small composite plates were manufactured and placed under cantilever bending. Plates were used as opposed to beams, to more closely represent the blade geometry. Also the mechanics of plate deformations are different to high aspect ratio beam mechanics. (A marine propeller blade is rarely a high aspect ratio beam). Care was taken that a proper encastré mounting was used for each cantilever. Substantial steel packing pieces were used in the clamping of each plate, figure 6.6. A cantilever was considered more appropriate than a three point bend test because the twist at the free end could be observed more easily.

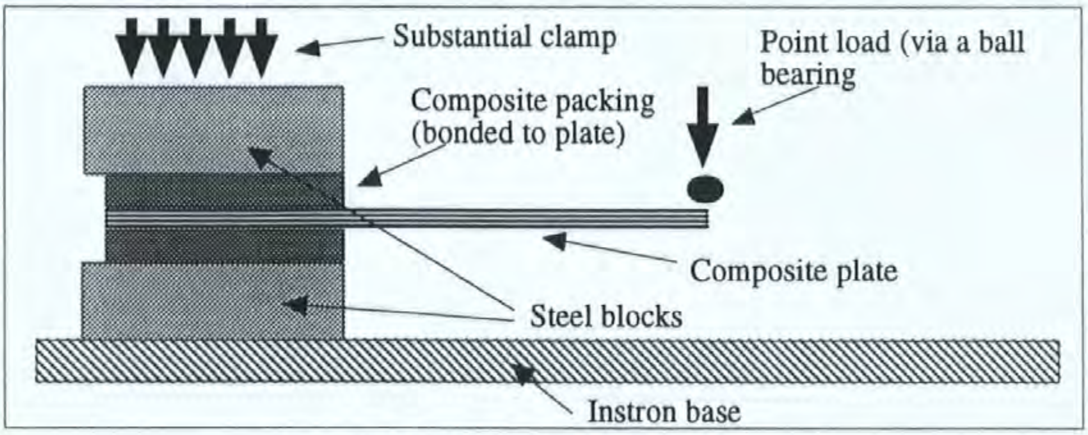


Figure 6.6 Plate FEA validation experiment.

Sample plate 1 consisted of uni–directional, E–glass fibres aligned at 0° to the direction of greatest stress. Sample plate 2 had the same, only at 30° to the direction of greatest stress. Table 7.1 gives further detail.

	Plate 1	Plate 2
Fibre	E-glass	E-glass
Resin	Epoxy	Epoxy
Volume fraction	0.55	0.55
Fibre angle	0°	30°
Number of plies	8	8
Dimensions	0.1m x 0.06m	0.1m x 0.06m
Laminate thickness	3.3mm	3.3mm
Load	0–200 N	0–200 N
Fibre form	Uni Directional	Uni Directional

Table 6.1 Laminate details of the 2 plate types used.

Plate 6.1 show each sample plate subjected to the bending loads in the laboratory. The twist, bending coupling is clearly shown for plate 2. The twist was measured by bonding a straight edge to the free end of the plate, this was used to assist in measuring the angle of twist. The torsional angle was assumed to be constant, given that there were no discontinuities in the material.

Each plate was then modelled by FEA in order to compare the experimental results with the analytical approach. The deformation for the plate with 0° fibres was also determined by the classical equation for an encastré cantilever (equation 6.1). Figure 6.10 shows the FEA mesh (0° fibre) responding to the load. The deformation is exaggerated for clarity. The point load was placed at the centre of the free end, encastré restraints were applied to each node of the fixed end.

$$D = \frac{WL^3}{3\,EI}$$

$$E = 39.6 \text{ GPa}$$

.................................*Equation 6.1*

In addition to this comparison, a check was carried out on element types available in PAFEC, also the modulus in the materials data file was changed by ± 10% to check the sensitivity of the analysis to these input parameters. Two element types were used for anisotropic materials. 46215 is a flat plate element, 43215 is a solid brick element, further data on each element is included in appendix 8. Figures 6.7, 6.8, 6.9 show the comparisons between the FEA and the experimental results. Figure 6.10 shows the deformed FE mesh.

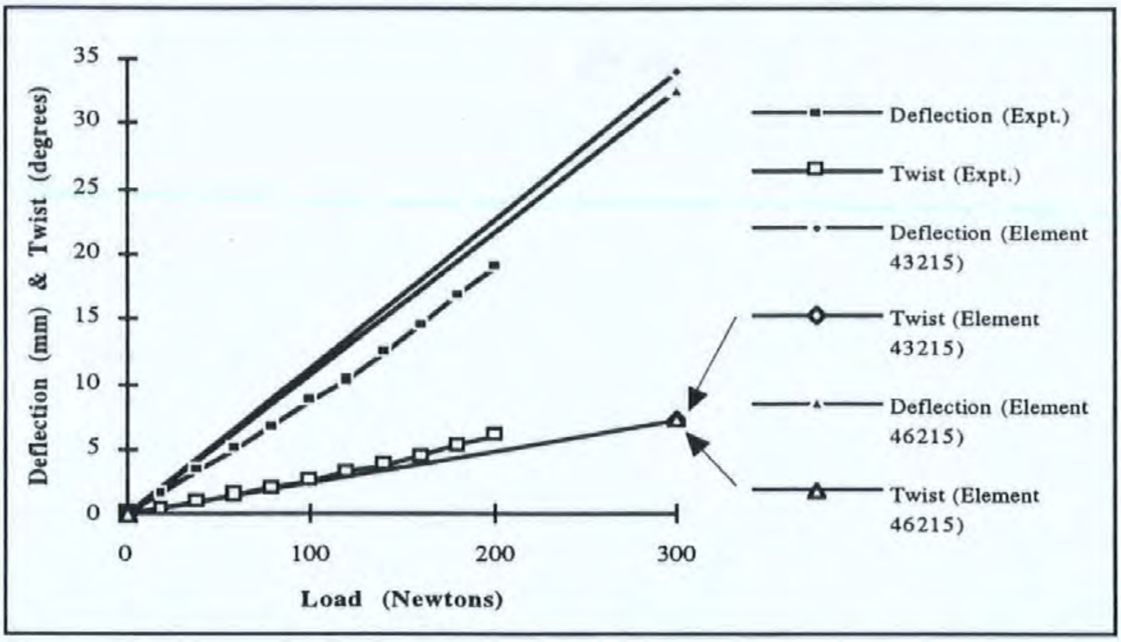


Figure 6.7 Comparison of experimental and FEA results using 2 element types (fibres at 30° to longitudinal axis).

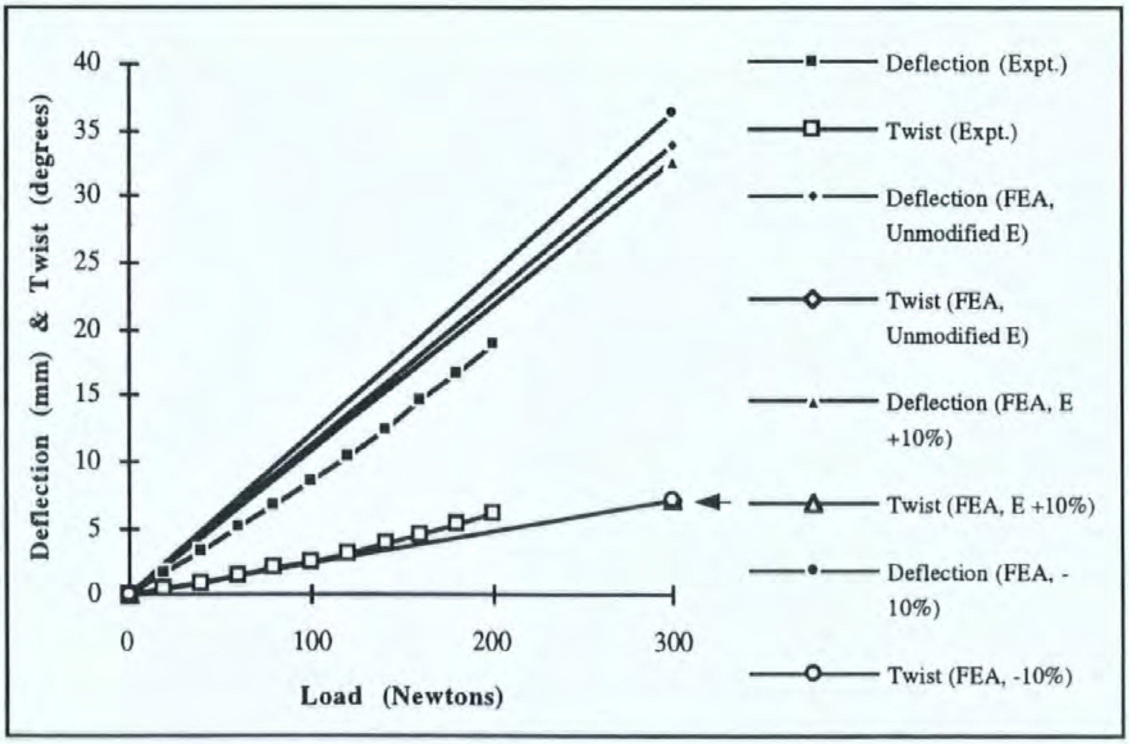


Figure 6.8 Deflection vs. load for different elastic moduli

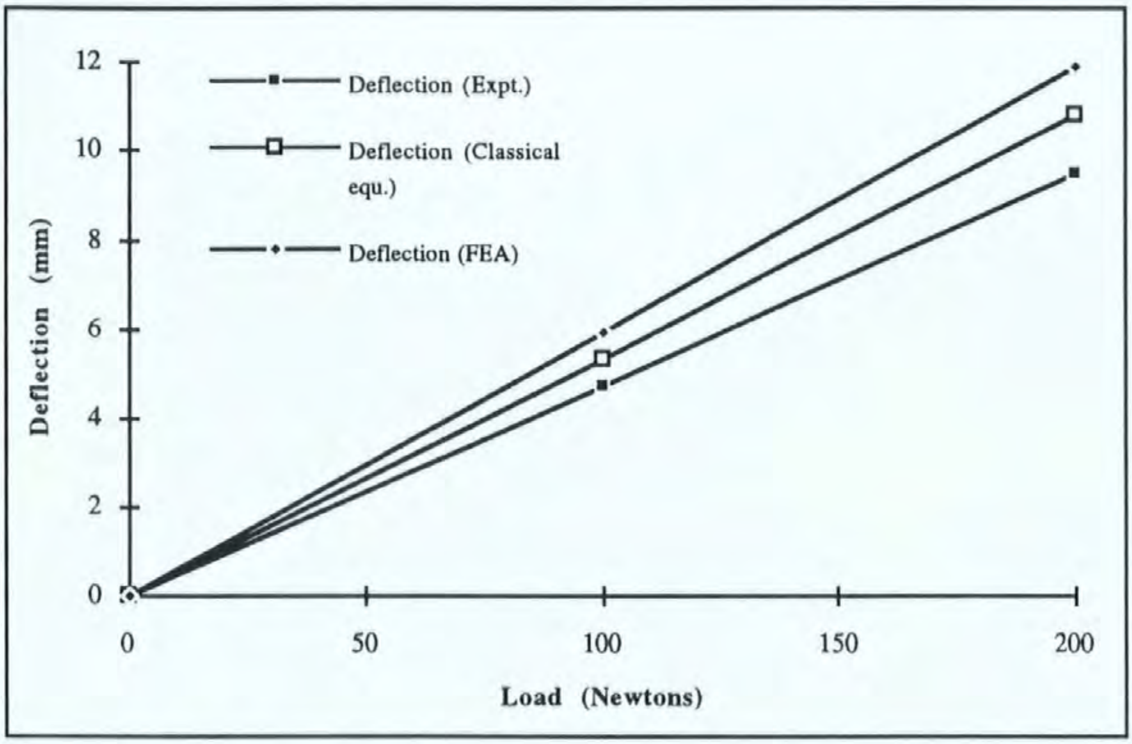
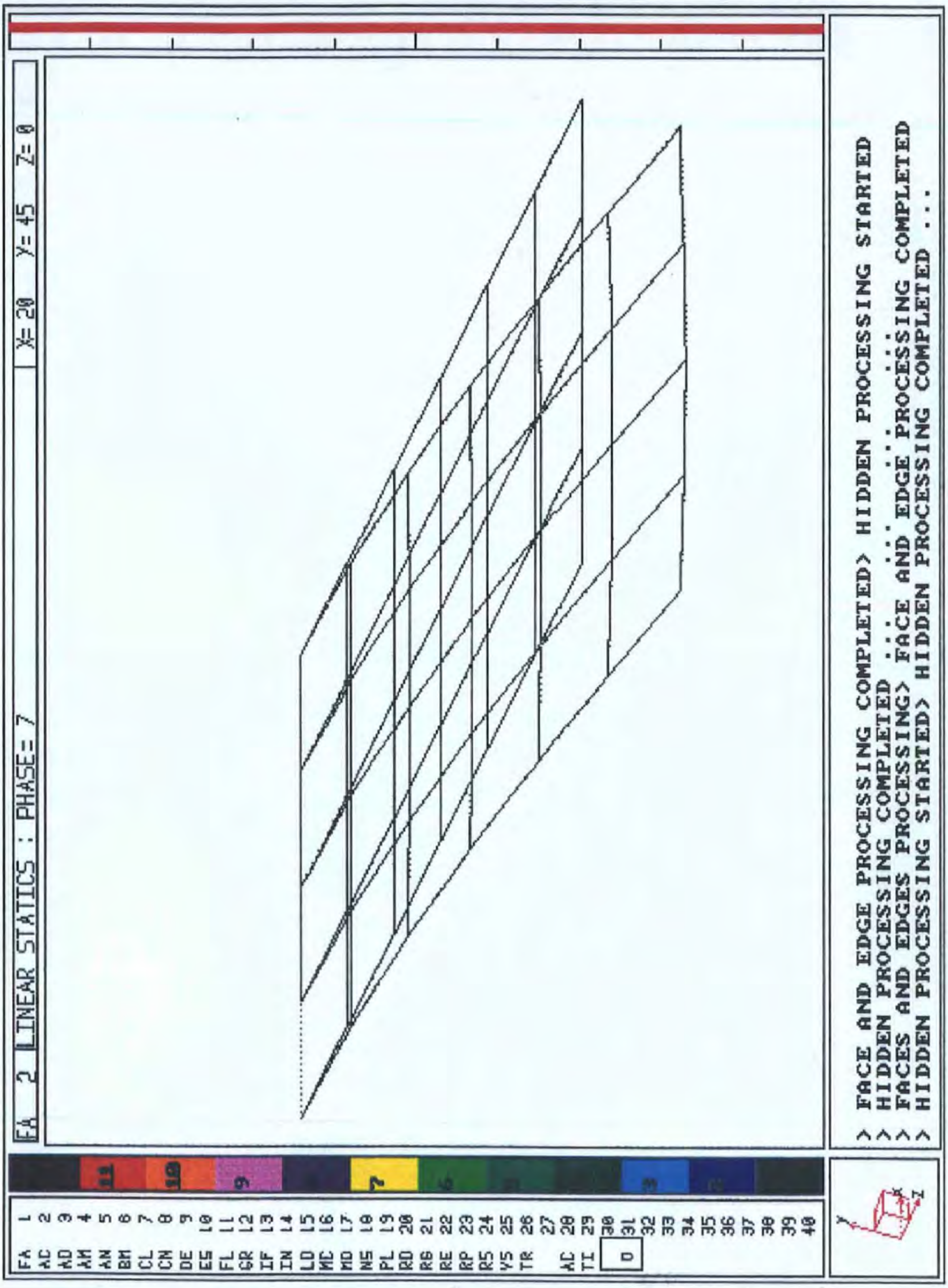


Figure 6.9 Comparison of experimental result, FEA result and analytical result (fibres 0° to longitudinal axis, element 43215).

Figure 6.10 Deformed FE mesh for the FEA validation.



```
> FACE AND EDGE PROCESSING COMPLETED> HIDDEN PROCESSING STARTED
> HIDDEN PROCESSING COMPLETED ...   ...   ...   ...
> FACES AND EDGES PROCESSING> FACE AND EDGE PROCESSING COMPLETED
> HIDDEN PROCESSING STARTED> HIDDEN PROCESSING COMPLETED ...
```

The FEA model does slightly exaggerate deflection and underestimate twist, however, the correlation was good enough to encourage further use of the software. The modulus has a small and appropriately proportioned influence on the end result. From this data some tentative confidence could be placed in the package and the input data used with it. Appendix 8 gives further information on the element type.

6.4 Load calculation for marine propellers.

6.4.1 Introduction.

Before the structural design of the propeller can begin, the loads to which it is subjected must be determined. Work has been carried out in this area. However, the predominant area of interest is the hydrodynamic design which has detracted from the subject of propeller loading. Historically any attempt at a structural solution to the design has generally been dominated by the rules imposed by classification societies, where specifications for the propeller design are defined. Although catastrophic blade failure is rare, interest in stress analysis grew with the increased powering of ships in the 1950's and the evolution of more complex propeller geometries, such as high skew. The foundations of work to determine loads that act on a propeller were laid at the beginning of the century [Taylor 1910]. Work was published on a method to determine the stresses upon propeller blades. In this method the propeller blade was treated as a simple cantilever beam acted upon by thrust, torque, centrifugal bending and centrifugal direct loads figure 6.11.

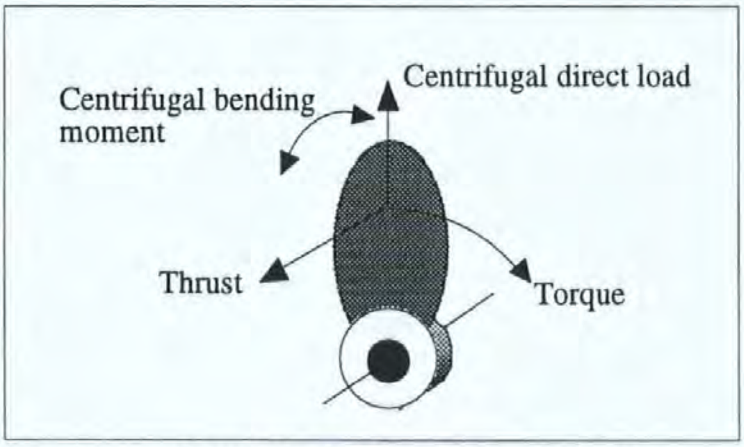


Figure 6.11 Major loads acting on a propeller

For most propeller shapes, in which blade width is not greater than the blade length [Conolly 1960] and whose geometry is not highly skewed, initial loads have been determined by treating the blade as a simple cantilever. This has been shown to give good results. (Within 10% of measured results [Carlton 1980]). However to determine the precise stress levels in the blade structure due to geometry, material distribution and externally applied loads, it is necessary to produce a finite element model. This is described later in this chapter.

The environment the propeller has to operate in is highly variable; water flow into the propeller disk is non homogeneous and has been the subject of considerable research. The non-uniformity of this wake field leads to some uncertainty when calculating loads [Carlton 1980].

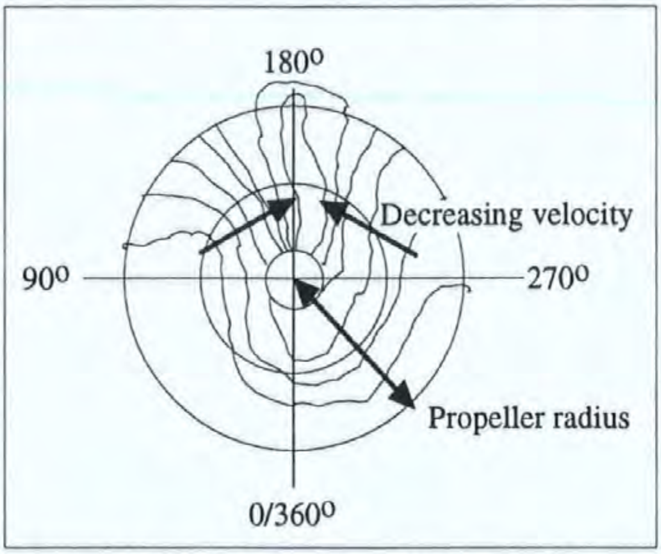


Figure 6.12 A typical wake field for a single screw full form hull, contours show equal axial velocity.

Parameters that influence the wake field are the vessel's hull form, trim, pitching, rolling and the weather conditions. Figure 6.12 shows the typical variability in wake flow velocities expected in the region of the propeller behind a displacement vessel. It is possible to calculate the average velocity in this area by the empirically derived Taylor wake fraction coefficient [W_t]. This ranges from about 0.04 to 0.40 for high speed planing vessels and heavy displacement vessels respectively. The water velocity in the area of the propeller, or velocity of advance [V_a] is given by equation 4.1.

$$\boxed{V_a = (1 - W_t)V_s} \quad \text{............................}\textit{Equation 6.2}$$

6.4.2 The maximum loading condition.

The maximum propeller loading condition is largely specific to the application and type of propeller, however in general terms the following include some of the conditions that should be considered [Brockett 1994]:-

- Full speed ahead and astern, full engine power.
- Bollard pull condition ahead and astern, full engine power.
- High speed turns.
- Reverse condition for skewed propellers.
- Rough weather operation.
- The loads induced due to impacts with rogue objects.

6.4.3 Calculation of blade loading.

From figure 6.11 it can be seen that the blade loading comprises of 3 fundamental forces; thrust, torque and centrifugal loads. Since thrust acts perpendicular to the propeller disc and torque acts in plane with the propeller disc, the forces must be resolved for the angle of minimum second moment of area of the blade (figure 6.13), ie the forces are acting perpendicular to the blade.

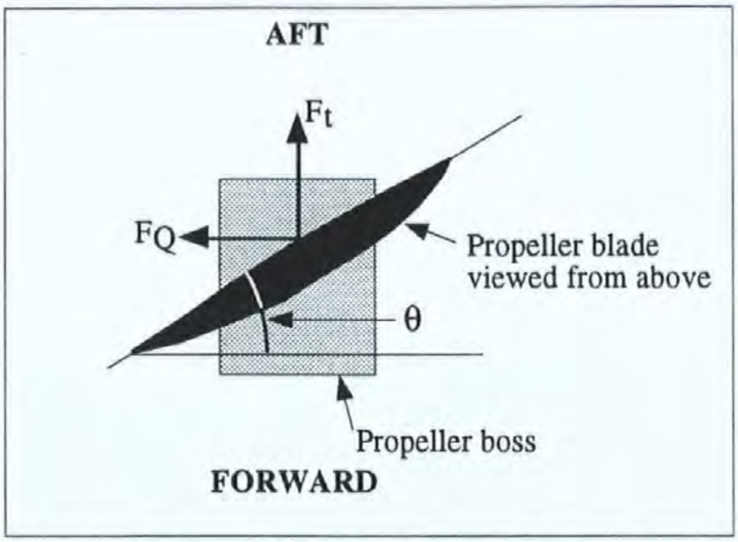


Figure 6.13 Thrust & Torque loads relative to the plane of minimum inertia of the blade

The root area of the blade generally coincides with 20-25% of the propeller's radius. This is the section where the greatest moment occurs. This holds true for all but the most extreme propeller geometries. The angle of the section is given by equation 6.3. (The assumption is made, that the pitch of the propeller is usually defined at 0.7 of the radius).

$$\theta = \tan^{-1} \left[\frac{P_0}{\pi X_0 D} \right]$$

.............................equation 6.3

Knowing this angle and the engine power, shaft efficiency, propeller efficiency, speed of advance, RPM and the number of blades, the loads due to torque and thrust can be calculated from equations 6.4 & 6.5 respectively. Shaft and propeller efficiency losses depends on the stern gear and propeller type, and must be taken into account. Equation 6.6 gives the centrifugal loads. [Carlton 1980].

$$Thrust\ [N] = \frac{P_s.\ \eta_m.\ \eta_p.\ \cos\theta}{V_a.\ B_L.}$$

...........Equation 6.4

$$\boxed{\text{Force due to torque } [N] = \frac{P_{s.}\ \eta_{m.} \sin\theta}{2\pi.\ b.\ n.\ B_L}}$$

.....Equation 6.5

$$\boxed{F_c\,[N] = 2\pi^2 \left[0.75.\ m \left[\frac{0.73\ \pi.D^2}{4.\ B_L}\right] \rho\right] x_c\, D\, n^2}$$

.....Equation 6.6

The thrust and torque loads are multiplied by the moment arms shown by figures 6.14 and 6.15, to obtain the bending moments about the blade root. This is done by representing the distribution of load over the blade as if it acts at one point. The moment arms are taken as the distances shown in figure 6.14. The moment arm for thrust for most blade geometries is 0.7 radius and for torque is 0.66 radius [Conolly 1960, Carlton 1980].

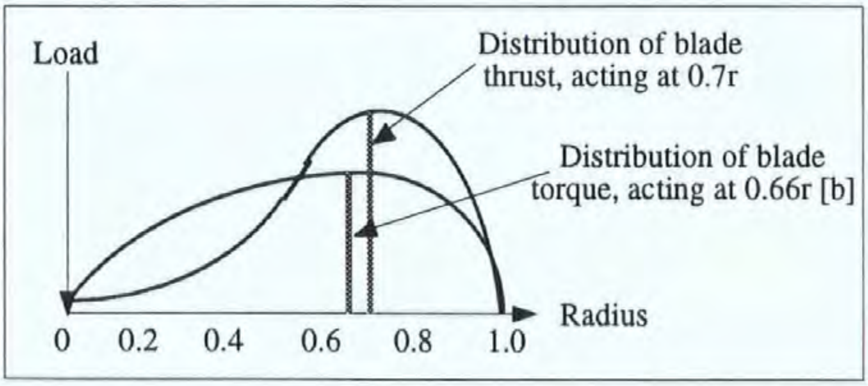


Figure 6.14 Distribution of thrust and torque loads with blade radius

Thus the bending moments due to thrust and torque can be found. In order to calculate the bending moment due to centrifugal loads on raked blades, the position of the blade centre of gravity relative to the neutral axis and thus the moment arm that induces the bending moment from the centrifugal force must be found. This is shown in figure 6.15 and by equation 6.7.

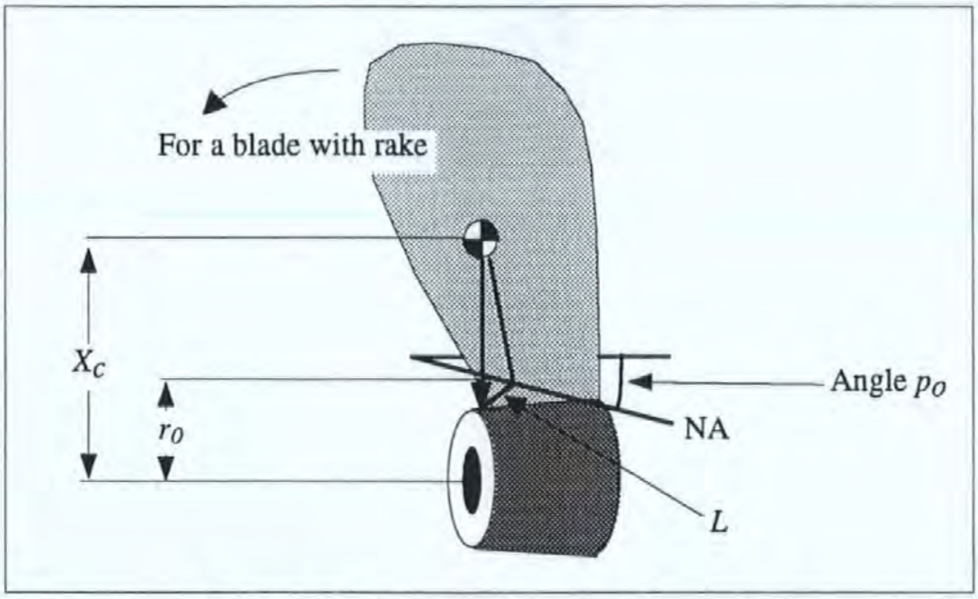


Figure 6.15 Centrifugal bending moment lever

$$\boxed{L = (X_c - r_O) \tan R. \sin p_O}$$ ....*Equation 6.7*

In order to calculate the stresses that arise from these loads, the area [*A*] and section modulus [*Z*] for the blade section at 0.2 of the radius must be calculated. Thus the total stress at this point can be given by equation 6.8. Equations 6.9 and 6.10 give the area and section modulus and figure 6.16 gives the dimensions required for calculation of these parameters.

It is convenient to use Simpson's rule to evaluate these equations numerically. This method lends itself to computation by spreadsheet. The spreadsheets by the author; sheet 6.1 and 6.2, (equations are given in appendix 6). Sheet 6.1 has been written to allow design parameters for any Wageningen B-series propeller to be entered to calculate the section area [*A*] and the section modulus [*Z*], for the sections at 0.2, 0.4, 0.6 & 0.8 radii.

The final form of the stress equations 6.11, 6.12, 6.13 and 6.14, are shown below. The total blade stress is given by equation 6.15. The stress unaccounted for so far $\sigma_{\perp}$, includes loads due to weather and impact with debris and must generally be dealt with by a suitable factor of safety. This is usually covered by the safety factor used for fatigue. Usual practice is to design to 10% of the UTS for manganese bronze and nickel aluminium bronze propellers.

$$\boxed{\sigma_{total} = \frac{BM_{total}}{Z} + \frac{CF}{A}}$$ ....*Equation 6.8*

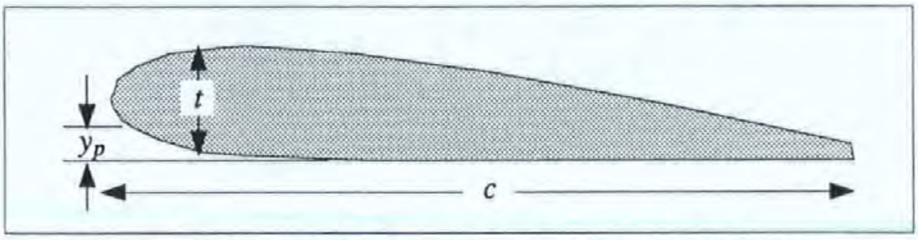


Figure 6.16 Incremental dimensions of propeller blade section.

$$\boxed{A = \int_0^c t\ .dc}$$ ....*Equation 6.9*

$$\boxed{Z = \frac{2\int_0^c [3y_p\,(y_p + t) + t^2]\ t.dc.\ \int_0^c t.dc}{3\int_0^c (2y_p + t)\ t.dc} - \frac{1}{2}\int_0^c (2y_p + t)\ t.dc}$$.*Equation 6.10*

$$\boxed{\sigma_T = \frac{P_{s.}\ \eta_{m.}\ \eta_{p.}\ (a\text{-}r_0)r.\ \cos\theta}{V_{a.}\ B_{L.}\ Z}}$$ ....*Equation 6.11*

$$\boxed{\sigma_Q = \frac{P_{s.}\ \eta_{m.}\ (b\text{-}r_0)\ \sin\theta}{2\pi.\ n.\ b.\ B_{L.}\ Z}}$$ ....*Equation 6.12*

$$\boxed{\sigma_{CF} = \frac{F_c}{A}}$$ ....*Equation 6.13*

$$\boxed{\sigma_{CMB} = \frac{F_c\ L}{Z}}$$ ....*Equation 6.14*

$$\boxed{\sigma_{total} = \sigma_T + \sigma_Q + \sigma_{CMB} + \sigma_{CF} + \sigma_\perp}$$ .....*Equation 6.15*

By summing all the components of stress, the maximum stress for the section is calculated. The results given by Taylor's early method, of which this is a refinement, has come under some criticism by a number of authors. It is pointed out [Conolly 1960] that for propellers whose width does not exceed their length, then the Taylor method gives reliable results. However, simple beam theory cannot give any reliable indication of chordwise stress distribution, although, generally this is small and not significant. Conolly develops a set of equations to calculate the maximum radial stress. The equations are based on the theory of thin shells; although more complex than the Taylor/Carlton method, it is still an approximation, as blade camber, shaft inclination and manoeuvring conditions are ignored. Conolly's method was primarily brought about because of the need to evaluate the stresses in wide blades. However, these can now be determined with finite element analysis (FEA), so long as the global loads upon each blade are known with confidence.

It is important to realise the complexity of this problem. Although a number of sophisticated analytical routes are available for the determination of the stresses within propeller blades and similar structures, a cast metallic component like the propeller has significant internal stresses. Therefore it is not possible to determine the actual stresses within the propeller [Schoenherr 1963]. Also, consideration should be given to the operating condition providing the greatest load upon the propeller. Full scale measurement and analysis can help in understanding this.

For propellers whose skew angle is less than 25°, classification societies permit the calculation of propeller loads by this beam method outlined. This means that loads other than pure bending, (e.g torque), can be ignored. Since the propeller that is considered for FEA work later in this chapter has a skew angle of only 10°, these assumptions can be applied. For the FEA the loads are calculated and shown in spreadsheet 6.3. These calculations give values for point loads of thrust and torque, which are distributed radially by the factors in the left hand columns in the thrust and torque loads tables. These loads were used in the FEA model. The distribution of the loads together with the restraints for the FEA model are shown in figure 6.18. The loads are off–centre; this is partly due to the constraints of the FEA, in that loads should not be applied to mid–side nodes, but only to corner nodes, or results can be erroneous. Additionally, the thickest part of the propeller is not quite mid–chord for these blade sections. Thus a slight approximation is inevitable. Increasing the number of elements would improve the accuracy of the model, (although not investigated here), this would be at the premium of increased processing time and the software is limited in the number of nodes a particular model can contain. Also the centre of lift for this type of foil section is marginally forward of the mid section. This generally holds true for most propellers except super cavitating propellers where the centre of pressure acts as much as 75% from the leading edge of the chord.

6.4.4 Full scale measurement.

Results from strain gauged propellers operating in their true environment give a good indication of stress levels, but there are complexities in wiring the strain gauges. Normal methods require the wiring for the strain gauges to be led through a hollow shaft to a set of slip rings. Radio telemetry is a better alternative, where the data from the strain gauges is transmitted through the water to a receiver on part of the hull structure. During the 1960's results were published from the testing of a propeller on a 42 000 ton tanker [Wereldsma 1964]. These results confirmed the following:-

- That in general past finite element models can be accurate [Carlton 1980].
- The leading and trailing edges were relatively unstressed.
- The largest principal stress was radial.

- The smallest principal stress is chordal and was largely insignificant.
- The theoretical cantilever load prediction shows a 10% difference from the measured values.

The accuracy of the load prediction by the equations given depends upon the accuracy of the data used in the calculations. Thus in order to place confidence in these data sets, it was decided to design and manufacture a load cell that would be capable of measuring the thrust and torque as seen by the propeller shaft on one of the University test vessels. The efficiency terms given in equations 6.11 and 6.12 are empirically derived and often merely estimated. Accurate measurement of thrust and torque enables greater confidence to be placed in the prescribed method of load computation.

6.4.5 Example load calculations.

So that a useful working design tool could be generated from the equations put forward, they were written into a spreadsheet. The stages used for the entire computation are summarised by figure 6.17.

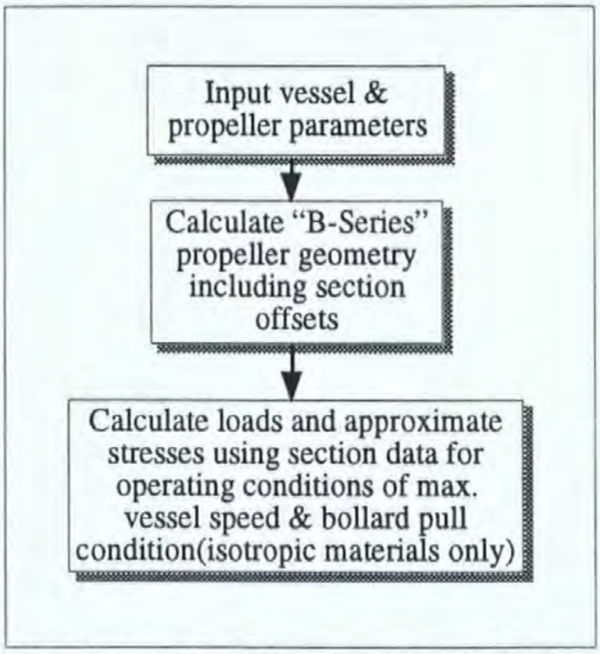
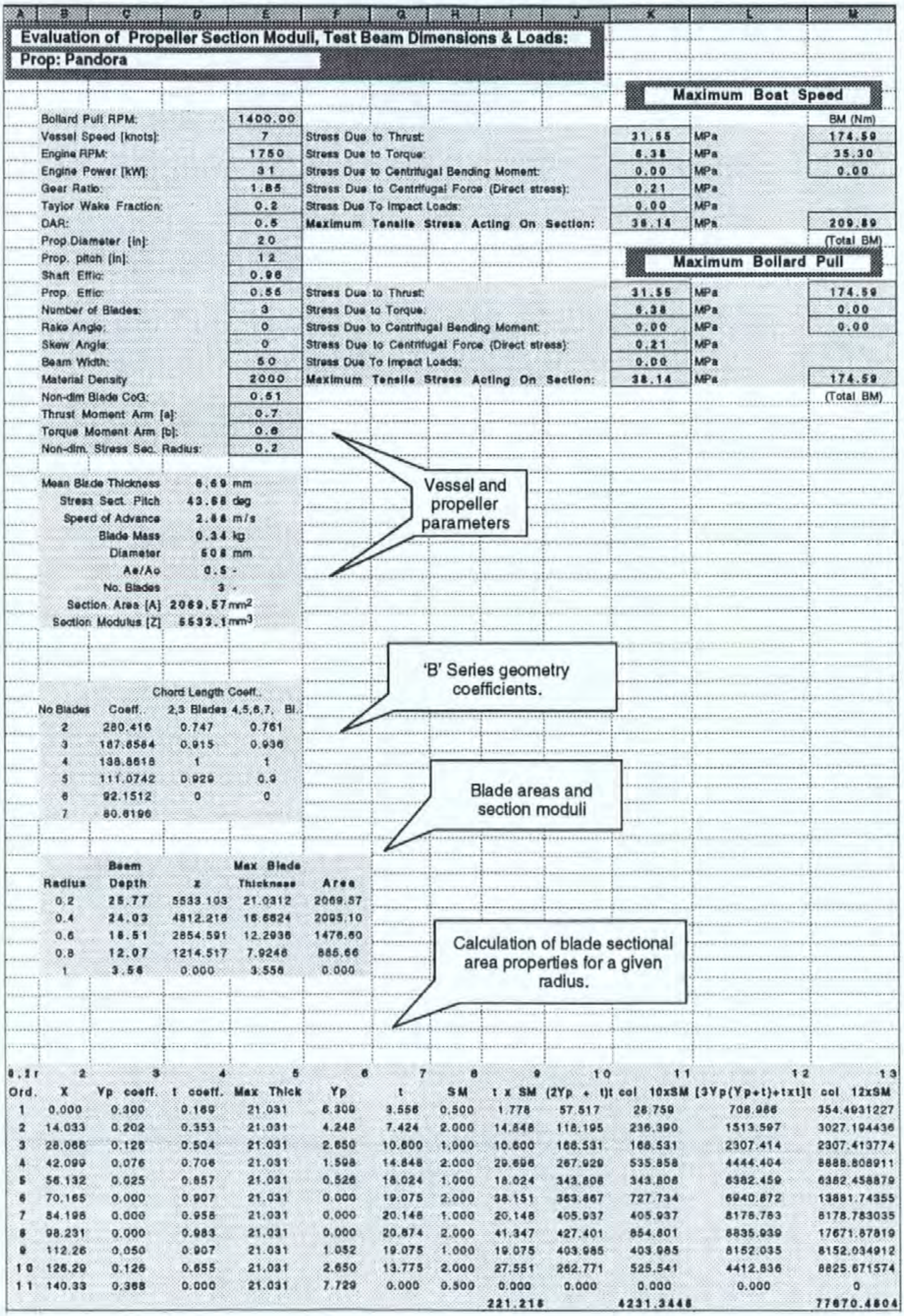


Figure 6.17 Flow chart for loads calculation.

The spreadsheet is designed to be generic for any Wageningen B–series propeller with 2 to 7 blades. Loads are calculated and the stresses are approximated using classical beam theory, thus a necessary part of the spreadsheet is the calculation of the section moduli at various radii of the propeller blade. Sheet 6.1 shows the spreadsheet.

Sheet 6.1 Spreadsheet calculation of the loads on the propeller for "Pandora"



Evaluation of Propeller Section Moduli, Test Beam Dimensions & Loads:

Prop: Pandora

Bollard Pull RPM:	1400.00
Vessel Speed [knots]:	7
Engine RPM:	1750
Engine Power [kW]:	31
Gear Ratio:	1.85
Taylor Wake Fraction:	0.2
DAR:	0.5
Prop.Diameter [in]:	20
Prop. pitch (in]:	12
Shaft Effic:	0.98
Prop. Effic:	0.56
Number of Blades:	3
Rake Angle:	0
Skew Angle:	0
Beam Width:	50
Material Density	2000
Non-dim Blade CoG:	0.51
Thrust Moment Arm [a]:	0.7
Torque Moment Arm [b]:	0.8
Non-dim. Stress Sec. Radius:	0.2

Maximum Boat Speed

			BM (Nm)
Stress Due to Thrust:	31.55	MPa	174.59
Stress Due to Torque:	6.38	MPa	35.30
Stress Due to Centrifugal Bending Moment:	0.00	MPa	0.00
Stress Due to Centrifugal Force (Direct stress):	0.21	MPa	
Stress Due To Impact Loads:	0.00	MPa	
Maximum Tensile Stress Acting On Section:	38.14	MPa	209.89
			(Total BM)

Maximum Bollard Pull

Stress Due to Thrust:	31.55	MPa	174.59
Stress Due to Torque:	6.38	MPa	0.00
Stress Due to Centrifugal Bending Moment:	0.00	MPa	0.00
Stress Due to Centrifugal Force (Direct stress):	0.21	MPa	
Stress Due To Impact Loads:	0.00	MPa	
Maximum Tensile Stress Acting On Section:	38.14	MPa	174.59
			(Total BM)

Vessel and propeller parameters

Mean Blade Thickness	6.69	mm
Stress Sect. Pitch	43.68	deg
Speed of Advance	2.88	m/s
Blade Mass	0.34	kg
Diameter	508	mm
Ae/Ao	0.5	-
No. Blades	3	-
Section Area [A]	2069.57	mm^2
Section Modulus [Z]	5533.1	mm^3

'B' Series geometry coefficients.

		Chord Length Coeff.	
No Blades	Coeff.	2,3 Blades	4,5,6,7, Bl.
2	280.416	0.747	0.761
3	187.8584	0.915	0.936
4	138.8618	1	1
5	111.0742	0.929	0.9
6	92.1512	0	0
7	80.6196		

Blade areas and section moduli

	Beam		Max Blade	
Radius	Depth	z	Thickness	Area
0.2	25.77	5533.103	21.0312	2069.57
0.4	24.03	4812.216	16.6624	2095.10
0.6	18.51	2854.591	12.2936	1476.60
0.8	12.07	1214.517	7.9248	885.66
1	3.56	0.000	3.558	0.000

Calculation of blade sectional area properties for a given radius.

0.1r	2	3	4	5	6	7	8	9	10	11	12	13
Ord.	X	Yp coeff.	t coeff.	Max Thick	Yp	t	SM	t x SM	(2Yp + t)t col	10xSM	[3Yp(Yp+t)+txt]t col	12xSM
1	0.000	0.300	0.169	21.031	6.309	3.556	0.500	1.778	57.517	28.759	708.986	354.4931227
2	14.033	0.202	0.353	21.031	4.248	7.424	2.000	14.848	118.195	236.390	1513.597	3027.194436
3	28.066	0.126	0.504	21.031	2.650	10.600	1.000	10.600	168.531	168.531	2307.414	2307.413774
4	42.099	0.076	0.706	21.031	1.598	14.848	2.000	29.696	267.929	535.858	4444.404	8888.808911
5	56.132	0.025	0.857	21.031	0.526	18.024	1.000	18.024	343.808	343.808	6382.459	6382.458879
6	70.165	0.000	0.907	21.031	0.000	19.075	2.000	38.151	363.867	727.734	6940.872	13881.74355
7	84.198	0.000	0.958	21.031	0.000	20.148	1.000	20.148	405.937	405.937	8178.783	8178.783035
8	98.231	0.000	0.983	21.031	0.000	20.674	2.000	41.347	427.401	854.801	8835.939	17671.87819
9	112.26	0.050	0.907	21.031	1.052	19.075	1.000	19.075	403.985	403.985	8152.035	8152.034912
10	126.29	0.126	0.655	21.031	2.650	13.775	2.000	27.551	262.771	525.541	4412.836	8825.671574
11	140.33	0.368	0.000	21.031	7.729	0.000	0.500	0.000	0.000	0.000	0.000	0
								221.216		4231.3448		77670.4804

Equations for the spreadsheet are given in appendix 6. Models such as the one shown in this chapter can give a reliable indication, of the loads that act on a marine propeller. However they must be used critically in view of the accuracy of the input parameters and verified earnestly with practical experience. Some factors are difficult or impossible to model accurately, such as the wake field the propeller has to operate in. Certain empirically derived parameters have been shown to be good approximations, such as the length of the thrust and torque moment arms. Full scale testing [Carlton 1980] has shown a 90% correlation with the theoretical cantilever prediction, thus enabling some considerable confidence to be placed in the method.

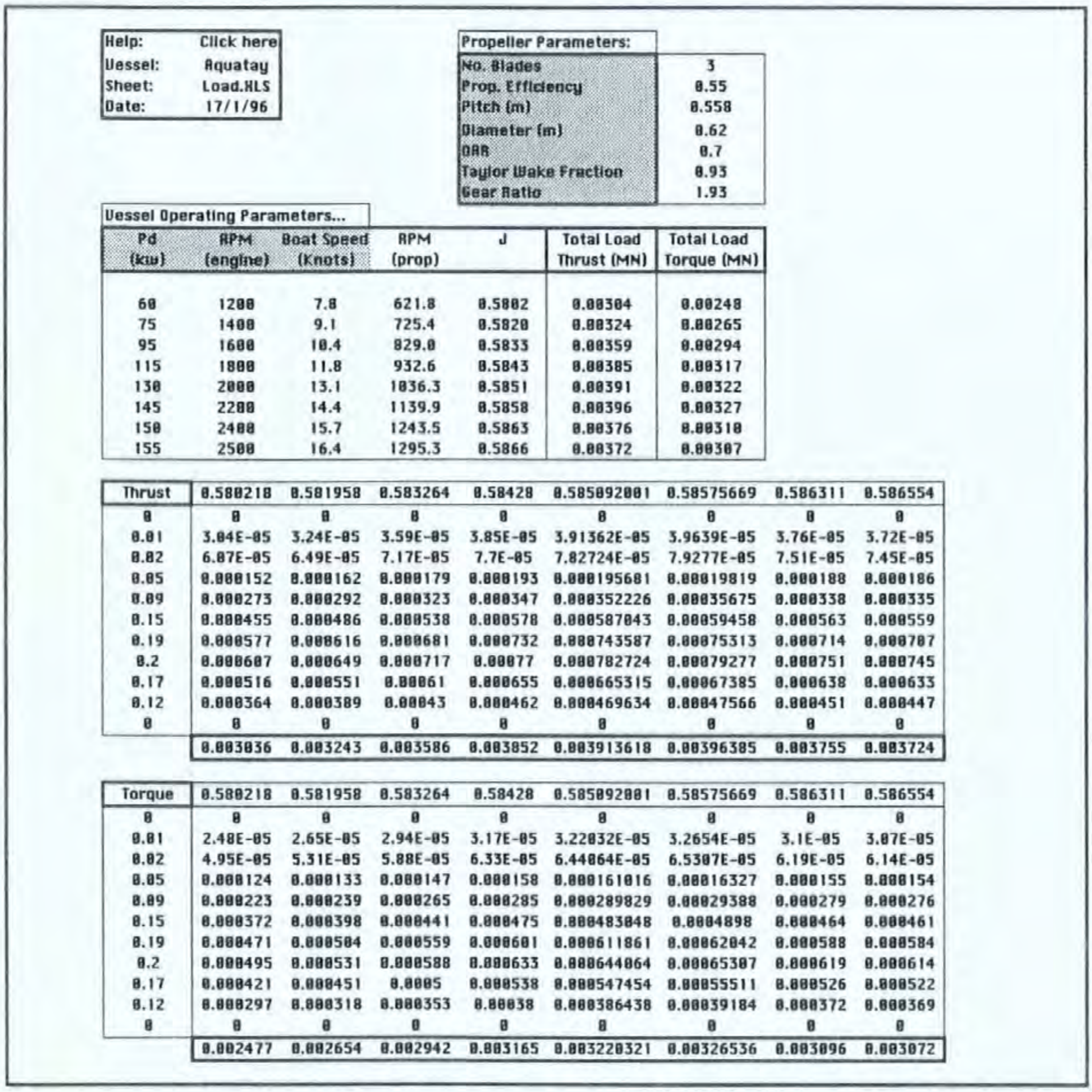
6.5 Finite element analysis.

6.5.1. Propeller selection.

The Aquatay propeller subject to the manufacturing investigation discussed in chapter 4 was used as a basis for the next stage of the model. Whilst FEA is a generic modelling process, using this particular propeller was convenient, as data from sea trials would be readily available when this work is continued.

In order to determine the coordinates that describe the geometry of the propeller for input into the pre–processing module of the FEA, the unconventional approach was to take "slices" of a previously moulded composite blade. Blade sections were then transferred to paper where the co–ordinates could be determined. The propeller sections are included in appendix 8. The FEA mesh is shown in figure 6.18, the thickness of the propeller sections and the corresponding FEA elements are specified in the data file (AQTH.dat), also in appendix 8.

Spreadsheet 6.3 Load calculations for FEA.



Help:	Click here
Vessel:	Aquatay
Sheet:	Load.XLS
Date:	17/1/96

Propeller Parameters:	
No. Blades	3
Prop. Efficiency	0.55
Pitch (m)	0.558
Diameter (m)	0.62
DAR	0.7
Taylor Wake Fraction	0.93
Gear Ratio	1.93

Vessel Operating Parameters...

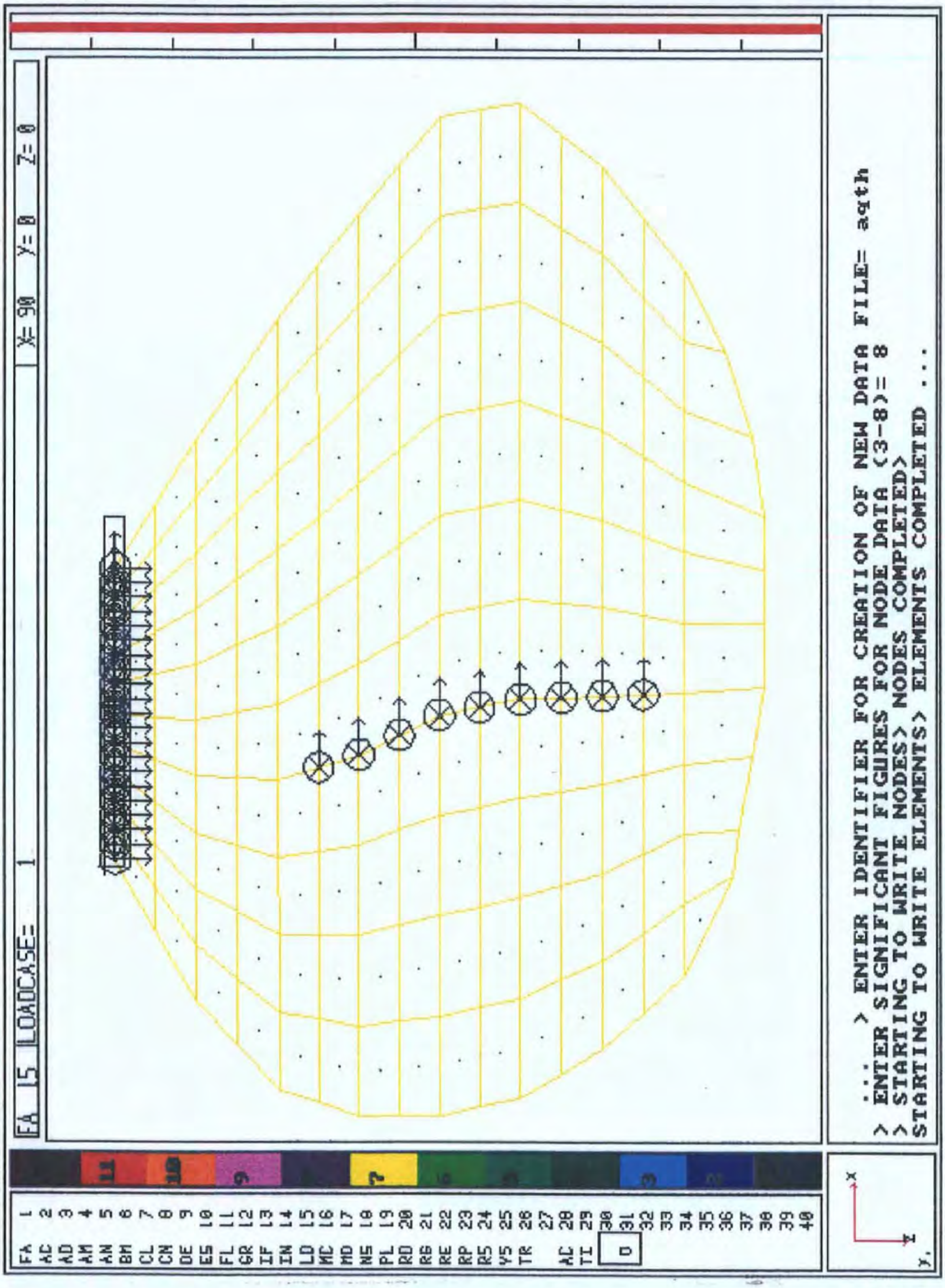
Pd (kw)	RPM (engine)	Boat Speed (Knots)	RPM (prop)	J	Total Load Thrust (MN)	Total Load Torque (MN)
60	1200	7.8	621.8	0.5802	0.00304	0.00248
75	1400	9.1	725.4	0.5820	0.00324	0.00265
95	1600	10.4	829.0	0.5833	0.00359	0.00294
115	1800	11.8	932.6	0.5843	0.00385	0.00317
130	2000	13.1	1036.3	0.5851	0.00391	0.00322
145	2200	14.4	1139.9	0.5858	0.00396	0.00327
150	2400	15.7	1243.5	0.5863	0.00376	0.00310
155	2500	16.4	1295.3	0.5866	0.00372	0.00307

Thrust	0.580218	0.581958	0.583264	0.58428	0.585092001	0.58575669	0.586311	0.586554
0	0	0	0	0	0	0	0	0
0.01	3.04E-05	3.24E-05	3.59E-05	3.85E-05	3.91362E-05	3.9639E-05	3.76E-05	3.72E-05
0.02	6.07E-05	6.49E-05	7.17E-05	7.7E-05	7.82724E-05	7.9277E-05	7.51E-05	7.45E-05
0.05	0.000152	0.000162	0.000179	0.000193	0.000195681	0.00019819	0.000188	0.000186
0.09	0.000273	0.000292	0.000323	0.000347	0.000352226	0.00035675	0.000338	0.000335
0.15	0.000455	0.000486	0.000538	0.000578	0.000587043	0.00059458	0.000563	0.000559
0.19	0.000577	0.000616	0.000681	0.000732	0.000743587	0.00075313	0.000714	0.000707
0.2	0.000607	0.000649	0.000717	0.00077	0.000782724	0.00079277	0.000751	0.000745
0.17	0.000516	0.000551	0.00061	0.000655	0.000665315	0.00067385	0.000638	0.000633
0.12	0.000364	0.000389	0.00043	0.000462	0.000469634	0.00047566	0.000451	0.000447
0	0	0	0	0	0	0	0	0
	0.003036	0.003243	0.003586	0.003852	0.003913618	0.00396385	0.003755	0.003724

Torque	0.580218	0.581958	0.583264	0.58428	0.585092001	0.58575669	0.586311	0.586554
0	0	0	0	0	0	0	0	0
0.01	2.48E-05	2.65E-05	2.94E-05	3.17E-05	3.22032E-05	3.2654E-05	3.1E-05	3.07E-05
0.02	4.95E-05	5.31E-05	5.88E-05	6.33E-05	6.44064E-05	6.5307E-05	6.19E-05	6.14E-05
0.05	0.000124	0.000133	0.000147	0.000158	0.000161016	0.00016327	0.000155	0.000154
0.09	0.000223	0.000239	0.000265	0.000285	0.000289829	0.00029388	0.000279	0.000276
0.15	0.000372	0.000398	0.000441	0.000475	0.000483048	0.0004898	0.000464	0.000461
0.19	0.000471	0.000504	0.000559	0.000601	0.000611861	0.00062042	0.000588	0.000584
0.2	0.000495	0.000531	0.000588	0.000633	0.000644064	0.00065307	0.000619	0.000614
0.17	0.000421	0.000451	0.0005	0.000538	0.000547454	0.00055511	0.000526	0.000522
0.12	0.000297	0.000318	0.000353	0.00038	0.000386438	0.00039184	0.000372	0.000369
0	0	0	0	0	0	0	0	0
	0.002477	0.002654	0.002942	0.003165	0.003220321	0.00326536	0.003096	0.003072

Figure 6.18 Loads and restraints on the propeller FE mesh

Restraints are shown at the top of the figure, coinciding with the propeller root at 20% radius. Loads are shown distributed radially.



```
... > ENTER IDENTIFIER FOR CREATION OF NEW DATA FILE= aqth
> ENTER SIGNIFICANT FIGURES FOR NODE DATA (3-8)= 8
> STARTING TO WRITE NODES> NODES COMPLETED>
STARTING TO WRITE ELEMENTS> ELEMENTS COMPLETED ...
```

6.5.2 Modelling the propeller blade.

Certain idiosyncrasies exist within the PAFEC modelling environment that should be considered whilst the model is being set up.

- Quadrilateral elements are not permitted to have corner node angles greater than 155°.
- The through thickness direction of each element of the structure to be modelled must be aligned with the global Z axis, as fibre angles are expressed relative to the X axis. Thus the global axis must be rotated so that this is true, (figure 6.19). (A transformation file within PAFEC is used to achieve this).

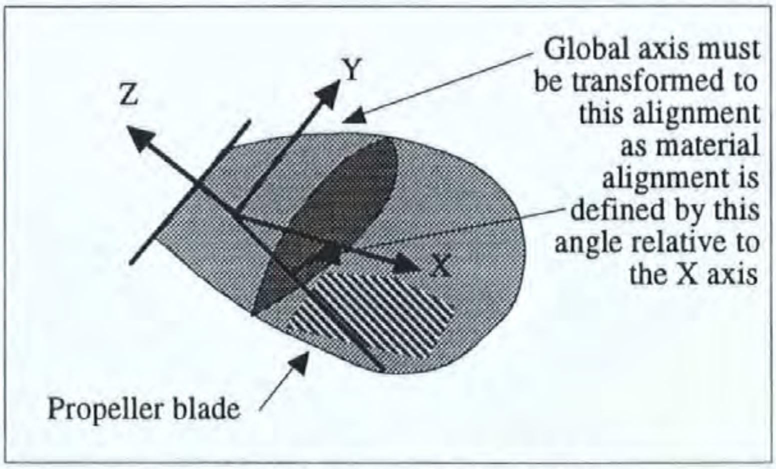


Figure 6.19 Alignment of global FEA axis.

Once these are considered the element mesh is created from the geometry determined in section 6.5.1. The loads are applied and encastré restraints imposed at the propeller root. The laminate structure of each element was approximated in that the anisotropy and stacking sequence of plies were defined as a single ply the same thickness as each element with directional properties. This worked for the earlier plate validation, however, whilst coupling effects are considered with this approach inter–laminar shear effects are not. This approach saved a considerable amount of time at the data input stage and would be modified at a later stage if appropriate.

6.5.3 Material Configuration for the analysis.

In order to maximise the efficiency change, the pitch diameter ratio and therefore the elastic deformation under load of the propeller must be maximised. In order to achieve this, the following material configurations were modelled:

- Manganese Bronze, included as a bench mark.

- Uni–directional E–glass at 50% volume fraction oriented at 0° to 180° to the X axis in 10° increments.

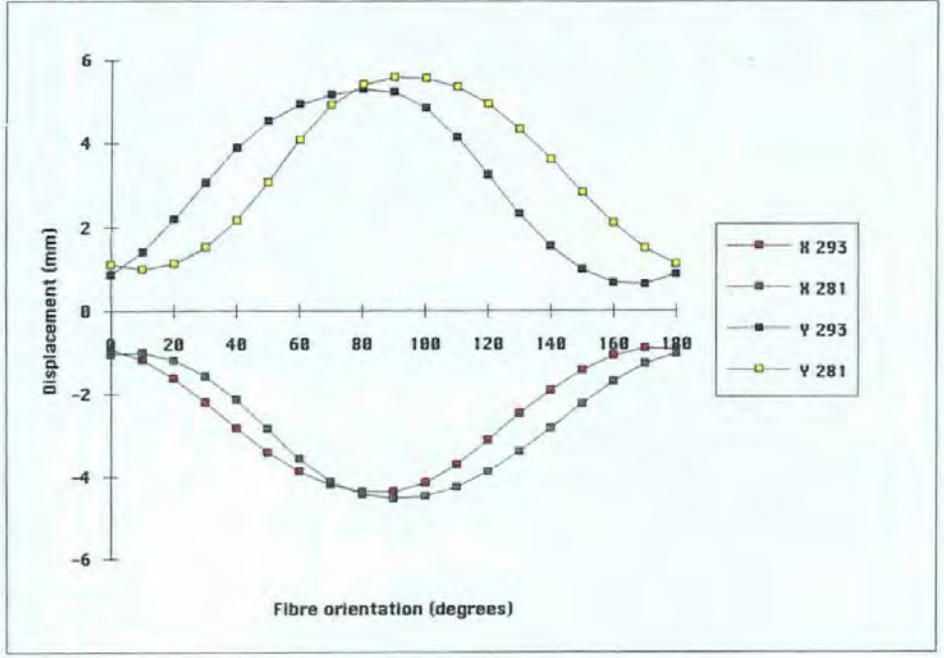
Spreadsheet 6.4 Nodal displacements and transformations.

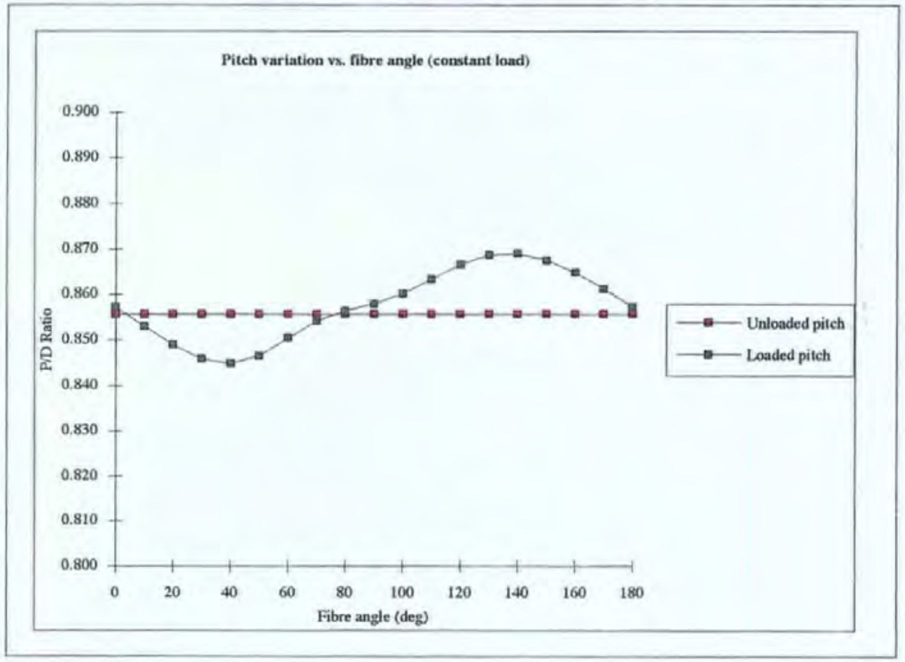
Displacements at Nodes 293 and 281

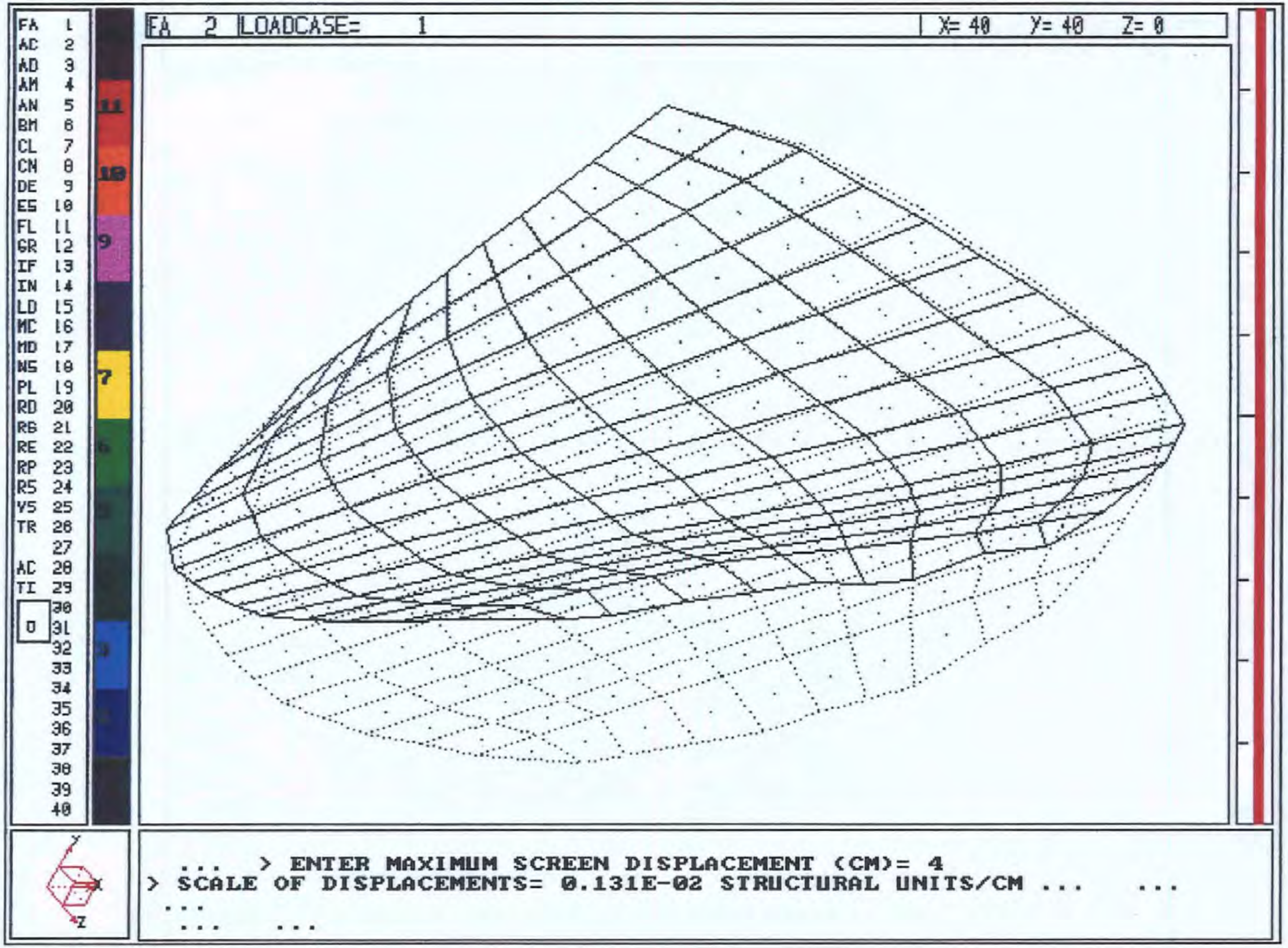
Degrees	X 293	X 281	Y 293	Y 281	Z 293	Z 281
0	-0.9198	-1.0283	0.873	1.1191	-0.2586	1.3918
10	-1.1711	-1.0007	1.4096	0.9925	-0.1978	1.3473
20	-1.6211	-1.1826	2.1871	1.1234	-0.1661	1.5644
30	-2.1985	-1.5641	3.0652	1.5144	-0.1785	2.1333
40	-2.8236	-2.1325	3.8918	2.1711	-0.2515	2.9424
50	-3.4082	-2.8418	4.5362	3.0785	-0.3836	3.929
60	-3.8708	-3.562	4.9346	4.0909	-0.545	4.9042
70	-4.1867	-4.1182	5.1606	4.9218	-0.6843	5.643
80	-4.3615	-4.4278	5.2878	5.4027	-0.7695	6.0461
90	-4.3629	-4.5252	5.2261	5.5796	-0.8109	6.1697
100	-4.1493	-4.4644	4.8528	5.5547	-0.8295	6.087
110	-3.7134	-4.2502	4.1542	5.3493	-0.8287	5.7984
120	-3.1147	-3.8787	3.2417	4.9414	-0.8029	5.2947
130	-2.4777	-3.3859	2.3154	4.3442	-0.7479	4.6226
140	-1.9044	-2.8244	1.5402	3.6187	-0.6652	3.8541
150	-1.4265	-2.2367	0.9826	2.8389	-0.561	3.049
160	-1.0751	-1.6903	0.6734	2.0986	-0.4486	2.3015
170	-0.8946	-1.2675	0.6321	1.4995	-0.3439	1.7229
180	-0.9198	-1.0283	0.873	1.1191	-0.2586	1.3918

Degrees	X' 293	X' 281	Y' 293	Y' 281	Z' 293	Z' 281
0	-148.9198	223.9717	-116.127	33.1191	216.7414	218.3918
10	-149.1711	223.9993	-115.5904	32.9925	216.8022	218.3473
20	-149.6211	223.8174	-114.8129	33.1234	216.8339	218.5644
30	-150.1985	223.4359	-113.9348	33.5144	216.8215	219.1333
40	-150.8236	222.8675	-113.1082	34.1711	216.7485	219.9424
50	-151.4082	222.1582	-112.4638	35.0785	216.6164	220.929
60	-151.8708	221.438	-112.0654	36.0909	216.455	221.9042
70	-152.1867	220.8818	-111.8394	36.9218	216.3157	222.643
80	-152.3615	220.5722	-111.7122	37.4027	216.2305	223.0461
90	-152.3629	220.4748	-111.7739	37.5796	216.1891	223.1697
100	-152.1493	220.5356	-112.1472	37.5547	216.1705	223.087
110	-151.7134	220.7498	-112.8458	37.3493	216.1713	222.7984
120	-151.1147	221.1213	-113.7583	36.9414	216.1971	222.2947
130	-150.4777	221.6141	-114.6846	36.3442	216.2521	221.6226
140	-149.9044	222.1756	-115.4598	35.6187	216.3348	220.8541
150	-149.4265	222.7633	-116.0174	34.8389	216.439	220.049
160	-149.0751	223.3097	-116.3266	34.0986	216.5514	219.3015
170	-148.8946	223.7325	-116.3679	33.4995	216.6561	218.7229
180	-148.9198	223.9717	-116.127	33.1191	216.7414	218.3918

Degrees	• Unloaded Pitch (in)	NAB Loaded Pitch (in)	FRP Loaded Pitch (in)
0	0.856	0.856	0.857
10	0.856	0.856	0.853
20	0.856	0.856	0.849
30	0.856	0.856	0.846
40	0.856	0.856	0.845
50	0.856	0.856	0.847
60	0.856	0.856	0.850
70	0.856	0.856	0.854
80	0.856	0.856	0.856
90	0.856	0.856	0.858
100	0.856	0.856	0.860
110	0.856	0.856	0.863
120	0.856	0.856	0.867
130	0.856	0.856	0.869
140	0.856	0.856	0.869
150	0.856	0.856	0.868
160	0.856	0.856	0.865
170	0.856	0.856	0.861
180	0.856	0.856	0.857







```
 ...   > ENTER MAXIMUM SCREEN DISPLACEMENT (CM)= 4
> SCALE OF DISPLACEMENTS= 0.131E-02 STRUCTURAL UNITS/CM ...    ...
 ...
 ...    ...
```

Figure 6.20 Propeller mesh deformation.

6.5.4 FEA Output.

The nodal displacements given by PAFEC are shown in spreadsheet 6.4. (nodal displacements are held in the file AQTH.o07). Figure 6.20 shows the deformed (exaggerated) propeller mesh. The pitch change at this radius can be determined by simple geometric transformation:-

1. Select tip nodes at 0.7 radius on the blade periphery.
2. Read displacements from file AQTH.o07.
3. Perform geometric transformations that express the angle of twist of a line joining the 2 nodes.
4. Calculate the pitch change.
5. Plot.

These transformations are performed in spreadsheet 6.4. (Equations given in appendix 6). The pitch change is expressed by convention as a pitch / diameter ratio, (P/D).

6.5.5 Fibre angle that gives the most bend twist coupling.

The following can be seen from the graphs on spreadsheet 6.4:-

- The fibre angles (θ_f) that give greatest pitch change for this particular propeller are 40°and 130°.
- The fibre angles for zero pitch change are 5°, 78°and 185°.
- The pitch change is small; change in pitch diameter ratio ($\Delta P/D$) is 0.856 to 0.845.

At this stage this pitch change is too small to make any worthwhile difference to the performance of the propeller. Thus in order to produce a further pitch change the fibre volume fraction must be reduced to give greater flexibility, as the geometry of the propeller is fixed. However, the angle θ_f may be volume fraction dependent, this must be established before further FEA models are run.

6.6 The influence of fibre volume fraction.

6.6.1 The angle of maximum bend/twist coupling.

From the preliminary finite element analysis, it can be seen that for a given propeller geometry and uni-directional laminate, a fibre angle exists that gives the maximum twist for a given bending load. Figure 6.21. shows these angles to be 40° and 130°.

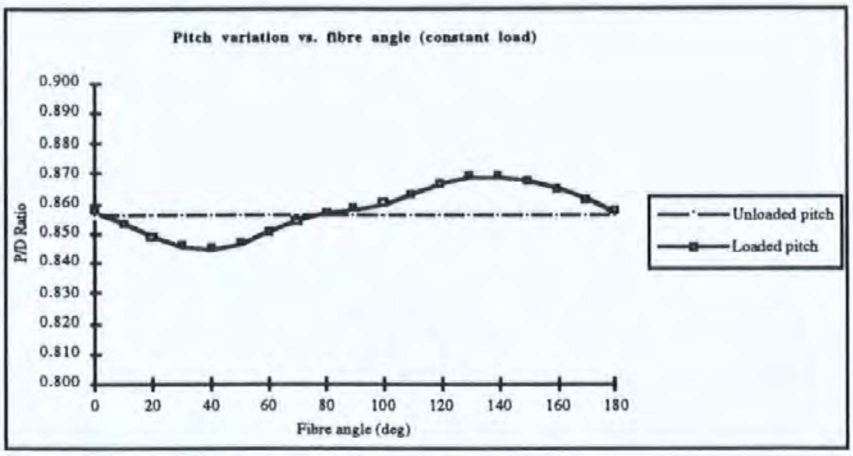


Figure 6.21 Uni-directional fibre angle that gives maximum propeller blade twist.

In order to maximise this laminate twist and therefore achievable P/D ratio change, other parameters must also be considered. The fibre volume fraction and the proportion of fibre required perpendicular to the primary uni-directional load bearing fibre must be varied to determine their influence on the optimum fibre angle. The relationship between these fundamental parameters must be established.

6.6.2 The influence of fibre volume fraction.

To provide some initial insight a glass/epoxy plate was modelled that had the properties outlined in table 6.2. Genlam[1] general laminate analysis software was used to determine the elastic deformations of a family of laminates, where each laminate was characterised by varying fibre angle and volume fraction.

Fibre	E glass
Resin	Epoxy
Ply thickness	0.125mm
N° plies	20
Load type	Uniform moment
Load	1Nm
Plate dimensions	Unit (1m X 1m)
Anisotropy	Uni-directional

Table 6.2 Modelled laminate properties.

Output data for the elastic deformations is expressed as a curvature coefficient "K" value,

---

[1] Genlam, General laminate analysis software from Think Composites.

where "K" is the inverse of the radius of curvature, table 6.3.

K value	Interpretation
K1	1/radius of curvature X direction
K2	1/radius of curvature Y direction
K6	1/radius of curvature XY direction (twist)

Table 6.3 K value interpretation.

The numerical data from the model is given in appendix 8; however the following figures 6.22 - 6.24 show the graphical output.

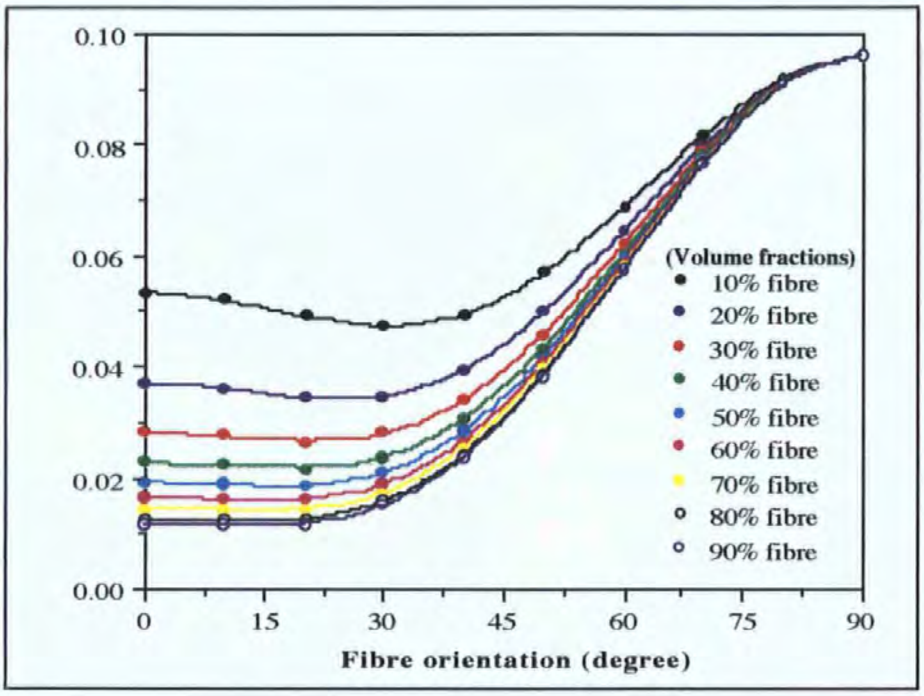


Figure 6.22 Curvature coefficient K1 vs. fibre orientation for various fibre volume fractions.

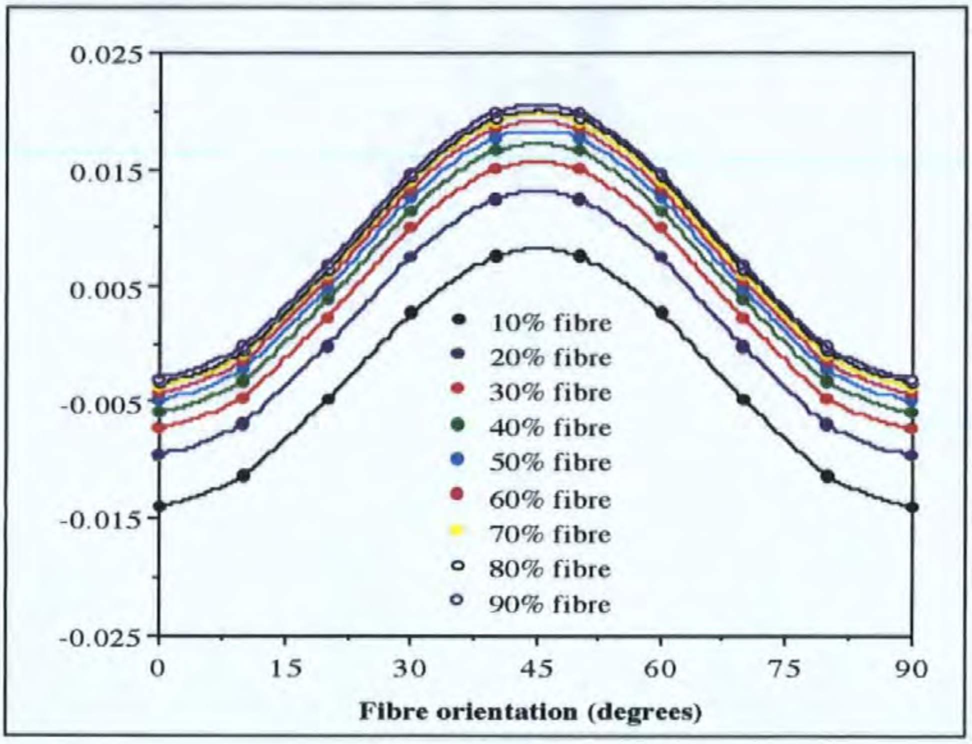


Figure 6.23 Curvature coefficient K2 vs. fibre orientation for various fibre volume fractions.

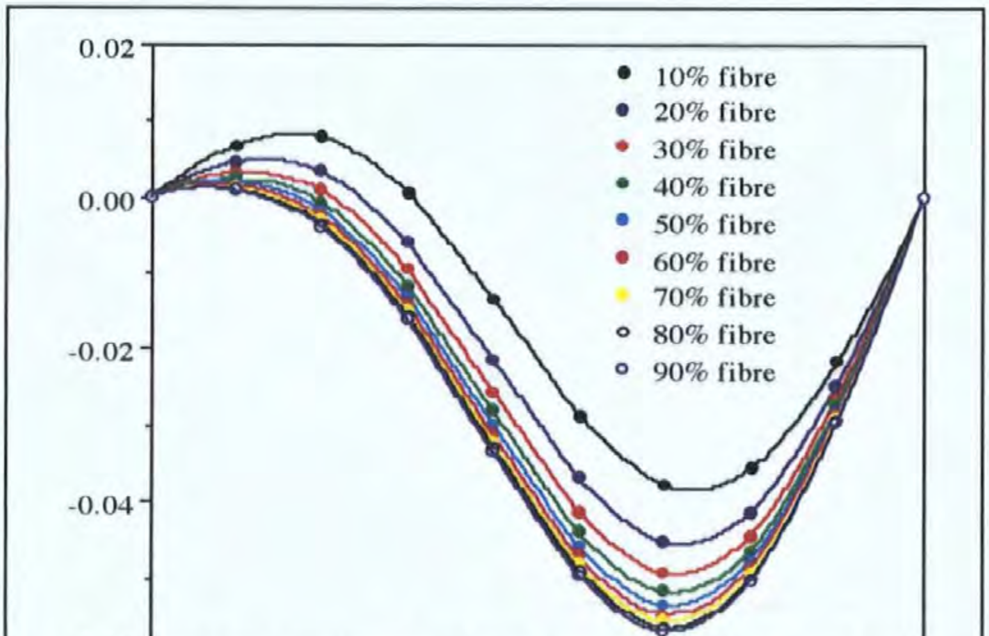


Figure 6.24 Curvature coeff. K6 vs. fibre orientation for various fibre volume fractions.

6.6.3 Interpretation of the graphical output.

All three curvature coefficient graphs have been given for completeness.

K1 gives a maximum curvature at 90° fibre orientation, where the matrix dominates and is independent of fibre volume fraction.
K2 gives a maximum curvature at 45° and this angle is independent of volume fraction.
K6 is the coefficient that indicates any bend/twist coupling:

- When K6 is zero, no bend/twist coupling exists, this is seen at fibre angles of 0° and 90° and some intermediate values.
- The curvatures at angles between 0° and 30° are possibly caused by internal stresses in the laminate and are small.
- The maximum magnitude of curvature varies between 60° and 65° and is slightly dependent on fibre volume fraction.

Over the range of usable fibre volume fractions, these differences described above are small, and can be ignored. Thus the fibre angle that gives the maximum bend/twist coupling is for practical purposes independent of fibre volume fraction.

6.6.4 The influence of fibres perpendicular to the primary uni-directional load bearing fibres.

Laminated composite structures often have complex loading regimes that require more than uni-axial fibre placement. Such is the case with propeller blades, where some proportion of fibres placed at 90° to the major load path are required. Thus the effect of these on the fibre angle that gives the maximum bend/twist coupling must be determined.

To do this a comparison was made, again by modelling a glass/epoxy plate with Genlam the same as the previous example, the three laminates investigated are given in table 6.5.

Laminate	**1**	**2**	**3**
% O° fibre	50	37.5	25
% 90° fibre	0	12.5	25
Fibre volume fraction	50	50	50

Table 6.5 Laminates for the orthotropic comparison.

Again, all three curvature coefficients were plotted for completeness and these are shown in figures 6.25-6.27. The numerical data and laminate data is given in appendix 8.

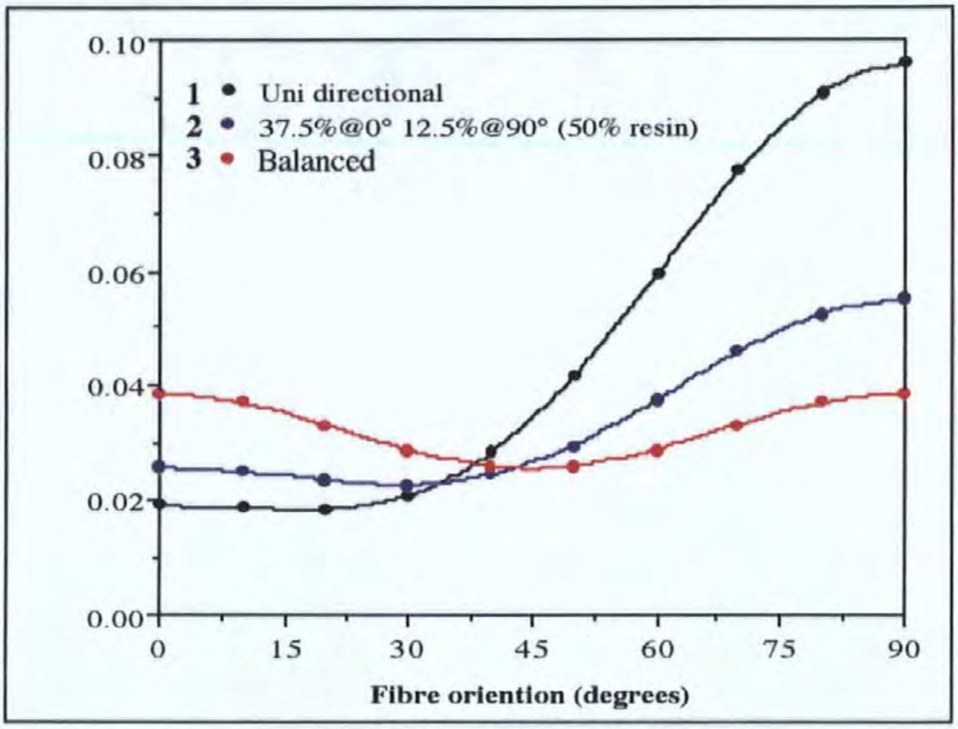


Figure 6.25 Curvature coefficient K1 vs. fibre orientation for different levels of anisotropy.

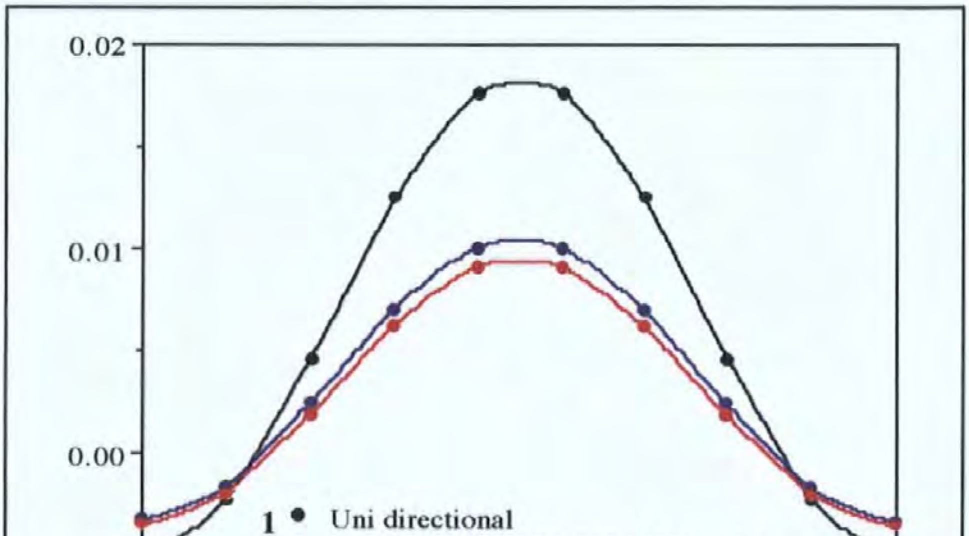


Figure 6.26 Curvature coefficient K2 vs. fibre orientation for different levels of anisotropy.

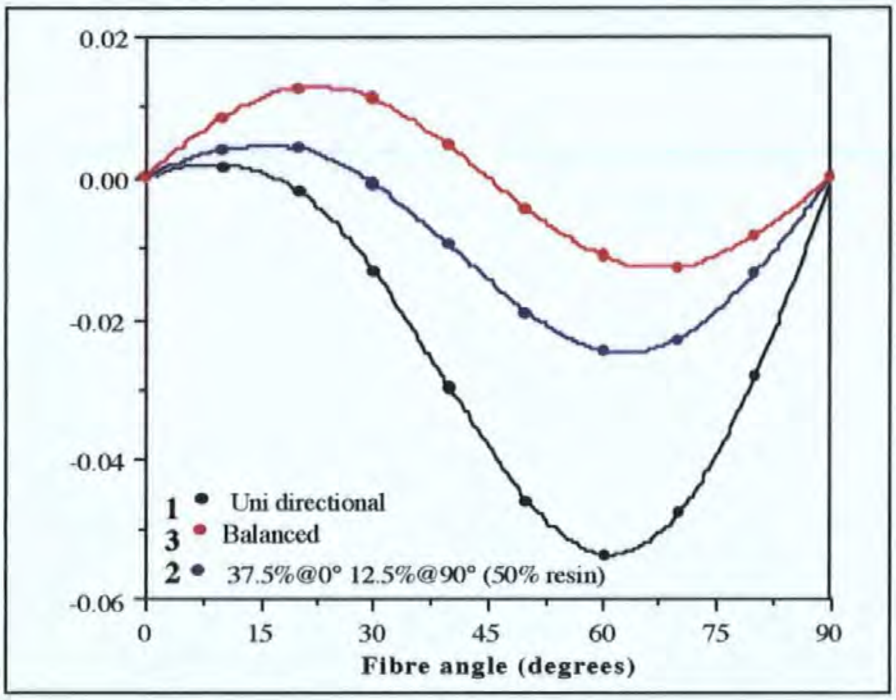


Figure 6.27 Curvature coefficient K6 vs. fibre orientation for different levels of anisotropy.

6.6.5 Interpretation of graphical output.

The important graph is figure 6.27 where curvature coefficient K6 gives the indication of any influence the extra fibre has on the fibre angle that gives maximum bend/twist coupling. The fibre angle shifts from 60° for the fully uni-directional laminate, to 67.5° for the fully orthotropic laminate. Thus the addition of small quantities of fibre perpendicular to the primary load bearing fibre will have a small effect and may be considered too small to be of any consequence.

6.7 Prediction of ΔP/D vs. fibre volume fraction.

Thus, in order to pursue further the goal of maximum ΔP/D, further FEA was carried out, this time the materials data file was modified so that three different fibre volume fractions could be modelled. These are summarised in table 6.6.

	1	2	3
Fibre orientation	40°	40°	40°
Fibre alignment	UD	UD	UD
Fibre volume fraction	25.00%	50.00%	75.00%

Table 6.6 Material modifications.

Apart from these modifications, the FEA model was run again with the same input parameters. The nodal displacements were treated in the same manner to obtain the ΔP/D. Figure 6.28 shows the effect of reducing the fibre content on ΔP/D.

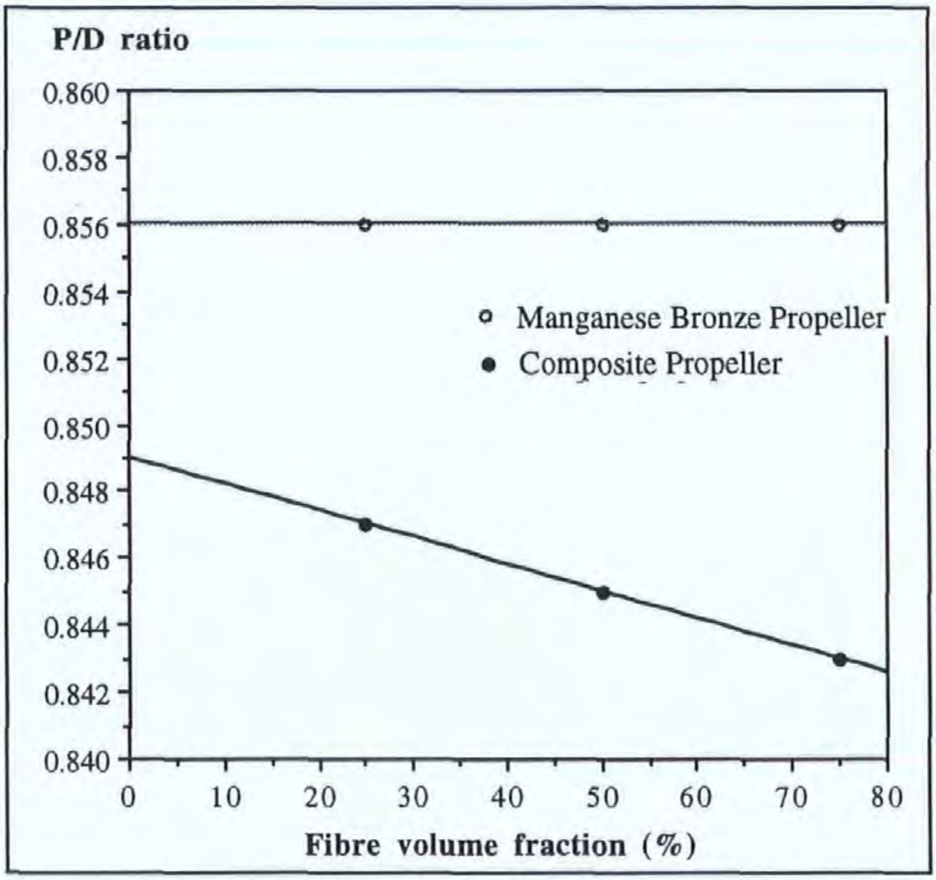


Figure 6.28 Change in P/D ratio for different fibre volume fractions.

Figure 6.28 illustrates the stiffness of the composite propeller and shows only a small change in pitch. In fact, it is clear from the graph that the bend/twist coupling is actually greater at higher volume fractions. This is expected, as the fibre volume fraction tends to zero the blade becomes more isotropic. The manganese bronze propeller can be considered the bench mark. This exhibited zero twist under load and it was subject to the same loading as the composite propeller.

These geometric changes in response to the predicted propeller loads are small and will have a negligible hydrodynamic effect. This is an important conclusion, the propeller considered for this model is near geometrically to a standard B-Series propeller. Thus for propellers of this type which are inherently stiff because of their geometry, alternative approaches must be adopted. In particular considering blades of thinner sections.

6.8 Summary.

It has been shown that for a propeller of a particular geometry, designed with a given uni-directional laminate, a fibre angle can be defined by the finite element analysis procedure outlined, that gives a maximum bend/twist coupling relationship. This angle for practical purposes has been shown to be:

- Independent of fibre volume fraction.
- Only marginally affected by the addition of small quantities of fibre perpendicular to the major reinforcing fibres.

This chapter has considered the possibility that a propeller made from composite materials that has bend/twist coupling deformation properties, would have a significant hydrodynamic performance advantages. It is clear that this material phenomenon does exist and that a variable pitch propeller is beneficial.

However, what has also become apparent from the modelling, is the blades of conventional propeller geometries are very stiff. (the propeller modelled here is a typical example). The maximum pitch change predicted from the example researched here, is only 0.3 inch.

Thus, in order to exploit the hydrodynamic advantages possible with the use of highly anisotropic material, a more compliant blade must be produced by using a thinner blade section and a composite with a lower modulus. When this is achieved, performance improvements will be available for propulsion systems that are required to operate below the optimum matching point for a traditionally stiff propeller.

Chapter Seven

Discussion and conclusions.

7.1 Project overview.

7.1.1 Aims of the thesis.

The purpose of this work has been to investigate the hypothesis that the novel approach of manufacturing marine propellers from moulded, continuous fibre, anisotropic, polymer composite materials has some significant advantages. These include the following:

1. That there are economic benefits in producing certain propeller types in composite.
2. That it is possible to effectively manufacture marine propellers in composite materials.
3. That they can be designed in composite with sufficient strength.
4. That they have sufficient longevity.
5. And that there is the potential for hydrodynamic performance advantages.

Each area was studied systematically in order to prove or disprove each of the ideas put forward.

7.1.2 Economics.

A fundamental issue with the manufacture of marine propellers is that each propeller must be designed to match the powering and speed requirements of the vessel for which it is intended. This means that there are a large number of different propeller designs, many of which are "one offs" and there are rarely large production runs of any one design. The exception to this is with outboard motor propellers and some smaller "stock" AB2 propellers, where large numbers of one design are produced. The economic analysis is presented in chapter 3 and does indicate that for relatively small production runs, a composite propeller manufactured by RTM would give a viable economic margin. This is largely dependent on the cost of the tooling, which, as argued in chapter 3 and discussed in the next section can be produced cheaply. And as the RTM industry matures, the process will become more cost effective still.

The material cost for AB2 and HTB1 propellers is usually about 5% of the propeller market price. For 50% (by volume) glass epoxy composites this figure is nearer 4%. This material cost is in favour of the composite propeller. The studies of this thesis indicate that for even small numbers of 12 or 15 propellers of non complex geometries (eg 0.5 DAR and 3 blades), the margin is likely to be improved over the equivalent metallic propeller.

7.1.3 Manufacture.

Four different designs of propeller were produced successfully during this project. Because of the complex laminate configurations of the propeller shape and thick root sections, large amounts of fibre are required. This most conveniently comes in heavy weight fabrics, which required some important process optimisation.

What has become clear through the process experimentation is that some fibre forms exhibit very different flow characteristics. Experimentation demonstrated that with two different fibre arrangements the difference in fill time for the same mould with resin can be up to 10 times as long, even though the fibre content is kept the same. With the complex shape of the propeller, it is sometimes difficult to control precisely the position of the fibre in the mould and therefore the fibre fraction in parts of the blade. Using a fibre pack that has good resin flow attributes has allowed a far greater chance of sound mouldings. This type of process optimisation meant that successful propeller manufacture was more probable.

Incorporating a metallic shaft interface into the composite propeller has proved successful. It has been shown by experience that this style of interface is very conveniently incorporated at the fibre layup stage. Experience with the propeller at operating at sea has shown no measurable mechanical weakness with this attachment after 200 hours of logged use.

Manufacturing technology seldom stands still, the following areas indicate the likely developments in composite manufacturing technology that will facilitate the future production of composite propellers.

1. NC machining of mould tools from a thermo plastic, which can then be recycled.
2. Low cost RTM tooling skins that fit into standard clamping and porting systems.
3. Increasing use of rapid prototyping technology, primarily for producing patterns and moulds.
4. Robotically controlled spray up composite tools.

Some new metallic propeller designs require re-pitching after initial sea trials. This is not possible with composite propellers, (although, if the composite is heated and deliberately distorted, a small permanent geometry change is possible. This, however is not an option for major pitch changes). For some non-specalised propellers which will not use hydro-elastic tailoring, prototyping could be carried out in metal and when the design is correct the production of the composite propeller follows. A common problem in the propeller installation for production powerboats occurs when the final hull weight of the vessel varies from that of the original specified design weight. This results from inconsistent manufacture of the composite parts of the vessel. With this variation in weight and consequently the powering of the vessel required for a given speed, the propellers for these vessels often have to be re-pitched.

This is a related problem that comes from poor manufacturing control of the hull laminate manufacture that the composite boat building industry should address if a standard composite propeller is to be supplied to a standard vessel. However, a more compliant hydro-elastically tailored propeller would be less sensitive to variations in final vessel weight.

7.1.4 Propeller strength.

Boat tests have shown that the propellers manufactured so far have sufficient strength for the usual operating conditions the vessel experiences. The main evidence for this was from the testing on the vessel "Pandora" where a composite propeller was used over a period of 9 months, accumulating nearly 200 hours running time, until the propeller failed on impact with a solid object. Prior to this the regular inspections of the propeller could not detect any visual sign that the propeller was not strong enough or degrading with use. The fact that on no occasion during any of the boat trials with the composite propeller was there any loss of performance, indicates that the composite propellers were well able to absorb the power delivered to them.

7.1.5 Propeller longevity.

Incidents were recorded where one of the propellers had a 15 mm diameter polypropylene rope wrapped around it. On another occasion an electrical cable became entangled. Apart from some minor abrasion on one blade edge and around the boss, neither incident caused any significant damage or fall off in performance. However, as testing experience was gathered it became apparent that the propellers tested do not seem to have sufficient toughness for certain levels of impact damage.

On the two occasions that catastrophic propeller failures occurred, very little information was available. The objects that struck each propeller were not recovered. The first propeller lost all three blades and the second propeller lost two blades. Before significant conclusions can be drawn, more data must be gathered. Whilst there are other issues that pertain to the composite propeller longevity, that are discussed presently, appropriate propeller toughness is the main issue that requires further research. A further crucial question that remains unanswered is what damage would the metal propeller have suffered with the same impact.

Propellers of most descriptions experience a degree of cyclic loading. However there was no evidence to suggest that fatigue was primarily the cause for any of the two failures.

7.1.6 Hydrodynamic performance.

The introduction of an anisotropic material to the marine propeller allows some design possibilities that metals do not have. Initially it was recognised that by using a material of a different modulus there may be a performance difference. In order to investigate this, the testing on "Pandora" was carried out. The vessel speed for given RPM and the thrust generated in the bollard pull condition indicated that there was no performance penalty for this vessel using a propeller that had more compliant blades than the metal propeller it had replaced.

Secondly, the possibility of introducing a hydrodynamic advantage to the propeller by introducing directionally elastic materials was investigated. By designing a blade that was flexible to allow a small pitch change as the load increased, in theory some efficiency gain may be possible. This can either be by allowing the efficiency envelope to widen slightly, or allowing a little reserve pitch for acceleration before the propeller reaches the matching point. (See figure 6.4).

The work carried out in the towing tank and cavitation tunnel confirmed that a small change in the shape of the efficiency envelope was possible by changing the flexural characteristics of the propeller. However the FEA modelling confirmed that in order for this idea to have any significance the propeller blade must be far more compliant. This must be achieved by using a material with a lower modulus and a propeller with a thinner blade section.

7.2 Immediate applications.

It is evident from the work that has been done, that some specific propeller types are marketable and very little research is required to realise this. Although not the main thrust of this thesis, outboard motor propellers made from continuous fibre composite materials have some clear benefits over the conventional materials used for these types of propeller. These propellers are characterised by high volume production in quantities that have allowed injection moulding to be economic. However, a continuous fibre composite allows mechanical stiffnesses and strengths not otherwise possible from glass filled thermoplastics. The innovative blade configurations explained in this thesis, manufactured cost effectively by RTM have shown significant technical and economic progress. To date no manufacturer has been identified who is producing continuous fibre composite outboard motor propellers.

Large numbers of manganese bronze propellers are produced as stock items. Generally these propellers are for displacement or semi–displacement vessels up to 40' in length. They are robust and they are for vessels of only moderate performance. Generally the propeller geometry is not highly critical. Resin transfer moulding is a low investment process and this propeller type lends itself to production in composite.

7.3 Future applications.

Certain vessel types are range limited. This is true of a number of vessels in the fleet of the Royal National Lifeboat Institution. (RNLI). The payload including fuel is limited. Thus any weight saving measures that allow more fuel to be carried thus extending the range of the vessel are beneficial. Composite propellers that weigh 25% of their metal counterparts in conjunction with other composite stern gear, will give some effective extension to the range of operation of these vessels.

Sophisticated, high performance propellers that require high geometric tolerances, thinner blade sections and stealth characteristics will benefit from the elastic tailoring that can best be produced in composite. It is this propeller type that has stirred the most interest from industry. Significant financial investments will be required to realise the clear potential available to this market sector.

7.4 Conclusions.

This thesis has shown that it should be possible to economically manufacture small, monolithic marine propellers of simple geometries in composite materials by resin transfer moulding. With some developments in tooling manufacture and the continuing maturing of resin transfer moulding an improved economic margin may be possible over certain types of metallic propeller. This has been well established. Also it is clear that the composite raw material costs are slightly cheaper than AB2 or HTB1.

A key manufacturing issue that must be addressed before a composite propeller will be manufactured by mainstream marine industries, is a cultural one. Most propeller manufacturers are expert in processing and casting metals, a process that has developed over many years. For most, the change to processing a different material is an unacceptably high risk, coupled with the perception that composite materials are too fragile.

The fundamental requirement for a successful composite propeller is to identify by how much the toughness must be increased. This requires a failure analysis as, the two catastrophic propeller failures occurred as a result of contact with an unidentified and unrecoverable solid object in the water. Some further work is necessary to study the statistical and mechanical nature of propeller impacts with solid objects. Laminates should be optimised for maximum toughness. The failure mode exhibited so far has shown the shedding of the whole of the propeller blade, rendering zero propulsion. A more effective failure mode would enable the blade to fail somewhere away from the root area, thus leaving some blade area still intact, thus allowing some propulsion.

In order that greater confidence can be placed in composite propellers as a viable method of propulsion, significantly more time must be logged at sea. Only when a large quantity of data is available will it be possible to prioritise the further issues of longevity. The marine industry is conservative, the concept of composite propellers must necessarily be sold on anecdotal evidence and experience as well as scientific rational.

The exploitation of propeller blades that have greater compliances for improved hydrodynamic efficiency should be studied further. This must be coupled with the development of effective failure models that enable determination of thinner blade sections. Thinner blade sections will inevitably lead to efficiency gains, however this must be looked at in the light of the toughness of the propeller structure.

A number of areas have been highlighted that require further generic research which have not been studied in this thesis. The following areas carry on from the work already undertaken they will contribute to the future effectiveness of composite propeller development:

- Water absorption.
- Fatigue in seawater.
- New shaft attachments.
- Cavitation erosion.
- Particle erosion.
- The use of low modulus resins.

The concept of a small, monolithic composite marine propeller is viable economically, should there be sufficient numbers to produce. The fundamental issue to solve is that of propeller toughness, this is not insurmountable but more intelligence is required pertaining to the nature of propeller impacts. When this is understood, then a more compliant blade can be introduced to gain some hydrodynamic advantage.

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Appendix 1

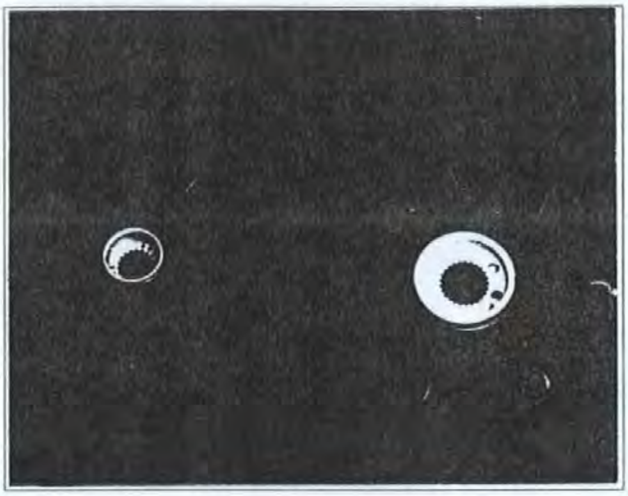
Composite propellers manufactured to date.

The use of composites in propellers produced to date.

A number of solutions have been put forward, for the redesign of the marine propeller by changing its material to composite. Although the wide spread use of composite propellers does not seem to have materialised yet, many are still at the development stage but given time successful designs will emerge.

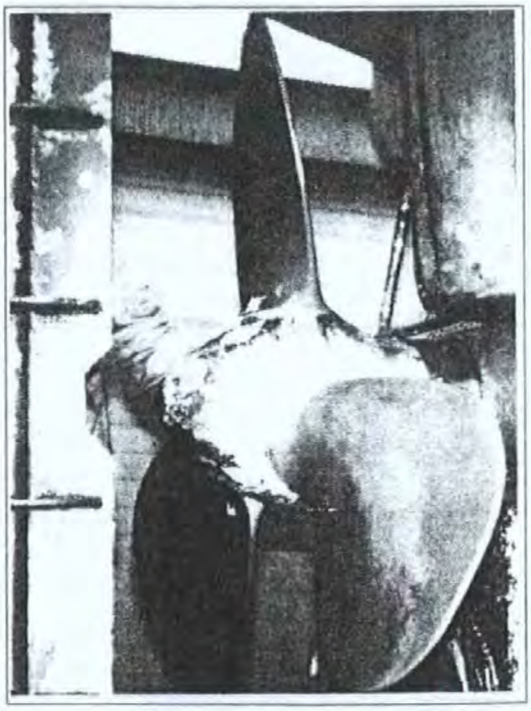
Torpedo Propellers[3]

Manufactured by: Reinhold Industries, Sante FE Springs, California, USA.
Year first produced: 1985.
Application: Torpedoes, military.
Size: 20/25 cm
Number of blades: 5/7.
Material: E glass reinforced polyester.
Process: Compression moulding.
Weight saving: 25%.
Cost saving: 55%
Size of production run: Many.
Particular advantages and design features:
Transparent to electronic detection, increase in performance, chemical inertness, direct retrofit for previous aluminium design, manufacturing consistency as the moulding process is not subject to tool wear like the previous process. The propeller is moulded in one piece.



"Flexprop"[4]

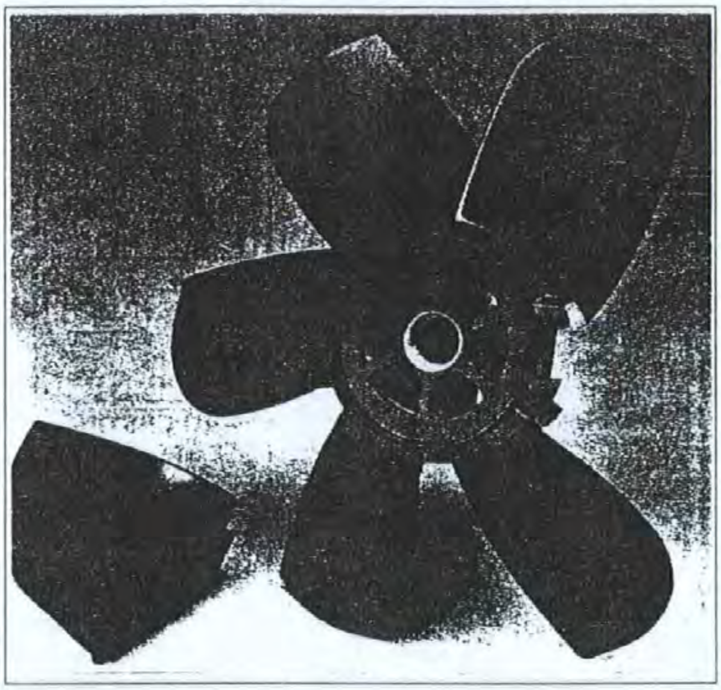
Manufactured by: Karskronavarvet, Sweden.
Year first produced: 1990, (development goes back 7 years before this).
Application: Military, submarines, civilian cruise vessels, ferries, RoRo bow thrusters.
Size: 2m.
Number of blades: 3.
Material: Not known other than "cheap of the shelf".
Process: Not known other than "simple and straight forward".
Weight saving: 80%
Size of production run: One offs.
Particular advantages and design features: Less vibration, 1/2 to 1/3 reduction in wake amplitude, reduction in load variations and fatigue, tests so far have shown a 6% increase in efficiency. The design features a load carrying spar in each blade, this transmits load to the bronze boss. Each blade is cemented to a bronze connecter that fits to the boss. So far the propeller is only for controlled pitch applications. A real advantage of the structure is the designed elastic properties of the blades that "flex" to reduce blade loading. As a



conventional bronze propeller is loaded during use a vicious circle of loads is created. As the load comes on the angle of attack increases so increasing blade load still further and so on. The Flexprop is able to overcome this loading cycle by having blades that do not increase their angle of attack as the load is developed upon them.

Dow Isoplast[5]

Manufactured by: Moline Il, USA.
Year first produced: 1989.
Application: Outboard engines, recreation.
Size: Up to 330hp.
Number of blades: 3.
Material: 60% glass filled isoplast.
Process: Injection moulding.
Size of production run: Many.
Particular advantages and design features: One piece moulding.

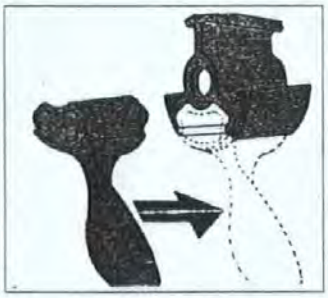


"Sixgun"[6]

Manufactured by: Gil Marine, USA.
Year first produced: 1991.
Application: Outboard engines, recreation.
Size: 14"
Number of blades: 6.
Size of production run: Many.
Particular advantages and design features: Longer life, reduced vibration, better low end power. Blades are detachable so damage can be rectified by replacing blades rather than the whole propeller. Pitch can also be changed by simply swapping blades over. 6 blades means blade load is reduced by 50% over a conventional 3 bladed propeller.

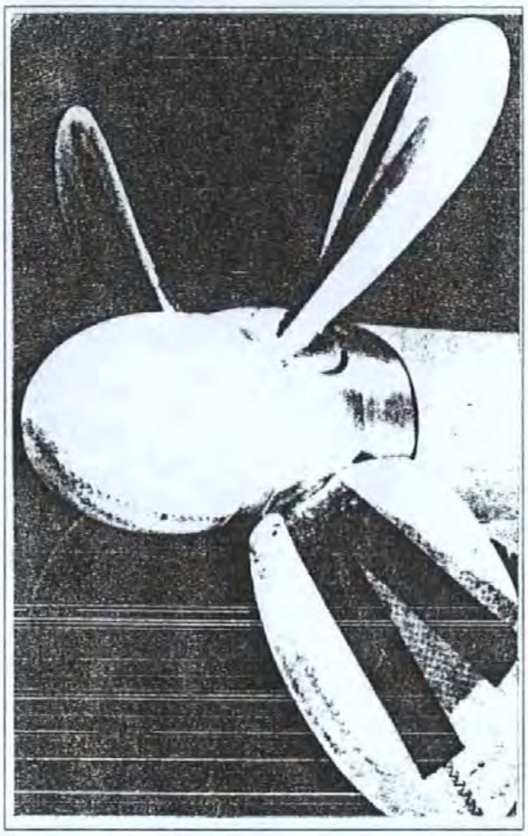
Piranha[7]

Manufactured by: Piranha Props.
Year first produced: 1990.
Application: Outboard engines, recreation.
Size: 35-260 hp.
Number of blades: 3 (detachable).
Material: Long glass reinforced nylon 66, VERTON® RF
Process: Injection moulding.
Cost saving: Up to 75% on repair costs, new blade costs $20 compared to $60 -$80 for repairing an aluminium propeller.
Size of production run: Many.
Particular advantages and design features: The propeller consists of a hub with front and rear caps to secure 3 detachable blades that are replaceable individually should one be damaged. The company makes blades



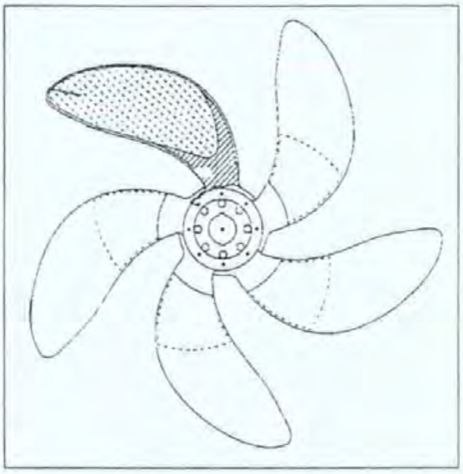
of 6 different pitches, that, its claimed cater for 80 to 90% of boating needs.

Southampton University[8]



Manufactured by: Nick Barlow (boat builder) & Southampton University.
Year produced: 1990.
Application: Wind tunnel testing for research into hull propeller interactions.
Size: 800mm.
Number of blades: 4.
Material: Quadrax E glass, carbon reinforced Ampreg 25
Process: Hand layup in female mould with vacuum bag consolidation.
Size of production run: One
Particular advantages and design features: 4 blades are bonded into machined aluminium connecters that fit to the boss. The propeller was made for wind tunnel testing. Due to the much higher speeds of the propeller compared to the same propeller and Reynolds number in water, centrifugal loads with a heavy bronze propeller would have been too high. So the lighter composite blades were more suitable.

Vickers Marine[9]



Application: Defence
Size: 2.4m
Number of blades: 5
Particular advantages and design features: The propeller has blades that are claimed to flex and therefore reduce the acoustic signature, cavitation, weight and cost. It is also claimed to be more efficient than conventional propellers.

Contur-propeller

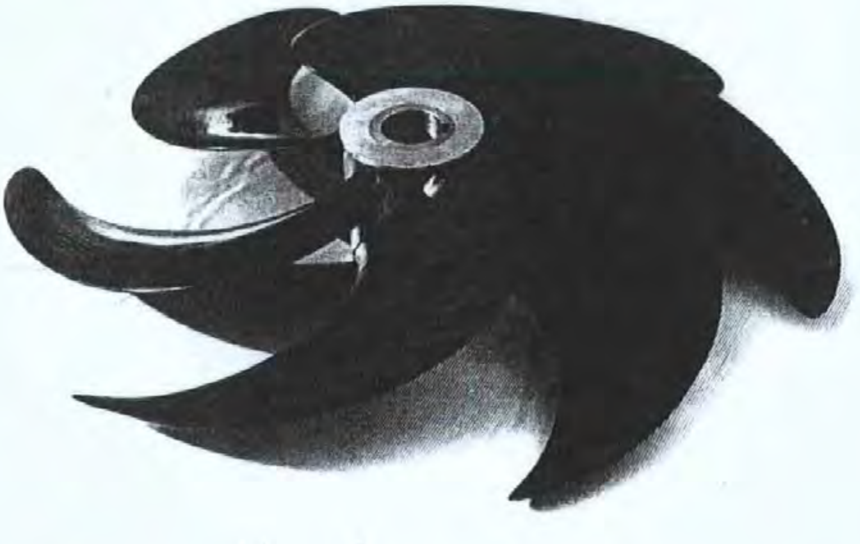
Propellers of a new quality

Proceeding on the basic principle of exchangeable blades, our engineers from the AIR Fertigung-Technologie GmbH developed a new principle of manufacture and design for ship and boat propellers. The result of this work is the Contur-propeller with individual blades made out of high strength fibre reinforced materials. However, only the use of these materials fully guarantees the characteristics of a top-quality propeller, as wished for and demanded by the user and the supplier.

What are the special merits of this propeller therefore?
These are, above all, its high efficiency, increased smoothness of running and its strength; characteristics which promise a pleasant and safe journey. If such a journey must however be interrupted at some time due to ship damage, there is no difficulty in quickly and easily replacing an individual blade. The further advantages of a propeller made out of composites should be of great interests particularly to professional users: its good vibratory stability, the distinct reduction in stress on the stuffing boxes and propeller bracket bearings, the increased resistance to cavitation and the fact that no corrosion results. The owner will also "feel" the low weight of the Contur-propellers made out of fibre reinforced materials when there is, in the truest sense of the word, only a "handbreadth of water under the keel".

As a result of extensive tests, propellers of a fully new quality with individual blades made out of carbon fibre reinforced plastic were thus developed, offering exceptional value for money.

Contur-propeller



AIR Fertigung-Technologie GmbH • Joachim-Jungius Straße 9 • 18059 Rostock
Telefon (03 81) 40 59 620 • Fax (03 81) 40 59 200

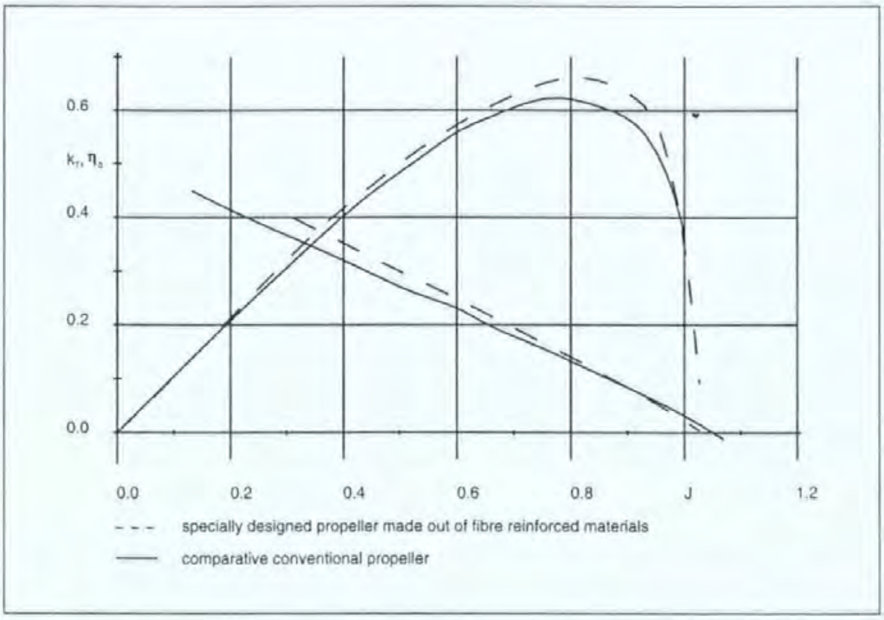
High efficiency and better quality

With the completely numerical description of the propeller geometry, the assignment of highly qualified technical staff, as well as the use of CNC processing and testing methods, consistent quality, very high surface quality and precision are achieved during the manufacture of the propellers. It becomes possible to implement the most complicated, unconventional and highly efficient propeller shapes.

The extraordinary strength properties of fibre reinforced designs enable a reduction in the thickness of the blades. In addition, a specially adapted propeller can be designed and constructed for each ship.

All these effects add up therefore to improvements in efficiency of 3 to 10 percent compared with a comparable metallic propeller.

Open-water-screw diagram of two comparative propellers



Lower weight

By using high-strength fibre reinforced materials as a blade material, the propeller's weight can be reduced to approximately 25 to 35 percent of that of a comparative metallic propeller. In the case of damage to blades, or even the loss of a blade, it is possible to continue the journey, as the resulting vibrations are, due to the low weight of the propeller blades, relatively small.

By reducing the mass moment of inertia to 15 to 18 percent compared with that of metallic propellers, its accelerating behaviour is improved.

Furthermore, it is easier to handle the propeller.

Excellent vibratory stability

Using the material, which is unusual in the sector of propeller manufacturing, likewise enables a clear reduction in vibrations. Practically no natural vibrations of the propeller occur therefore. An increased smoothness of running is achieved by means of the low weight of the Contur-propeller at the end of the shaft.

The "humming" normally regarded as a problem can be prevented here also without specially designing the edges of the blades.

As all blades are practically identical, no hydrodynamic balance errors occur. As a result of the possible reduction in the thickness of the blades, the pressure impulses on the shell are diminished.

The noise emission of such a propeller is reduced by up to 5 dB compared with a metallic propeller.

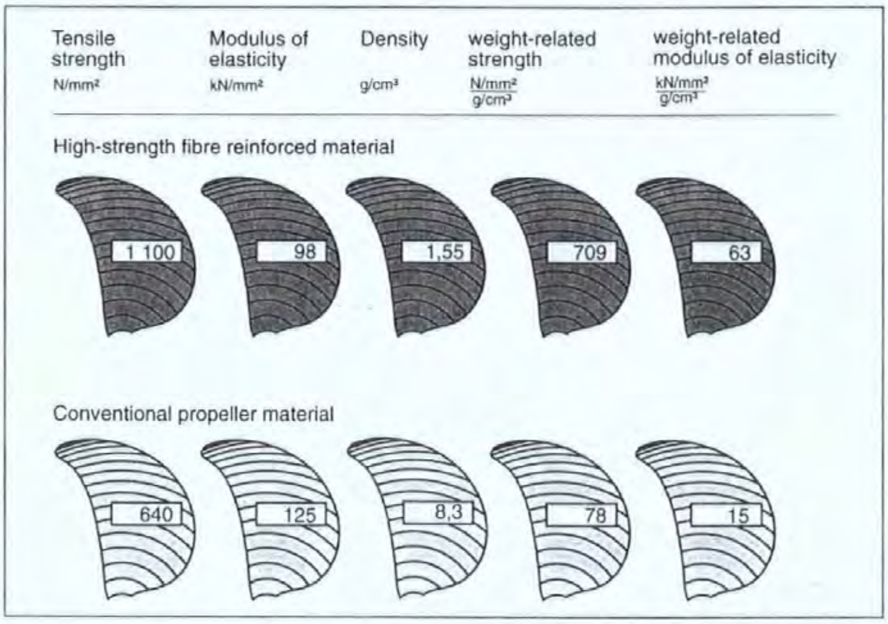
Favourable cavitation stability

Reducing the thickness of the blades in the tip area results further in an increase in protection against cavitation. By using special surface materials, it is possible to triple the propeller's resistance to cavitation and reduce the risk of damage due to cavitative corrosion.

High protection against corrosion

Resistance to corrosion is guaranteed on the one hand by the very high chemical resistance of the material to seawater. As, on the other hand, it is not a conducting material, electrochemical corrosion is also avoided.

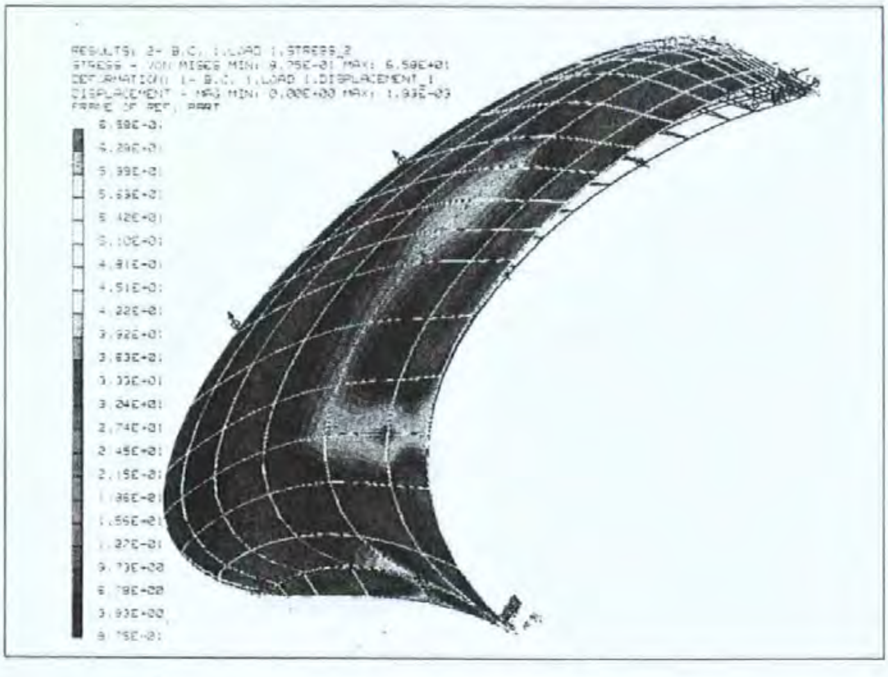
Key data relating to composite material and metal



Very great strength

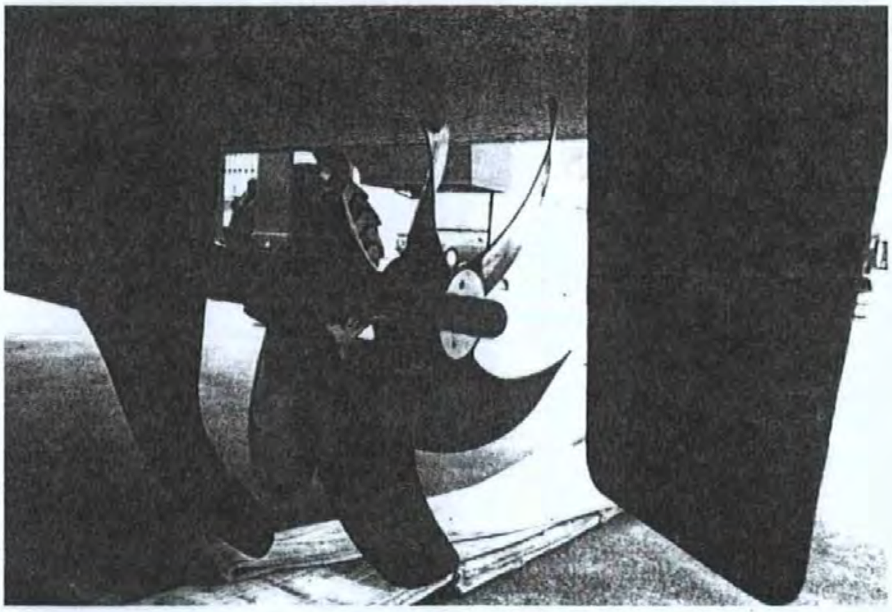
The strength of carbon fibres surpasses that of steel alloys of a higher strength. The combination of carbon, aramide and highly drawn polyethylene (PE)fibres at the edges of the blades guarantees a very high resistance to impact.

Calculation of strength by means of the computer



Model propeller in the cavitation tank

Contur-propeller on the ship



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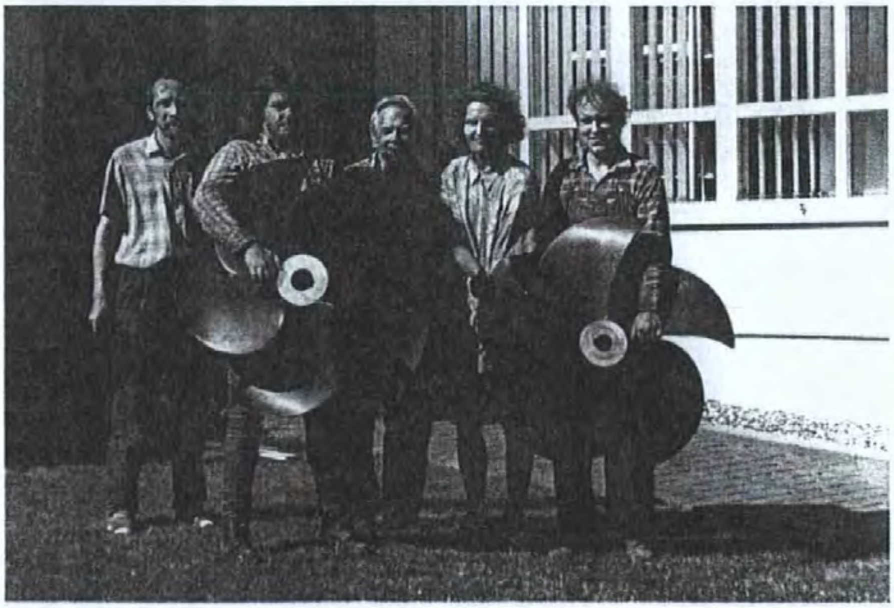

Appendix 2

RTM experimental data.

Fibre Volume Fraction (%)	CoTech 14 Degrees C (mm/min)	CoTech 24 Degrees C (mm/min)	BiAx 14 Degrees C (mm/min)	BiAx 24 Degrees C (mm/min)	
45.01	15				
47.34	15				
48.95	8				
51.34	7				
53.45	3				
54.96	2.17				
57.73	1.63				
60.35	1.1				
62.38	0.8				
63.84	0.4				
48.2		30			
48.38		9			
52.89		8			
54.96		3.5			
57		2			
58.11		2			
60.14		2.25			
47.17		62			
50.64		5			
52.62		6.5			
55.61		3			
58.11		2			
47.34		58			
50.64		14			
52.35		12			
54.65		2.5			
44.75			84		
51.1			56		
57.73			32		
63.84			20		
46.7				330	
59.3				93.33	
67.6				10	
47.34				439.76	
59.3				117.65	
66.47				16	

Time (min)	CoTech 30 Degrees C Area (cm^2)	CoTech 40 Degrees C Area (cm^2)	CoTech 70 Degrees C Area (cm^2)	CoTech 17 Degrees C Area (cm^2)
0.00	0.00	0.00	0.00	0.00
0.50	21.00	40.00		11.00
1.00	40.00	69.00		19.00
1.50	59.00	92.00		
2.00	71.00	98.00		31.00
2.50	83.00	99.60		
3.00	88.00			40.00
0.17			44.00	
0.33			68.00	
0.50			92.00	
0.67			98.00	
4.00				50.00
5.00				61.00
6.00				73.00
7.00				80.00
8.00				90.00
9.00				95.00
10.00				97.00
11.00				99.00
12.00				99.00

Time (min)	**CoTech 14 Degrees C Area (cm^2)**	**BiAx 14 Degrees C Area (cm^2)**	**CoTech 24 Degrees C Area (cm^2)**	**BiAx 24 Degrees C Area (cm^2)**	
0.00					
3.00	13.41				
4.00	44.06				
5.00	61.30				
6.00	67.82				
7.00	76.63				
10.00	82.38				
12.00	85.06				
14.00	86.21				
16.00	89.27				
20.00	93.49				
25.00	95.79				
30.00	97.70				
40.00	98.47				
0.00					
0.50		8.43			
1.00		27.97			
1.50		44.83			
2.00		65.13			
3.00		91.19			
4.00		97.32			
5.00		98.85			
0.00					
0.50			59.77		
1.00			80.84		
2.00			84.29		
4.00			90.04		
6.00			92.34		
10.00			95.79		
0.00					
0.20				26.05	
0.50				60.54	
1.00				87.36	
1.50				95.79	
3.00				99.62	
0.00					
0.20			33.72		
0.50			63.98		
1.00			82.76		
1.50			84.29		
2.00			86.59		
3.00			91.57		
0.00					
0.17				37.55	

0.33				65.13	
0.83				90.04	
1.50				98.08	
3.00				99.62	
0.00					
0.50			55.56		
1.00			64.75		
2.00			74.71		
3.00			81.23		
5.00			86.59		
7.00			91.95		
9.00			93.87		
11.00			96.17		

Sample No. 1
Material CoTech
Temp. 14 degrees

	A	B	C	D	E
1	Time Min	Time sec	Area Cm Sq	% Area	Log
2	0.00	0.00	0.00	0.00	0.00
3	3.00	180.00	35.00	13.41	-0.14
4	4.00	240.00	115.00	44.06	-0.58
5	5.00	300.00	160.00	61.30	-0.95
6	6.00	360.00	177.00	67.82	-1.13
7	7.00	420.00	200.00	76.63	-1.45
8	10.00	600.00	215.00	82.38	-1.74
9	12.00	720.00	222.00	85.06	-1.90
10	14.00	840.00	225.00	86.21	-1.98
11	16.00	960.00	233.00	89.27	-2.23
12	20.00	1200.00	244.00	93.49	-2.73
13	25.00	1500.00	250.00	95.79	-3.17
14	30.00	1800.00	255.00	97.70	-3.77
15	40.00	2400.00	257.00	98.47	-4.18
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Sample No. 2
Material BiAx
Temp. 14

	A	B	C	D	E
1	Time Min	Time sec	Area Cm Sq	% Area	Log
2	0.50	30.00	22.00	8.43	-0.09
3	1.00	60.00	73.00	27.97	-0.33
4	1.50	90.00	117.00	44.83	-0.59
5	2.00	120.00	170.00	65.13	-1.05
6	3.00	180.00	238.00	91.19	-2.43
7	4.00	240.00	254.00	97.32	-3.62
8	5.00	300.00	258.00	98.85	-4.47
9	0.00			0.00	0.00
10	0.00			0.00	0.00
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Sample No. 3
Material CoTech
Temp. 24

	A	B	C	D	E
1	Time Min	Time sec	Area Cm Sq	% Area	Log
2	0.00	0.00	0.00	0.00	0.00
3	0.50		156.00	59.77	-0.91
4	1.00		211.00	80.84	-1.65
5	2.00		220.00	84.29	-1.85
6	4.00		235.00	90.04	-2.31
7	6.00		241.00	92.34	-2.57
8	10.00		250.00	95.79	-3.17
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Sample No. 4
Material BiAx
Temp. 24 degrees

	A	B	C	D	E
1	Time Min	Time sec	Area Cm Sq	% Area	Log
2	0.20	12.00	68.00	26.05	-0.30
3	0.50	30.00	158.00	60.54	-0.93
4	1.00	60.00	228.00	87.36	-2.07
5	1.50	90.00	250.00	95.79	-3.17
6	3.00	180.00	260.00	99.62	-5.56
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Sample No. 5
Material CoTech
Temp. 24

	A	B	C	D	E
1	Time Min	Time sec	Area Cm Sq	% Area	Log
2	0.00	0.00	0.00	0.00	0.00
3	0.20		88.00	33.72	-0.41
4	0.50		167.00	63.98	-1.02
5	1.00		216.00	82.76	-1.76
6	1.50		220.00	84.29	-1.85
7	2.00		226.00	86.59	-2.01
8	3.00		239.00	91.57	-2.47
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Sample No. 6
Material BiAx
Temp. 25 degrees

	A	B	C	D	E
1	Time Min	Time sec	Area Cm Sq	% Area	Log
2	0.17	10.00	98.00	37.55	-0.47
3	0.33	20.00	170.00	65.13	-1.05
4	0.83	50.00	235.00	90.04	-2.31
5	1.50	90.00	256.00	98.08	-3.96
6	3.00	180.00	260.00	99.62	-5.56
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Sample No. 7
Material CoTech
Temp. 26 degrees

	A	B	C	D	E
1	Time Min	Time sec	Area Cm Sq	% Area	Log
2	0.00	0.00	0.00	0.00	0.00
3	0.50		145.00	55.56	-0.81
4	1.00		169.00	64.75	-1.04
5	2.00		195.00	74.71	-1.37
6	3.00		212.00	81.23	-1.67
7	5.00		226.00	86.59	-2.01
8	7.00		240.00	91.95	-2.52
9	9.00		245.00	93.87	-2.79
10	11.00		251.00	96.17	-3.26
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Sample No. 8
Material BiAx
Temp. 29 degrees

	A	B	C	D	E
1	Time Min	Time sec	Area Cm Sq	% Area	Log
2	0.17	10.00	211.00	80.84	-1.65
3	0.50	30.00	238.00	91.19	-2.43
4	1.00	60.00	250.00	95.79	-3.17
5	2.00	120.00	260.00	99.62	-5.56
6	0.00			0.00	0.00
7	0.00			0.00	0.00
8	0.00			0.00	0.00
9	0.00			0.00	0.00
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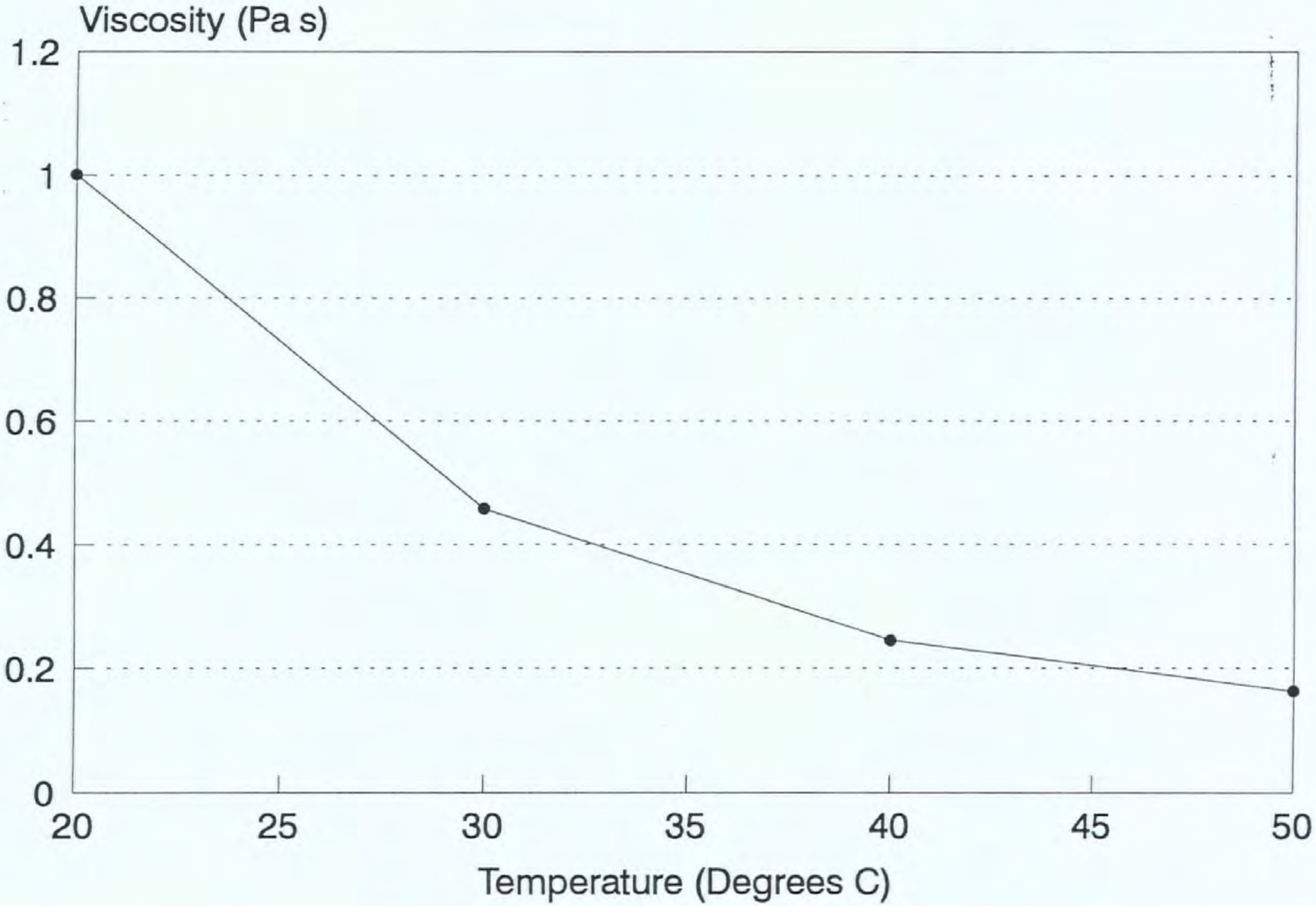
Sample No. 5
Material CoTech
Temp. 14 degrees

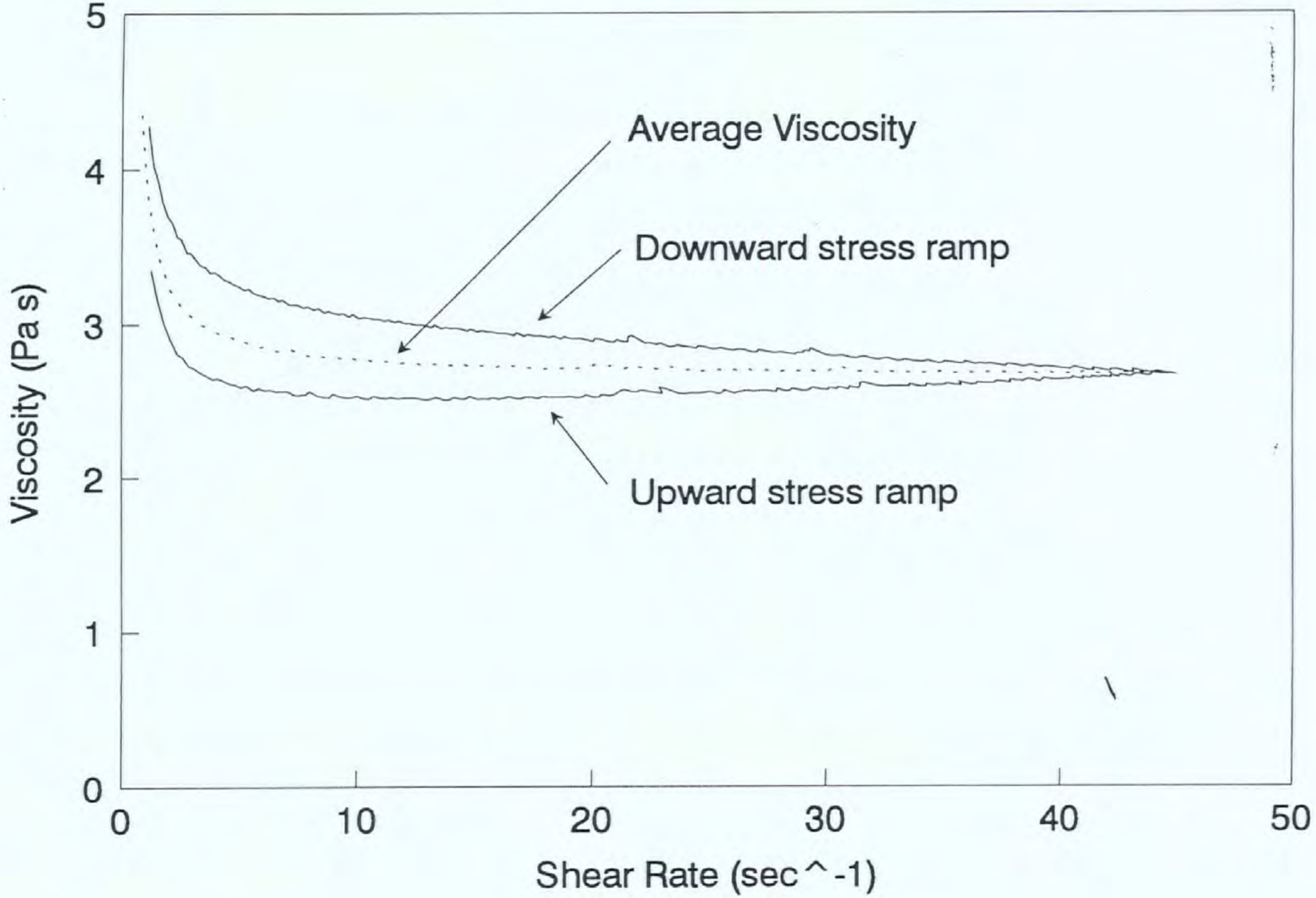
Time Min	Time sec	Area Cm Sq	% Area	Log
0.00	0.00	0.00	0.00	0.00
3.00	180.00	35.00	13.41	-0.14
4.00	240.00	115.00	44.06	-0.58
5.00	300.00	160.00	61.30	-0.95
6.00	360.00	177.00	67.82	-1.13
7.00	420.00	200.00	76.63	-1.45
10.00	600.00	215.00	82.38	-1.74
12.00	720.00	222.00	85.06	-1.90
14.00	840.00	225.00	86.21	-1.98
16.00	960.00	233.00	89.27	-2.23
20.00	1200.00	244.00	93.49	-2.73
25.00	1500.00	250.00	95.79	-3.17
30.00	1800.00	255.00	97.70	-3.77
40.00	2400.00	257.00	98.47	-4.18

Appendix 3

Resin rheology data.

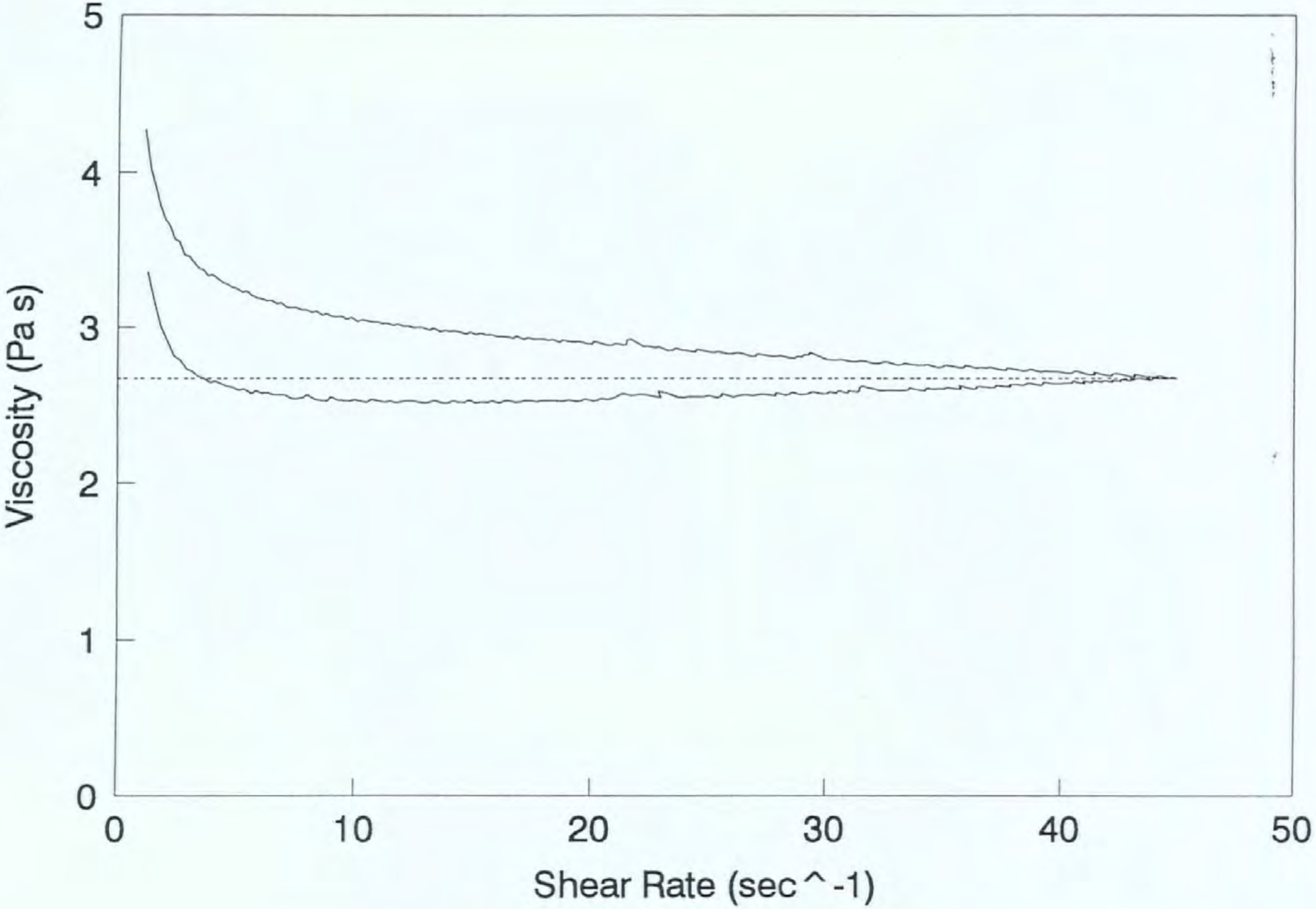
Viscosity vs Temperature for a 5052 Resin System





Viscosity vs Shear Rate for a 5052 Resin System

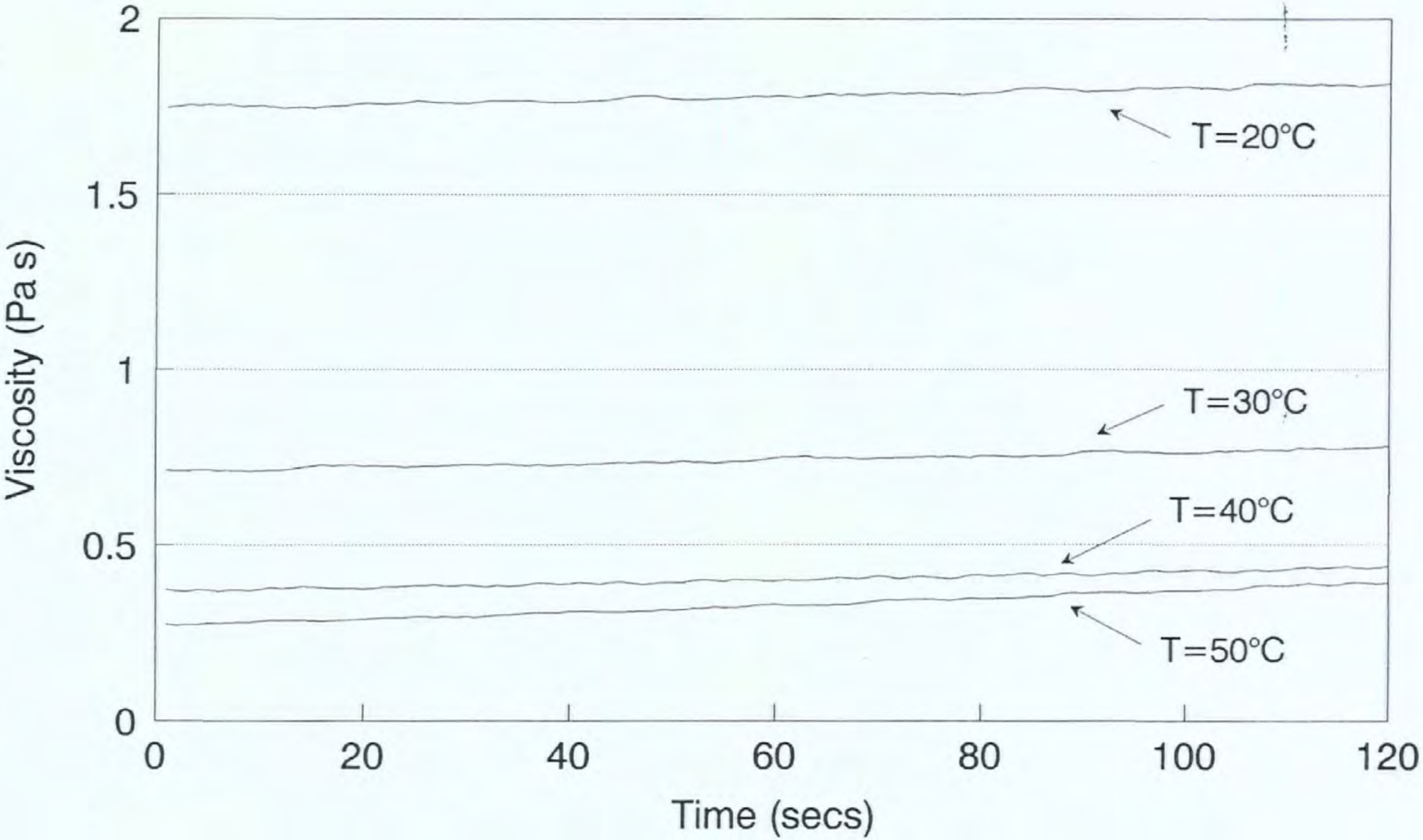
Viscosity vs Shear Rate for a 5052 Resin System



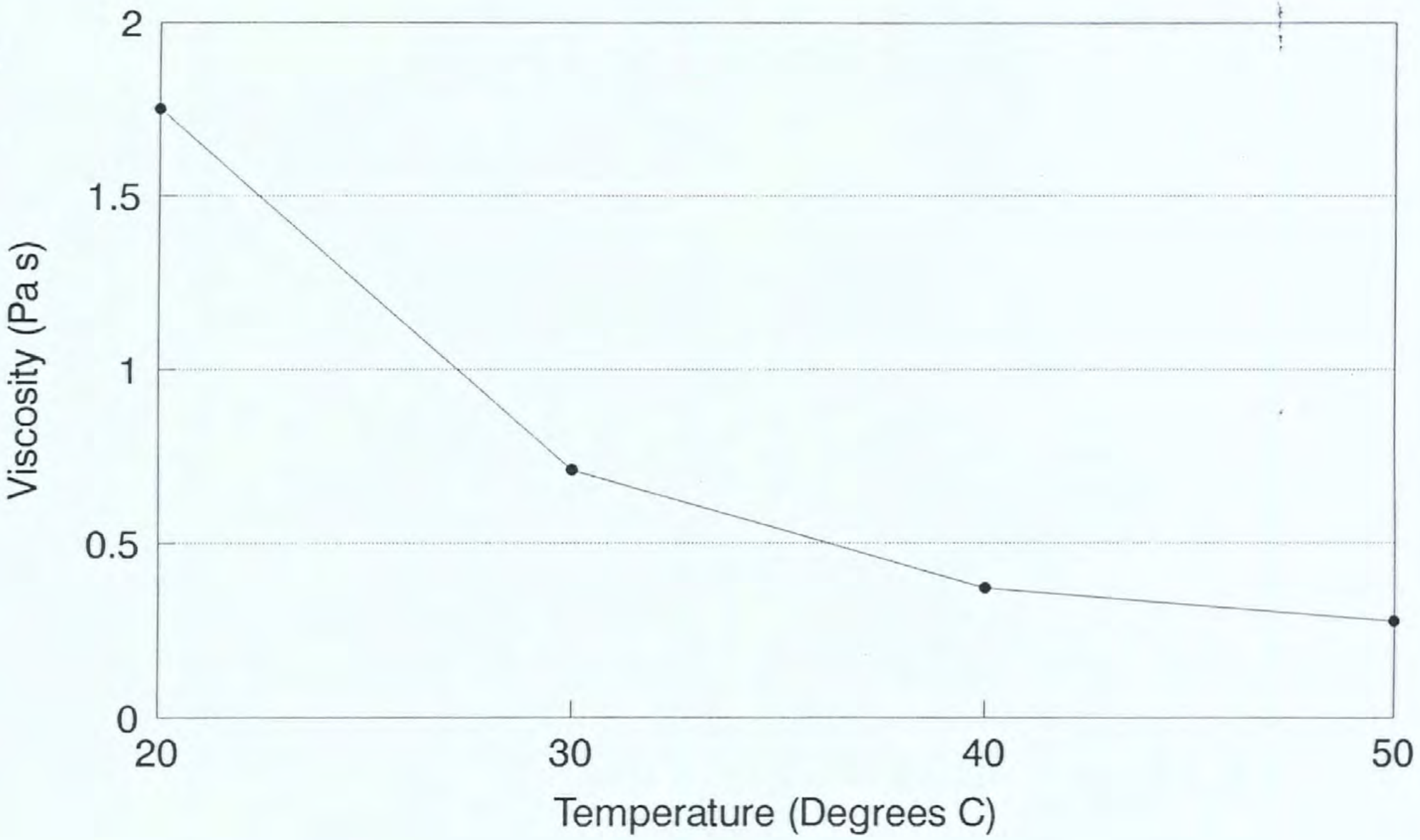
Time (secs)	Viscosity 30°C	Viscosity 20°C	Viscosity 40°C	Viscosity 50°C
1	7.11	17.47	3.737	2.754
2	7.103	17.51	3.694	2.727
3	7.105	17.54	3.679	2.739
4	7.114	17.53	3.718	2.743
5	7.111	17.54	3.7	2.762
6	7.09	17.53	3.673	2.777
7	7.102	17.54	3.717	2.797
8	7.105	17.49	3.72	2.816
9	7.079	17.5	3.707	2.805
10	7.102	17.52	3.73	2.839
11	7.118	17.5	3.784	2.862
12	7.118	17.46	3.753	2.868
13	7.142	17.47	3.776	2.871
14	7.194	17.49	3.815	2.86
15	7.231	17.46	3.795	2.856
16	7.267	17.5	3.78	2.839
17	7.236	17.52	3.753	2.854
18	7.257	17.53	3.756	2.873
19	7.266	17.57	3.763	2.879
20	7.232	17.6	3.746	2.889
21	7.239	17.59	3.757	2.908
22	7.234	17.58	3.796	2.937
23	7.234	17.6	3.8	2.943
24	7.194	17.62	3.82	2.94
25	7.212	17.67	3.838	2.959
26	7.222	17.64	3.842	2.961
27	7.231	17.61	3.851	2.95
28	7.247	17.62	3.825	2.963
29	7.251	17.6	3.823	2.953
30	7.273	17.6	3.856	2.967
31	7.276	17.63	3.823	2.953
32	7.262	17.67	3.795	2.973
33	7.279	17.67	3.839	3.007
34	7.286	17.67	3.82	3.026
35	7.257	17.67	3.832	3.041
36	7.246	17.67	3.875	3.062
37	7.267	17.64	3.913	3.077
38	7.242	17.63	3.9	3.084
39	7.262	17.63	3.878	3.074
40	7.266	17.63	3.893	3.105
41	7.257	17.65	3.927	3.11
42	7.286	17.68	3.906	3.111
43	7.286	17.69	3.875	3.094
44	7.313	17.71	3.93	3.094
45	7.332	17.77	3.938	3.095
46	7.31	17.82	3.907	3.111
47	7.334	17.83	3.879	3.124
48	7.337	17.83	3.885	3.124
49	7.318	17.76	3.929	3.16
50	7.346	17.73	3.928	3.15
51	7.366	17.71	3.928	3.168
52	7.335	17.71	3.981	3.192
53	7.335	17.72	4.006	3.198
54	7.315	17.74	3.98	3.232
55	7.34	17.75	3.964	3.221
56	7.351	17.77	4.01	3.218
57	7.356	17.8	3.997	3.23
58	7.38	17.82	3.994	3.277
59	7.411	17.8	3.966	3.287
60	7.462	17.83	3.977	3.307

Time (secs)	Viscosity 30°C	Viscosity 20°C	Viscosity 40°C	Viscosity 50°C
61	7.48	17.81	3.996	3.283
62	7.487	17.77	3.99	3.28
63	7.505	17.81	3.986	3.283
64	7.45	17.85	4.003	3.279
65	7.466	17.89	4.029	3.283
66	7.454	17.85	4.068	3.297
67	7.461	17.87	4.06	3.298
68	7.431	17.85	4.034	3.327
69	7.422	17.86	4.072	3.363
70	7.452	17.89	4.115	3.41
71	7.452	17.91	4.08	3.428
72	7.464	17.89	4.031	3.418
73	7.47	17.9	4.074	3.45
74	7.484	17.91	4.104	3.444
75	7.489	17.88	4.077	3.446
76	7.478	17.9	4.052	3.429
77	7.498	17.88	4.031	3.42
78	7.486	17.86	4.073	3.45
79	7.47	17.89	4.134	3.481
80	7.518	17.92	4.134	3.466
81	7.525	17.91	4.108	3.463
82	7.512	17.95	4.125	3.472
83	7.478	18.01	4.142	3.474
84	7.48	18.06	4.181	3.486
85	7.521	18.06	4.176	3.517
86	7.509	18.07	4.115	3.513
87	7.527	18.04	4.137	3.528
88	7.529	18.01	4.185	3.607
89	7.581	18.01	4.181	3.632
90	7.637	17.95	4.128	3.62
91	7.648	17.97	4.117	3.637
92	7.655	17.98	4.149	3.641
93	7.663	17.99	4.179	3.65
94	7.622	18	4.163	3.646
95	7.629	18.06	4.196	3.615
96	7.616	18.05	4.239	3.626
97	7.607	18.04	4.282	3.656
98	7.59	18.06	4.236	3.686
99	7.592	18.07	4.239	3.693
100	7.601	18.08	4.266	3.693
101	7.6	18.05	4.275	3.683
102	7.613	18.07	4.276	3.703
103	7.646	18.04	4.243	3.716
104	7.638	18.02	4.225	3.718
105	7.665	18.05	4.232	3.721
106	7.657	18.15	4.272	3.769
107	7.695	18.18	4.287	3.824
108	7.681	18.17	4.252	3.842
109	7.674	18.18	4.264	3.824
110	7.661	18.17	4.295	3.83
111	7.74	18.15	4.334	3.862
112	7.729	18.14	4.365	3.896
113	7.734	18.17	4.318	3.877
114	7.712	18.14	4.333	3.845
115	7.708	18.15	4.365	3.854
116	7.721	18.14	4.383	3.908
117	7.738	18.1	4.332	3.926
118	7.74	18.12	4.329	3.898
119	7.769	18.15	4.353	3.888
120	7.773	18.17	4.377	3.896

Viscosity of Ampreg 20 vs Time



Viscosity of Ampreg 20 vs Temperature



Appendix 4

Resin manufacturers data.

SP
SYSTEMS
MONTECATINI
ADVANCED
MATERIALS

SP Ampreg 20™

High performance epoxy laminating system

■ FEATURES

- Good mechanical properties
- DDM (MDA) and Phenol-free
- Low viscosity
- Good water and weathering resistance
- Generous working times
- Good HDT
- Useable with Ampreg UltraSlow Hardener

■ INTRODUCTION

Ampreg 20 is one of the new generation of wet lay-up laminating resins designed by SP Systems. It characterises the latest developments in epoxy chemistry and as a primary feature of this advance in technology, Ampreg 20 is formulated without DDM (MDA) or phenol. These significant improvements in the health and safety aspects have been achieved without detrimental effects to the mechanical properties.

The Ampreg 20 laminating system has been developed specifically for the manufacture of high strength, lightweight composites with glass, aramid or carbon fibres by wet lay-up techniques.

The low initial viscosity also allows laminates to be produced by contact pressure, vacuum or pressure bag techniques, filament winding, or vacuum assisted resin injection. Thorough wetting of reinforcement fibres is ensured by the low viscosity and excellent air release properties of the resin/hardener mixture. This, in particular, assists with the impregnation of aramid and carbon fibres.

Ampreg 20 exhibits good mechanical properties with an ambient temperature cure. However a post cure can be utilised to produce optimum properties from the resin system.

■ TECHNICAL DATA

SP Ampreg 20 resin is combined with SP Ampreg 20 fast, standard or slow hardeners in the following ratio:

Resin	:	**Hardener**
4	:	1 (by weight)
100	:	29 (volume)

PHYSICAL PROPERTIES

	Viscosity	Mixed Viscosity	Gel Time 150 g@ 25°C	Lam. Working Time @ 20°C
Resin	1240 cps	-	-	
Slow Hardener	70 cps	380 cps	200 min	5 - 7 hours
Standard Hardener	400 cps	800 cps	40 min	1.5 hours
Fast Hardener	2000 cps	1500 cps	15 min	0.5 hours

AMPREG PREGEL

Ampreg Pregel is a thixotropic resin modifier that can be used with Ampreg 20 hardeners. It must be mixed with the chosen Ampreg 20 hardener at a ratio of 100:25 by weight. It can be used in the following situations:

- As a resin modifier to reduce drainage in laminates.
- As an adhesive mix for bonding core materials to Ampreg 20 laminate skins.
- For the secondary bonding of preformed Ampreg 20 laminate components.

For more information, please see the separate data sheet.

VACUUM BAG INSULATION AND TECHNIQUES

Consolidation of the laminate can be obtained either by hand using paddle rollers or by vacuum or pressure bags. A typical vacuum bag arrangement is shown in figure 1. Due to the reduced volatile content, high vacuums may be used. However, as with all wet lay-up systems, extreme vacuums may remove system components before gelation. Heating can be economically and effectively achieved with either space heaters under an insulation tent or heated blankets with insulation over. Details of the various types of system are available from SP Systems Technical Services.

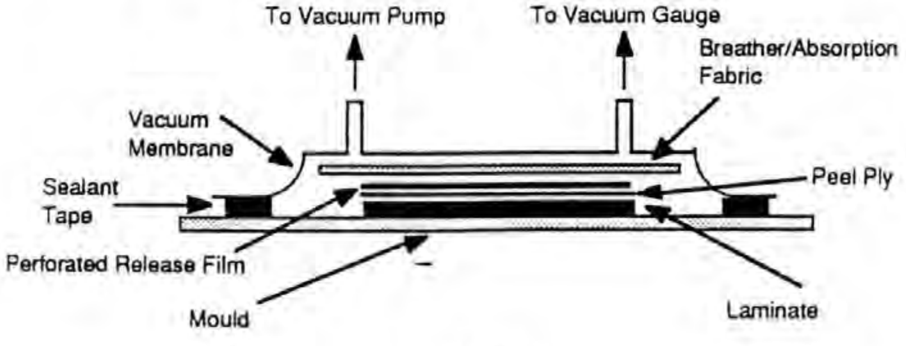


Figure 1

BONDING TECHNIQUES AND CORE MATERIALS

Where it is necessary for a bonding operation to be carried out following the cure of the Ampreg 20 laminate, Peel Ply (DP100) can be applied to the surface to be bonded during the lay-up process. After curing and just prior to bonding, the Peel Ply is stripped off leaving a clean, dust and grease-free, textured surface which does not need preparation before bonding.

Various core materials can be used with the Ampreg 20 system, including PVC and other foams, honeycombs and end-grain balsa as well as more specialised cores. Contact SP Systems Technical Services for further information.

CURING SCHEDULE

Ambient Temperature Cure - Ampreg 20 has been developed to return good mechanical properties after cure at ambient temperatures, the minimum recommended temperature being 18°C, and excellent properties after a slightly elevated temperature post-cure.

An initial cure of at least 48 hours (with slow hardener) or 16 hours (with fast hardener) at 18°C is recommended before de-moulding. Laminates subjected to an ambient temperature cure should be allowed 14 days before the system can be considered to be adequately cured and should be kept in a warm dry environment during this period. When using the slow hardener exclusively, an elevated temperature cure is strongly recommended.

Elevated Temperature Cure - Post curing the laminate will greatly increase mechanical properties as shown in Table 1 (see Technical Data). The Ampreg 20 system will achieve similar properties with a cure of either 5 hours at 80°C or 16 hours at 45-50°C but as the table shows, the cure has been optimised for 45-50°C. The latter temperatures are easily achievable with low cost heating and insulation techniques. The table below shows that these cure cycles improve the properties by up to 60%. There is a considerable increase in glass transition temperature and toughness of the system, with the elongation at break increasing to approximately 6.5%. The post cure need not be carried out immediately after laminating and it is possible to assemble several composite components and post cure the entire assembly together. It is recommended, however, that elevated temperature curing should be completed before any painting/finishing operations. Furthermore care should be taken to adequately support the laminate if it is to be post cured after demoulding and the laminate must be allowed to cool before the support is removed.

System	Cure Scheme	Flexural		Tensile		Elongation to Break	HDT (°C)
		Strength MPa	Modulus GPa	Strength MPa	Modulus GPa		
Resin/Slow Hardener	5 hrs @ 80°C	147	3.0	77	3.1	>5%	80
	16 hrs @ 50°C	156	3.4	82	3.3	>5%	71
	4 wks @ RT	112	3.6	58	3.5	2.6%	51
Resin/Std Hardener	5 hrs @ 80°C	159	3.5	80	3.3	>5%	78
	16 hrs @ 50°C	167	3.5	85	3.3	5.0%	71
	4 wks @ RT	126	3.7	71	3.5	2.9%	51

AMPREG ULTRA-SLOW HARDENER

A separate data sheet for Ampreg UltraSlow Hardener is available.

This hardener is intended for the manufacture of extremely large structures, and gives an extended working time (10-12 hours). It is used at a different mix ratio (100:30 by weight) than the other Ampreg 20 hardeners and details of the post-cure schedules required are given in the separate data sheet available for this product.

■ HEALTH & SAFETY

The following points must be considered:

1. Skin contact must be avoided by wearing disposable rubber gloves. The use of barrier creams is also recommended.
2. Care must be taken to avoid the risk of splashing resin or hardener into eyes. If this occurs the eye should be immediately well flushed with water for 15 minutes and medical advice sought.
3. The inhalation of sanding dust should be avoided and, in particular, care should be taken not to rub the eye area when exposed to sanding dust. After any sanding operation of reasonable size a shower or bath should be taken and should include hair washing.
4. Overalls or other protective clothing should be worn when laminating or sanding. Contaminated work clothes should be thoroughly cleaned before re-use.
5. Any areas of skin coming into contact with resin and hardener must be thoroughly cleansed. This should be achieved by the use of resin removing creams and washing with soap and water. Solvents should not be used on the skin.

   This cleaning should be routine:
   - before eating or drinking
   - before smoking
   - before using the lavatory
   - after finishing work
6. Ensure adequate ventilation and avoid excessive contact with solvent vapours which may cause dizziness and headaches.

■ TRANSPORT AND SOTRAGE

The resin and hardeners should be kept in securely closed containers during transport and storage. Any accidental spillage should be soaked up with sand, sawdust, cotton waste or any other absorbent material. The area should then be washed clean (see appropriate Safety Data Sheet).

Adequate long term storage conditions for both materials will result in shelf lives of 2 years or more for the resin and 1 year for the hardeners. Ideally, storage should be in a warm dry place out of direct sunlight and protected from frost. The temperature should be between 15°C and 30°C. Containers should be firmly closed. Hardeners, in particular, will suffer serious degradation if left exposed to air. Providing the above storage conditions are met this resin and its fast and slow hardeners have a guaranteed shelf life of one year.

A full material safety data sheet (MSDS) covering usage, transport, storage and emergencies, is available upon request.

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MATRIX SYSTEMS

ARALDITE LY 5052
HARDENER HY 5052

Cold and warm curing laminating system with low viscosity, solvent free for the production of advanced fibre reinforced structures.

APPLICATIONS

- Gliders / Airplane parts
- Boat building
- Car bodies and fuselages
- Sports equipment
- Repairing etc.

PROCESSING

- Injection (vacuum, pressure)
- Hand lay-up
- Winding
- Pressure moulding

FEATURES

- Excellent mechanical and dynamic strength
- Well suited as matrix system for all current reinforcement fibres
- High temperature resistance after post curing
- Fast and complete impregnation of reinforcing materials
- Easy handling

PRODUCT DATA

ARALDITE LY 5052

Viscosity at 25°C	mPa s	1'000 - 1'500
Epoxy content	equiv/kg	6.7 - 6.9
Flash point (DIN 51758)	°C	140
Specific gravity	g/cm³	1.16 - 1.18
Colour (Gardner)		2
As-supplied form		clear, liquid
Shelf life		1 year

HARDENER HY 5052

Viscosity at 25°C	mPa s	40 - 60
Flash point (DIN 51758)	°C	110
Specific gravity	g/cm³	0.93 - 0.95
Colour (Gardner)		4
Amine content	equiv/kg	9.6 - 9.8
As-supplied form		clear, liquid
Shelf life		1 year

STORAGE

The product described in this publication should be stored in their original, sealed containers, in a dry place at 18-25°C. They will then have the shelf life shown above. Partly emplied containers should be closed immediately after use.
Resin which has turned cloudy, i.e. crystallized in storage can be reliquified and restored to its original conditions by heating to 60-80°C.

PROCESSING PROPERTIES PRIOR TO CURE

Mix ratio

ARALDITE LY 5052	p.b.w.	100 ± 1.0
Hardener HY 5052	p.b.w.	38 ± 0.5

Initial viscosity (Hoeppler)

at 25°C	mPa s	600 - 700
at 40°C	mPa s	200 - 250

Possible cure

The following, different cure cycles are normally used:

7 d	at room temperature (23°C)
15 h	at 50°C
8 h	at 80°C

Pot life

Tecam (100 g)

at room temperature (23°C)	min	220 - 260
at 40°C	min	45 - 55

Isothermal, 15 g

at 25°C	- time to 1'500 mPa s	min	50 - 60
	- time to 3'000 mPa s	min	90 - 110
at 40°C	- time to 1'500 mPa s	min	40 - 45
	- time to 3'000 mPa s	min	50 - 60

Gel time

at 40°C	min	150 - 170
at 60°C	min	45 - 55
at 80°C	min	13 - 17
at 100°C	min	5 - 6
at 120°C	min	2 - 3

PROPERTIES OF THE CURED, UNREINFORCED SYSTEM

Deflection temperature

Cure			Glass transition temperature (Mettler TMA)
1 d	at 23°C	°C	50 - 52
7 d	at 23°C	°C	60 - 62

Cure		Glass transition temperature (Mettler TMA)
10 h at 40°C	°C	68 - 72
20 h at 40°C	°C	72 - 76
10 h at 50°C	°C	78 - 82
15 h at 50°C	°C	81 - 85
10 h at 60°C	°C	92 - 96
15 h at 60°C	°C	94 - 98
2 h at 80°C	°C	106 - 110
8 h at 80°C	°C	105 - 130
1 h at 90°C	°C	104 - 108
4 h at 90°C	°C	112 - 116
1 h at 100°C	°C	116 - 120
4 h at 100°C	°C	123 - 127

Tensile test (ISO / R 527)

Cure		7 d / 23°C	8 h / 80°C
Tensile strength	N/mm^2	49 - 71	75 - 88
Elongation at break	%	1.5 - 2.5	4.0 - 8.0
Elastic Modulus	N/mm^2	3'350 - 3'550	2'900 - 3'100

Water absorption (ISO / R 62, ISO / R 1117)

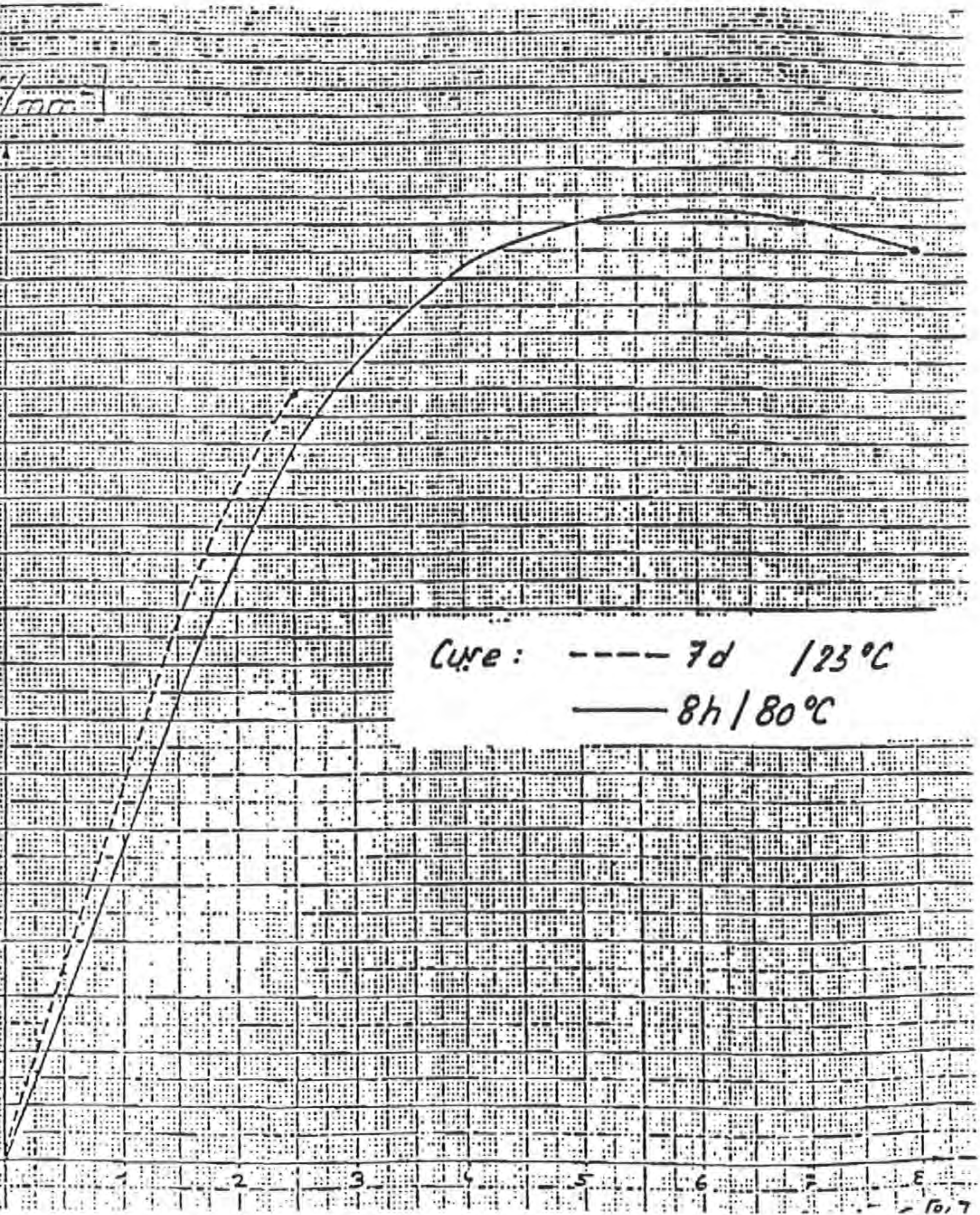
Cure		7 d / 23°C	8 h / 80°C
4 d in H_2O/ 23°C	%	0.45 - 0.50	0.40 - 0.45
10 d in H_2O/ 23°C	%	0.70 - 0.80	0.65 - 0.70
30 min in H_2O/100°C	%	0.55 - 0.60	0.45 - 0.50
60 min in H_2O/100°C	%	0.70 - 0.80	0.60 - 0.70

Coefficient of linear thermal expansion (VDE 0304, part 1)

Cure	limits of validity	Coeff. of linear expansion	
7 d /23°C	20 - 50°C	K^{-1}	$97 \cdot 10^{-6}$
15 h /50°C	20 - 90°C	K^{-1}	$71 \cdot 10^{-6}$
8 h /80°C	20 - 120°C	K^{-1}	$71 . 10^{-6}$

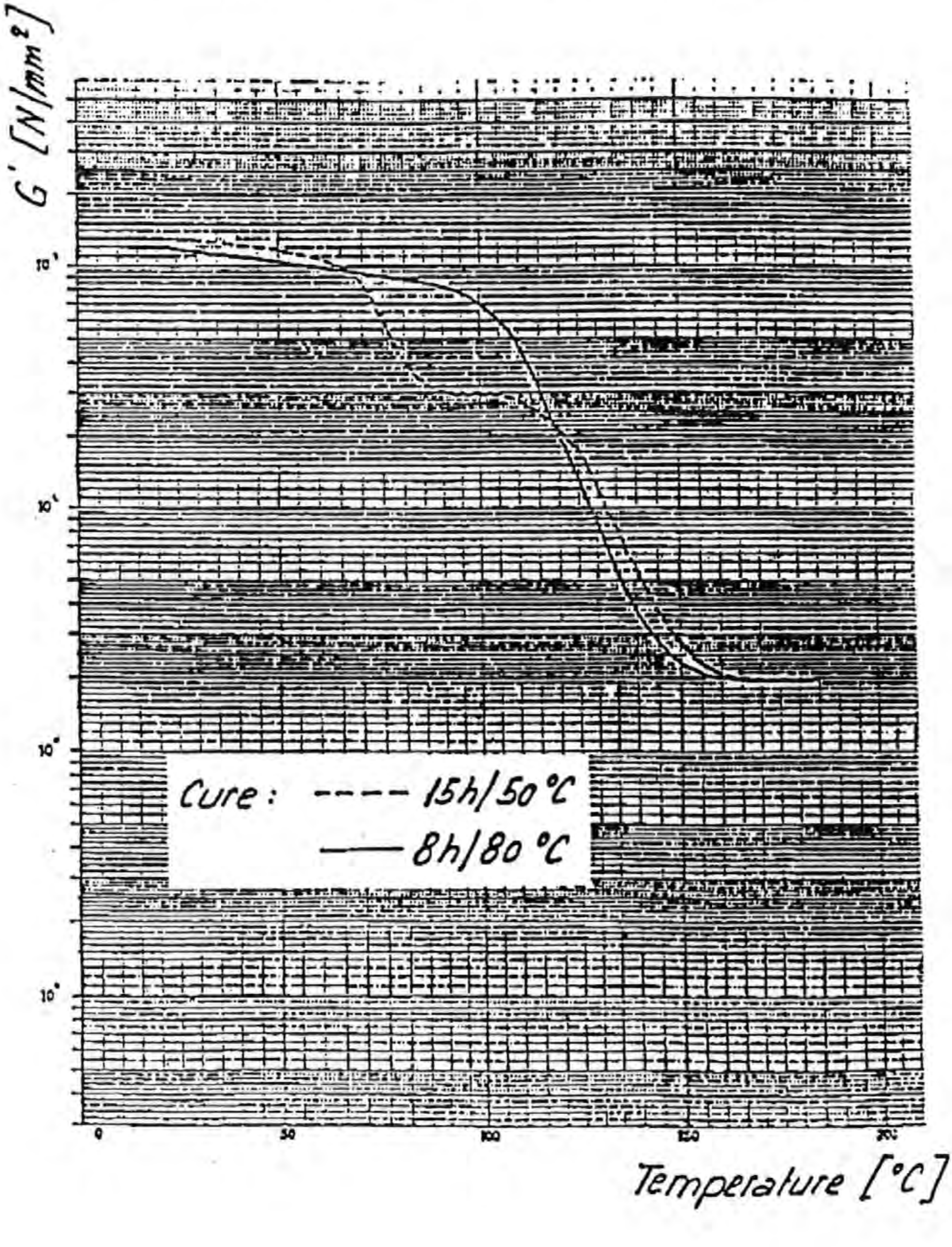
STRESS-STRAIN - Diagramme

(ISO / R 527, unreinforced system)



SHEAR MODULUS G' vs. Temperature

(Zwick Torsiomatic, ISO R / 537 or DIN 53445)



ROPERTIES OF THE CURED, REINFORCED SYSTEM

nterlaminar shear strength (ASTM-D 2344)

ample:
- Thickness 3.2 mm
- Reinforcement 12 layers fabric IG 92146 (Interglas)

ure		7 d / 23°C	8 h / 80°C
ibre content	% b.w.	74 - 78	74 - 78
after curing	N/mm^2	55 - 61	60 - 65
fter 1h H_2O/100°C	N/mm^2	53 - 61	56 - 62

Tensile-, Compressive-, Torsional-strength (TCT)

Determination: CIBA-GEIGY TCT

This CIBA-GEIGY test method is explained in the brochure 'An explanation of the mechanical and processing data given in instruction sheets' (Publ.No. 24801/e). The test results are basic values for calculations using the multilayer-theory by Prof. Puck.

Rowing	OCF 859 - 885 Tex
Fibre content	60 % - b.vol

Transverse tensile test

Cure		7 d / 23°C	15 h / 50°C
Transverse tensile strength $\sigma_{\perp zB}$	N/mm^2	29.0 - 34.0	29.0 - 50.0
Elongation at break $\varepsilon_{\perp zB}$	%	0.23 - 0.27	0.23 - 0.39
Elastic modulus $E_{\perp z}$	N/mm^2	12'000 - 13'000	12'000 - 13'000

Torsional load test

Cure		7 d / 23°C	15 h / 50°C
Shear strength $\tau_{\#B}$	N/mm^2	52.0 - 56.0	57.0 - 69.0
Shear angle $\gamma_{\#B}$	%	5 - 7	4 - 6
Shear modulus $G_{\#}$	N/mm^2	4'500 - 5'000	4'250 - 4'750

Transverse compression test

Cure		7 d / 23°C	15 h / 50°C
Transverse compressive strength $\sigma_{\perp dB}$	N/mm^2	102.0 - 120.0	119.0 - 129.0
Elongation at break $\varepsilon_{\perp dB}$	%	1.0 - 1.4	1.4 - 1.6
Elastic modulus $E_{\perp d}$	N/mm^2	13'000 - 15'000	13'000 - 14'000

INDUSTRIAL HYGIENE

Epoxy resins and hardeners are chemicals. All mandated and recommended industrial hygiene procedures should be followed whenever they are being handled. For details, please consult 'Hygienic precautions for handling plastics products of CIBA-GEIGY' (Publication No. 24264/e).

SUPPLEMENTARY LITERATURE

Details of the tests referred to in this Instruction Sheet will be found in Araldite Laminating Resin Systems - 'An Explanation of the Mechanical and Processing Data Given in Instruction Sheets' (Publication No. 24801/e).

The commonly used methods of processing laminating resins are described in 'The Structure and Processing of Fibre-reinforced Plastics'.

These publications will be gladly supplied on request.

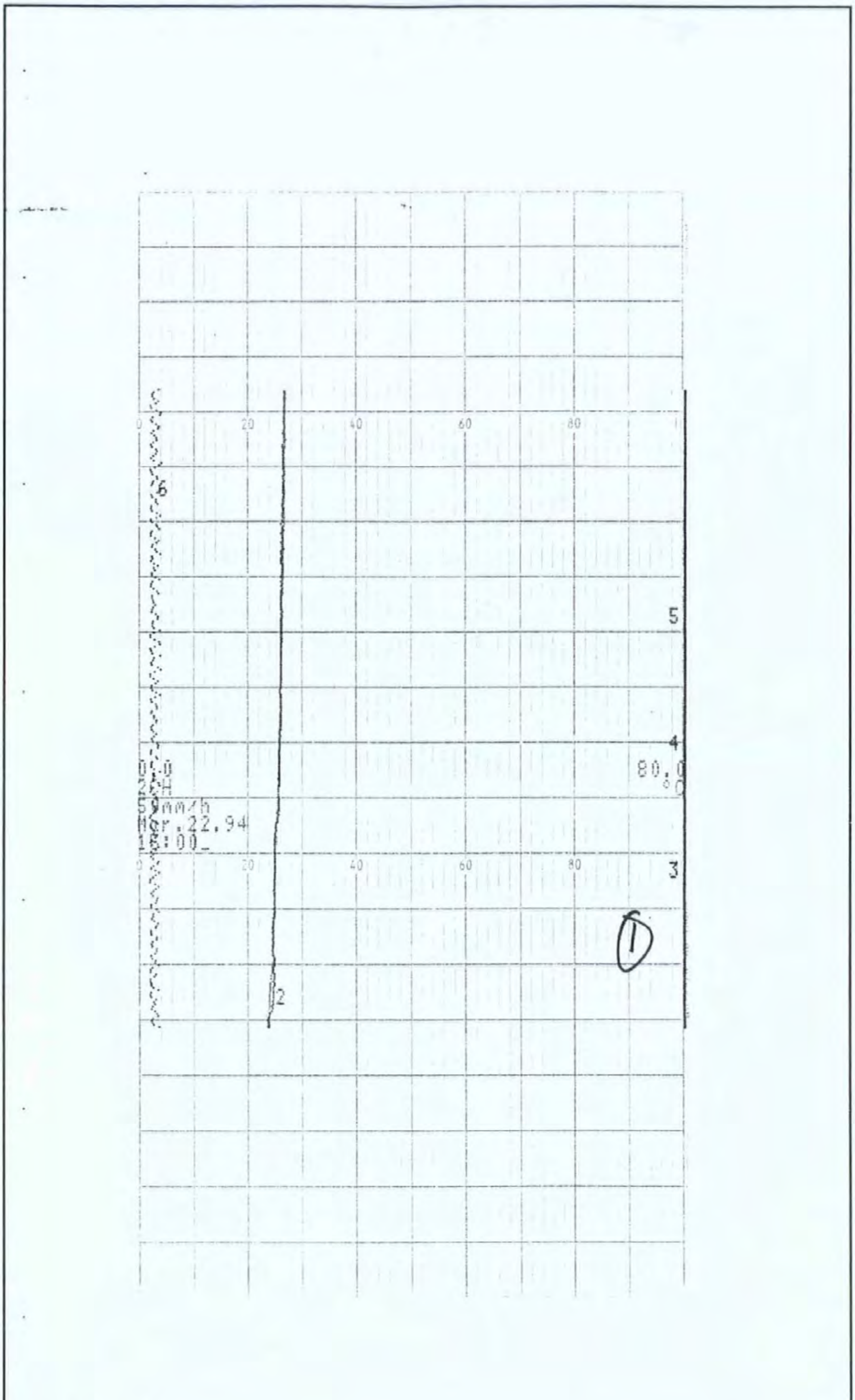
CIBA-GEIGY

®Registered trademark

March 1988 /sl

Appendix 4a

Temperature plots.



Coupon 1.

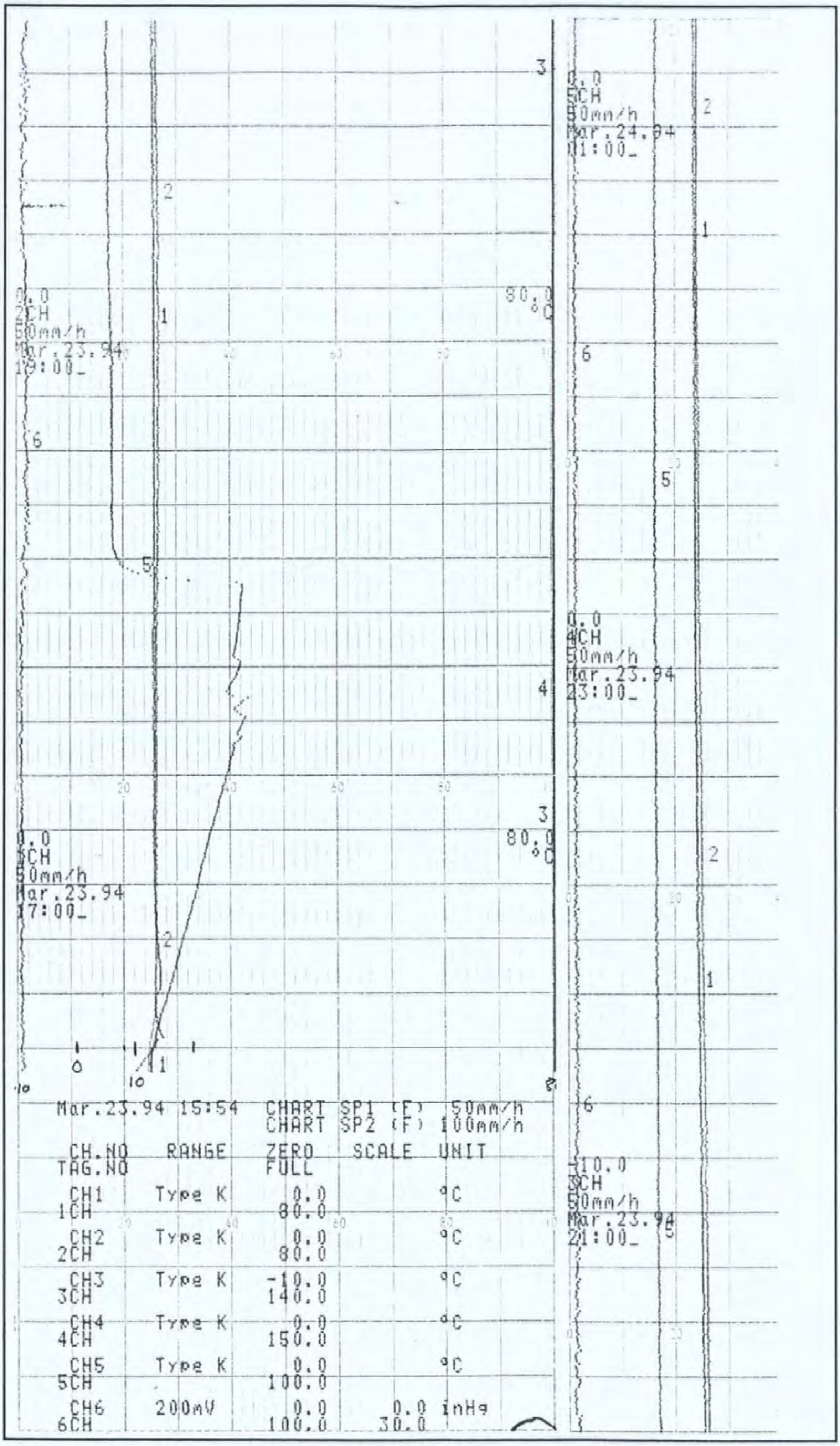


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                  CHART SP2 (F) 100mm/h

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 TAG.NO                FULL

  CH1       Type K      0.0            °C
 1CH                   80.0

  CH2       Type K      0.0            °C
 2CH                   80.0

  CH3       Type K    -10.0            °C
 3CH                  140.0

  CH4       Type K      0.0            °C
 4CH                  150.0

  CH5       Type K      0.0            °C
 5CH                  100.0

  CH6       200mV       0.0      0.0   inHg
 6CH                  100.0     30.0
```

Coupon 2.

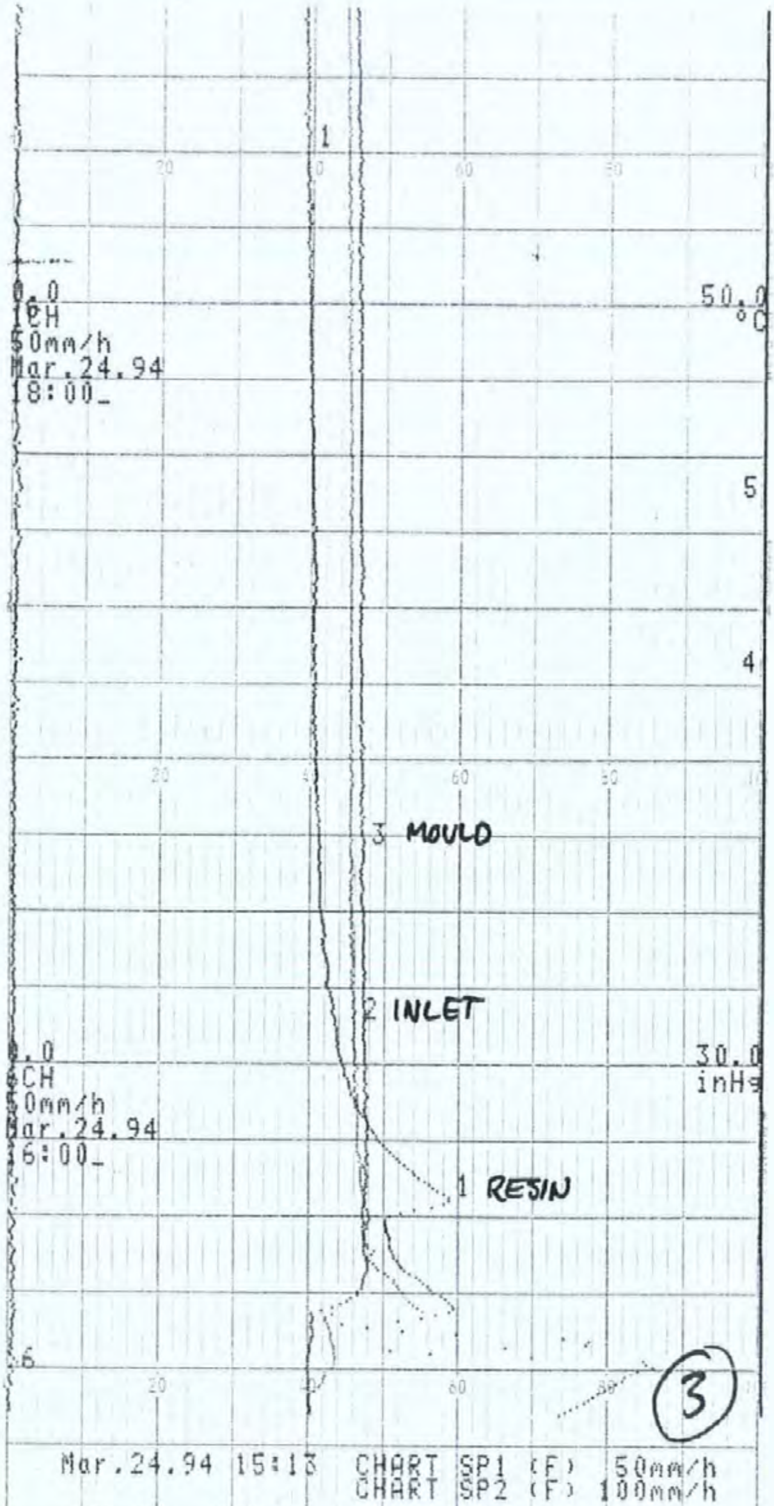

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                  CHART SP2 (F) 100mm/h
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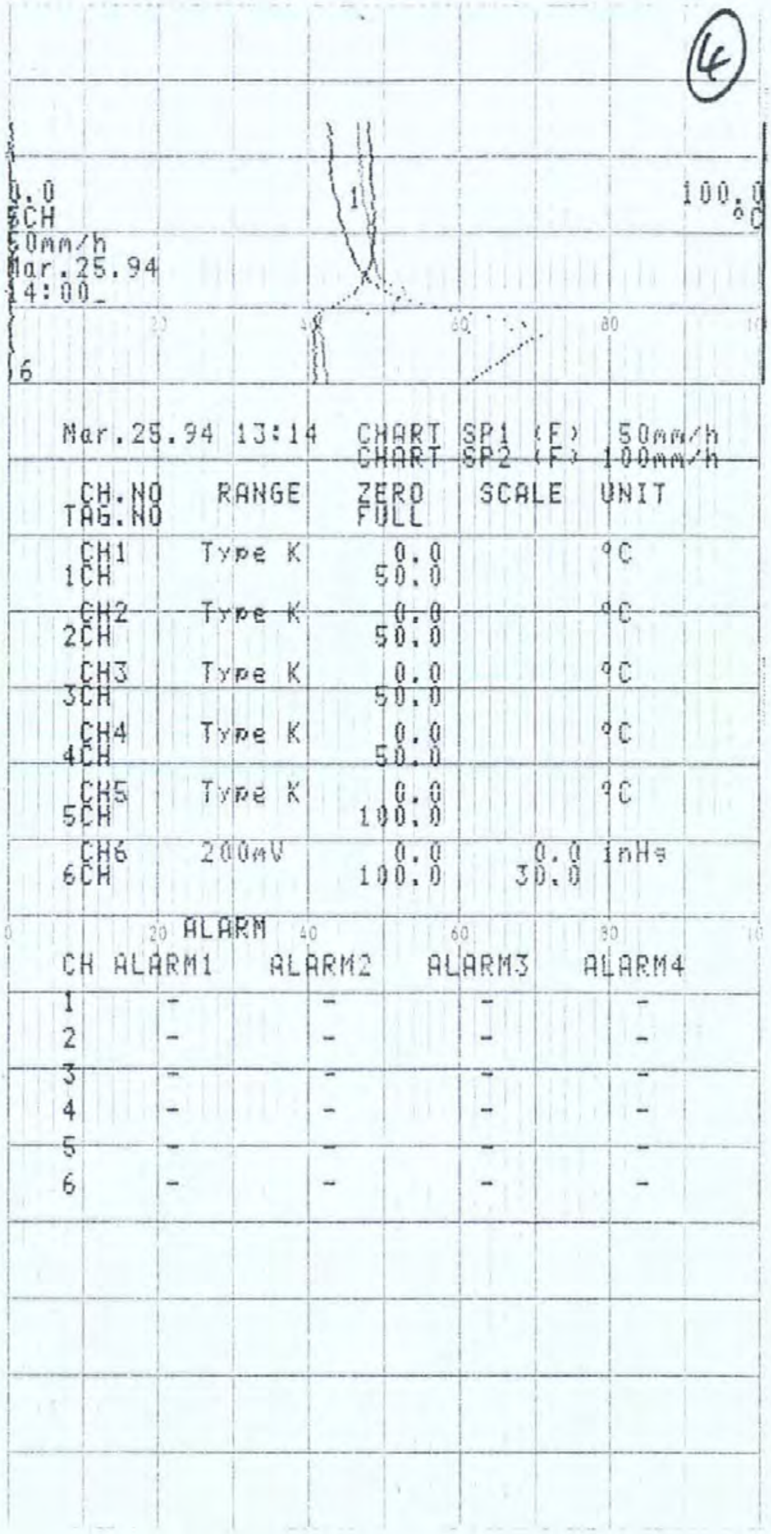
TAG.NO            FULL
  CH1     Type K    0.0          °C
 1CH               50.0
  CH2     Type K    0.0          °C
 2CH               50.0
  CH3     Type K    0.0          °C
 3CH               50.0
  CH4     Type K    0.0          °C
 4CH               50.0
  CH5     Type K    0.0          °C
 5CH              100.0
  CH6     200mV     0.0     0.0 inHg
 6CH              100.0    30.0

          ALARM
```

Coupon 3.



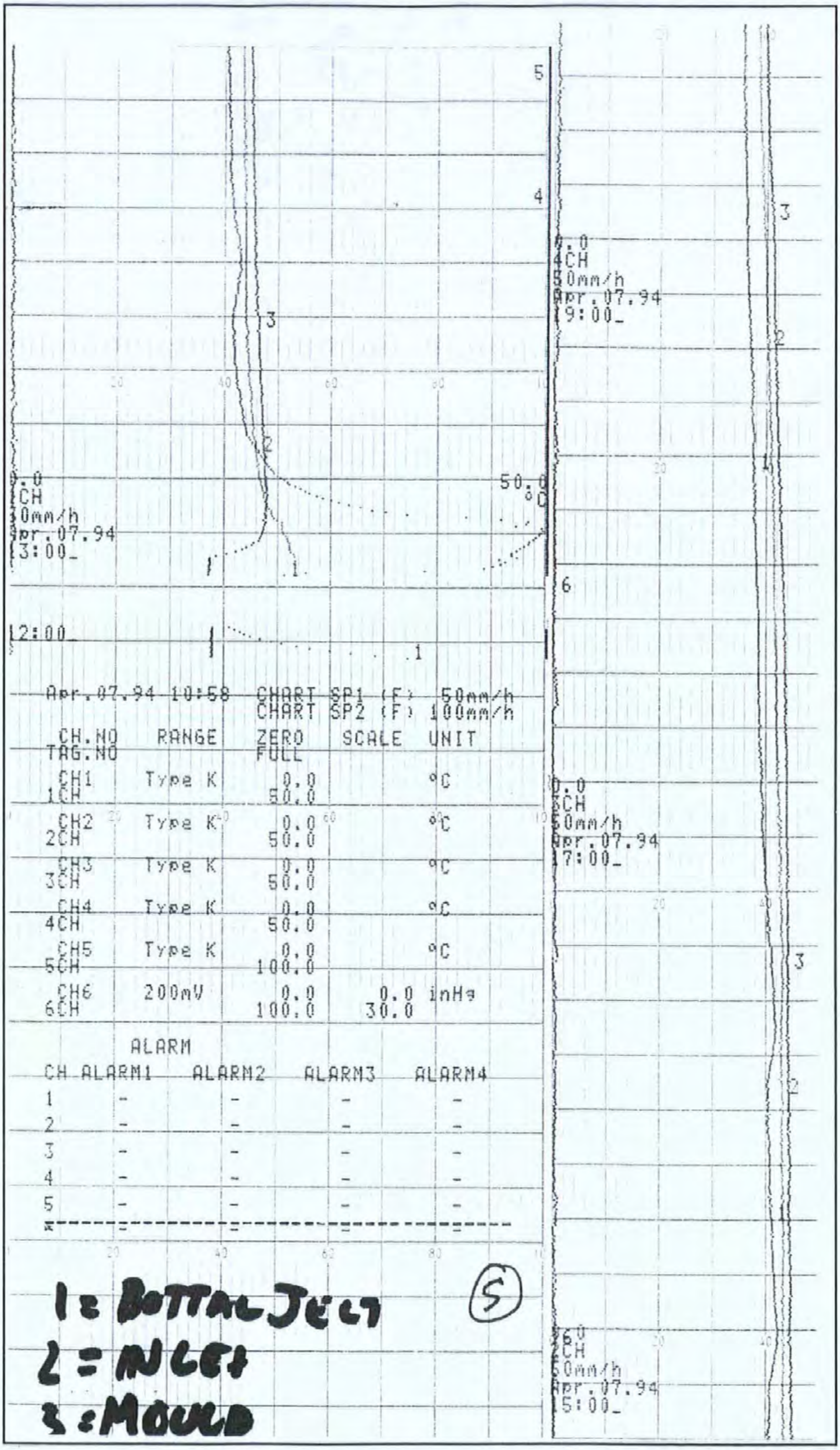
Mar.25.94 13:14 CHART SP1 (F) 50mm/h
CHART SP2 (F) 100mm/h

CH.NO TAG.NO	RANGE	ZERO FULL	SCALE	UNIT
CH1 1CH	Type K	0.0 50.0		°C
CH2 2CH	Type K	0.0 50.0		°C
CH3 3CH	Type K	0.0 50.0		°C
CH4 4CH	Type K	0.0 50.0		°C
CH5 5CH	Type K	0.0 100.0		°C
CH6 6CH	200mV	0.0 100.0	0.0 30.0	inHg

ALARM

CH	ALARM1	ALARM2	ALARM3	ALARM4
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-	-	-	-

Coupon 4.



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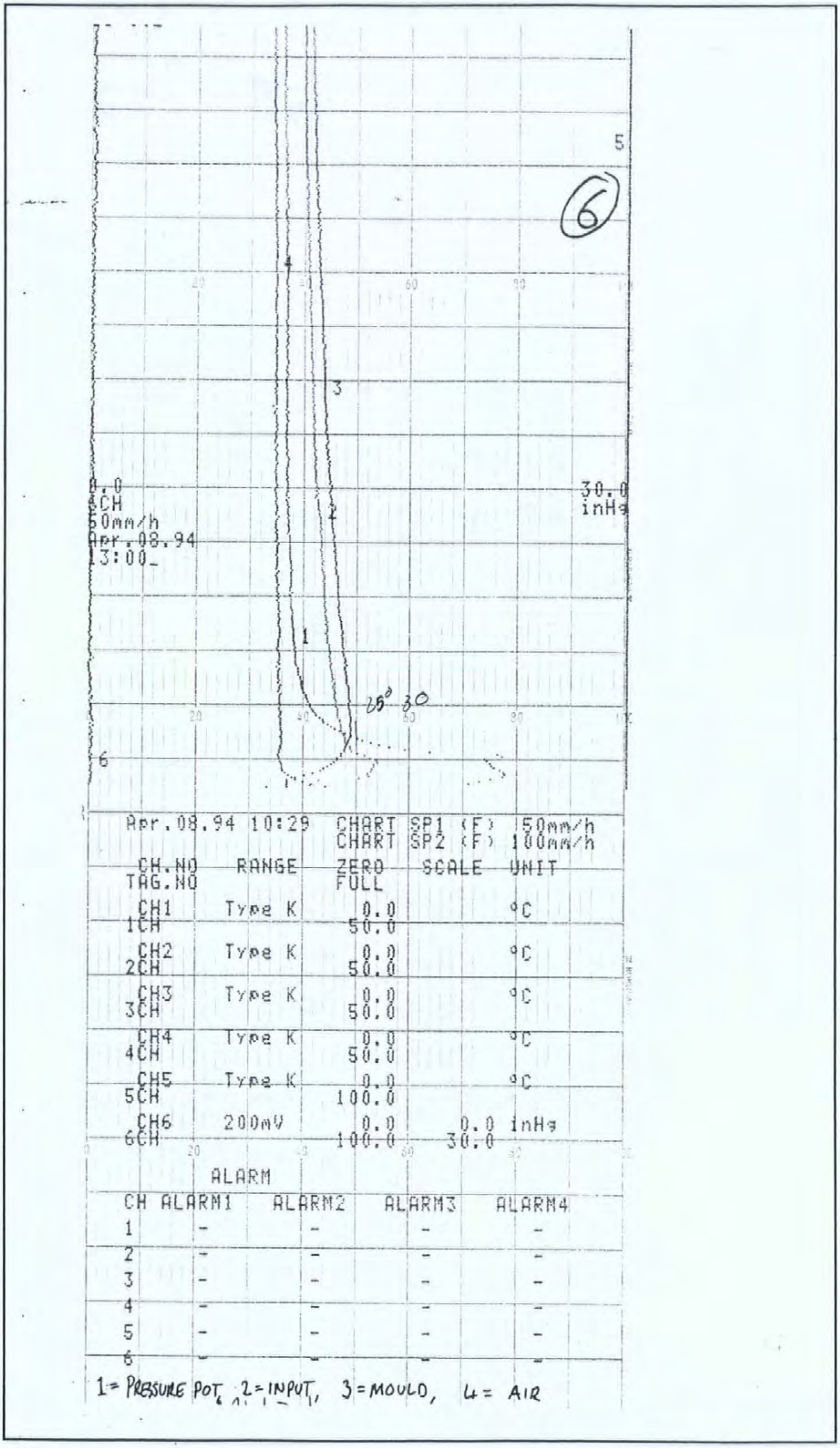
Apr.07.94 10:58   CHART SP1 (F)  50mm/h
                  CHART SP2 (F) 100mm/h
 CH.NO    RANGE   ZERO   SCALE  UNIT
TAG.NO            FULL
 CH1     Type K    0.0          °C
1CH               50.0
 CH2     Type K    0.0          °C
2CH               50.0
 CH3     Type K    0.0          °C
3CH               50.0
 CH4     Type K    0.0          °C
4CH               50.0
 CH5     Type K    0.0          °C
5CH              100.0
 CH6     200mV     0.0     0.0 inHg
6CH              100.0    30.0

       ALARM
CH ALARM1   ALARM2   ALARM3   ALARM4
1    -        -        -        -
2    -        -        -        -
3    -        -        -        -
4    -        -        -        -
5    -        -        -        -
*----=--------=--------=--------=-----
```

1 = BOTTOM JECT
2 = INLET
3 = MOULD

⑤

Coupon 5.



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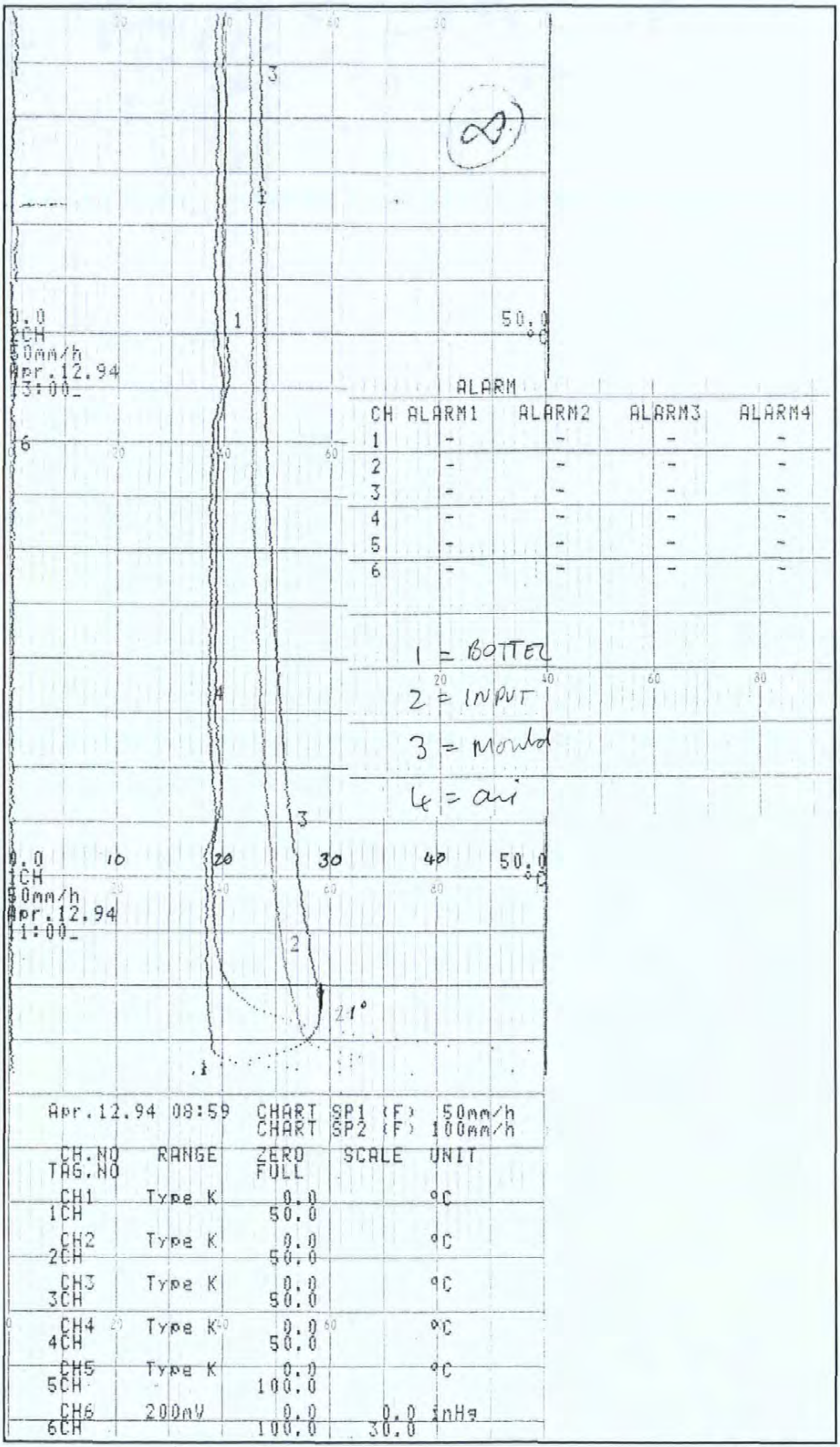
Apr.08.94 10:29   CHART SP1 (F)  50mm/h
                  CHART SP2 (F) 100mm/h
  CH.NO    RANGE    ZERO    SCALE   UNIT
 TAG.NO             FULL
  CH1     Type K     0.0            °C
 1CH                50.0
  CH2     Type K     0.0            °C
 2CH                50.0
  CH3     Type K     0.0            °C
 3CH                50.0
  CH4     Type K     0.0            °C
 4CH                50.0
  CH5     Type K     0.0            °C
 5CH               100.0
  CH6     200mV      0.0      0.0  inHg
 6CH               100.0     30.0

         ALARM
 CH ALARM1   ALARM2   ALARM3   ALARM4
 1    -        -        -        -
 2    -        -        -        -
 3    -        -        -        -
 4    -        -        -        -
 5    -        -        -        -
 6    -        -        -        -
```

1= PRESSURE POT, 2= INPUT, 3= MOULD, 4= AIR

Coupon 6.



ALARM

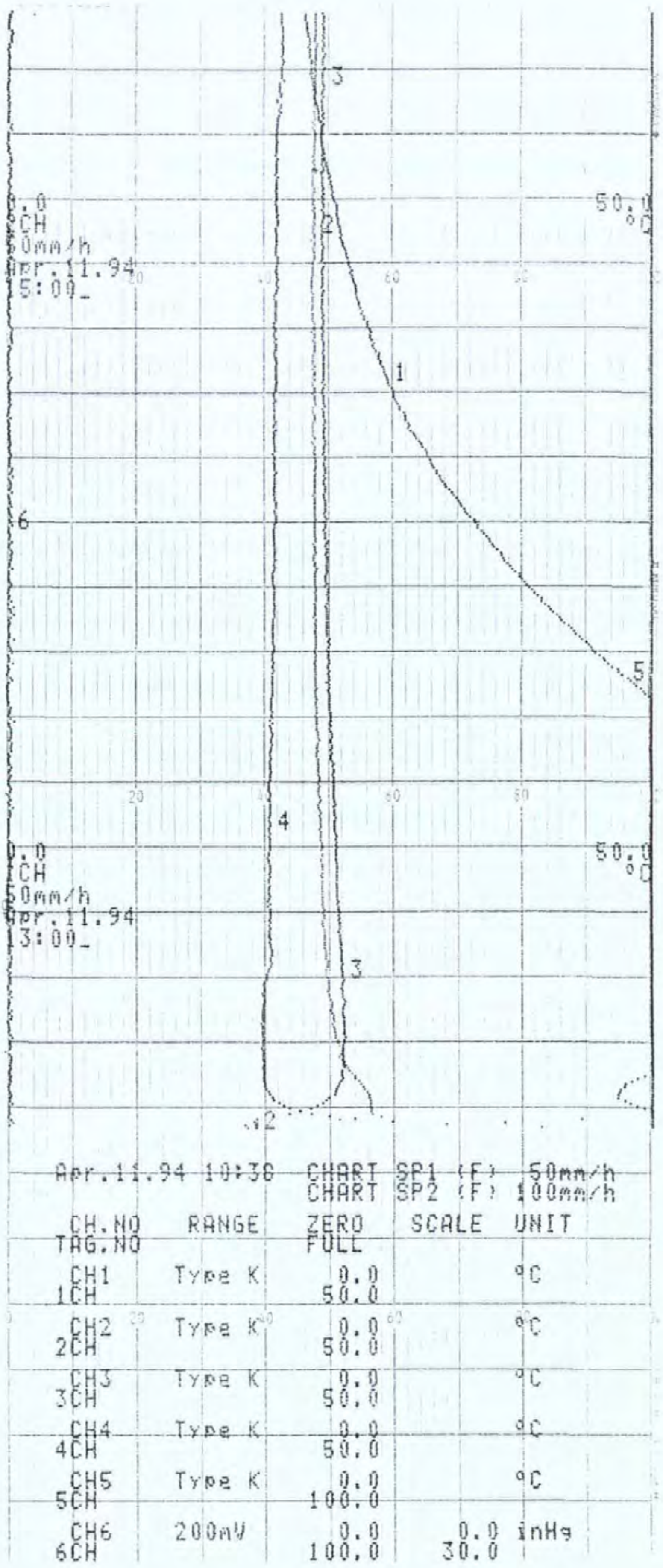
CH	ALARM1	ALARM2	ALARM3	ALARM4
1	-	-	-	-
2	-	-	-	-
3	-	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-	-	-	-

1 = BOTTEL
2 = INPUT
3 = Mould
4 = air

Apr.12.94 08:59 CHART SP1 (F) 50mm/h
CHART SP2 (F) 100mm/h

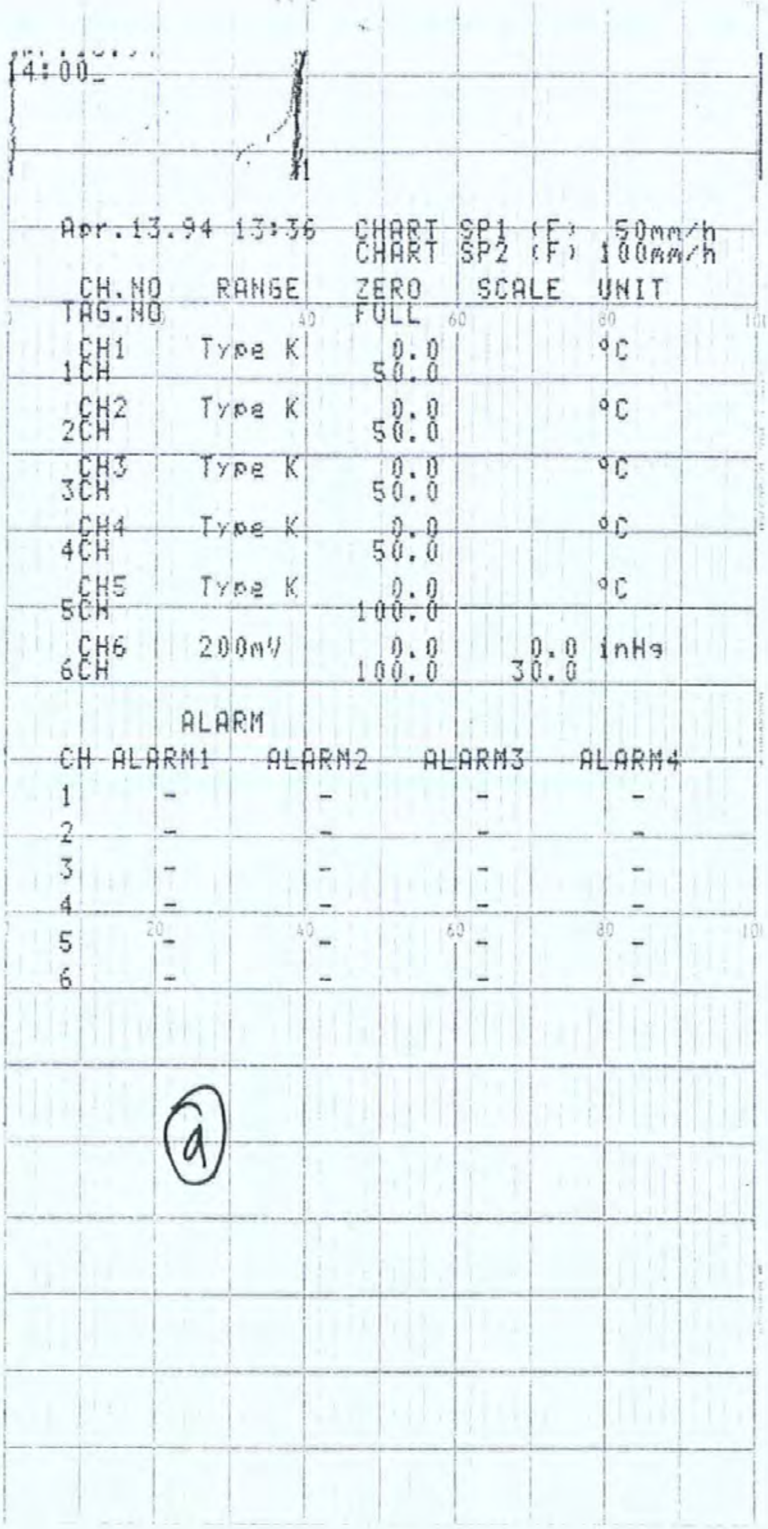
CH.NO TAG.NO	RANGE	ZERO FULL	SCALE	UNIT
CH1 1CH	Type K	0.0 50.0		°C
CH2 2CH	Type K	0.0 50.0		°C
CH3 3CH	Type K	0.0 50.0		°C
CH4 4CH	Type K	0.0 50.0		°C
CH5 5CH	Type K	0.0 100.0		°C
CH6 6CH	200mV	0.0 100.0	0.0 30.0	inHg

Coupon 8.



```
Apr.11.94 10:30   CHART SP1 (F)  50mm/h
                  CHART SP2 (F) 100mm/h
 CH.NO    RANGE   ZERO   SCALE  UNIT
TAG.NO            FULL
 CH1     Type K     0.0          °C
1CH                50.0
 CH2     Type K     0.0          °C
2CH                50.0
 CH3     Type K     0.0          °C
3CH                50.0
 CH4     Type K     0.0          °C
4CH                50.0
 CH5     Type K     0.0          °C
5CH               100.0
 CH6     200mV      0.0     0.0 inHg
6CH               100.0    30.0
```

Coupon 7.



```
14:00_
                      1

Apr.13.94 13:36   CHART SP1 (F)  50mm/h
                  CHART SP2 (F) 100mm/h

 CH.NO   RANGE    ZERO    SCALE  UNIT
TAG.NO            FULL
 CH1     Type K     0.0           °C
1CH                50.0
 CH2     Type K     0.0           °C
2CH                50.0
 CH3     Type K     0.0           °C
3CH                50.0
 CH4     Type K     0.0           °C
4CH                50.0
 CH5     Type K     0.0           °C
5CH               100.0
 CH6     200mV      0.0      0.0 inHg
6CH               100.0     30.0

        ALARM
CH ALARM1   ALARM2   ALARM3   ALARM4
1    -        -        -        -
2    -        -        -        -
3    -        -        -        -
4    -        -        -        -
5    -        -        -        -
6    -        -        -        -
```

9

Coupon 9.

Appendix 5

Composite materials property data.

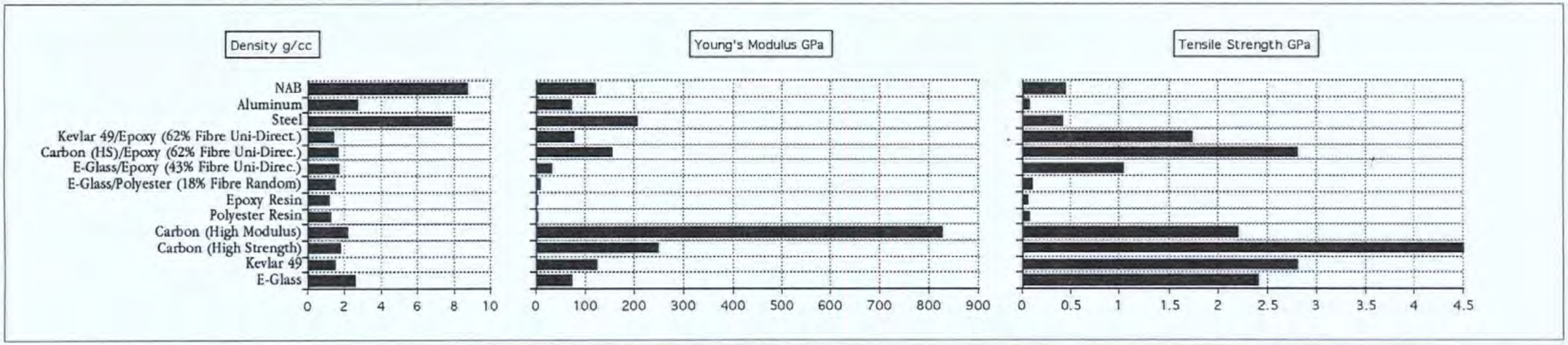
Typical Properties of Some Composite Mateials

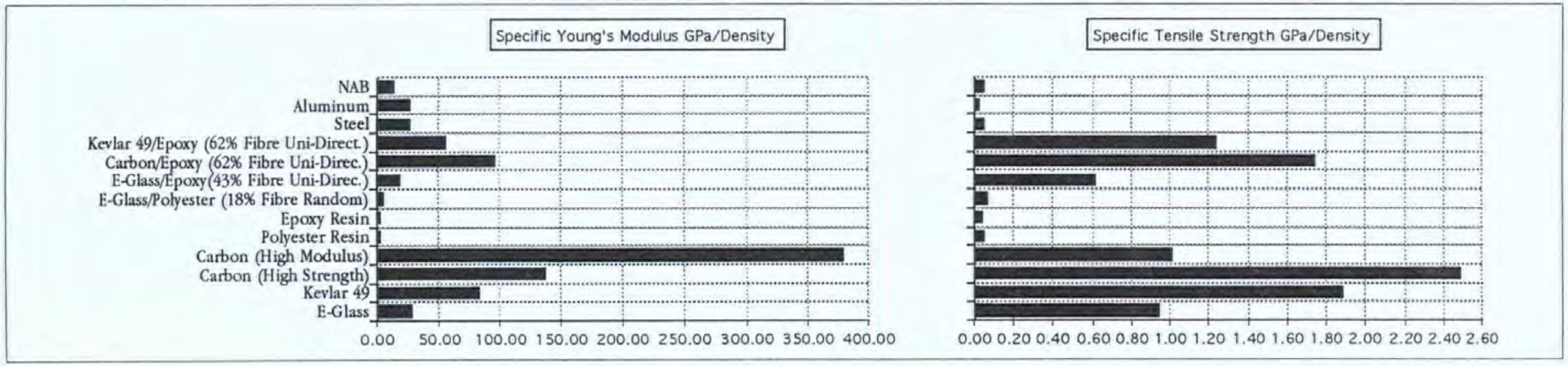
Continuous fibre reinforced composite materials have now a good track record for enabling stiff low weight and strong engineering components to be built.

A major difference exists between composites and metals, the composite has a variety of properties that are engineered to suit the application, the constituent parts of the composite are put together at the same time as the component is fabricated. As it can be seen from the table the fibre properties on there own are impressive, but these need to be combined with the resin properties to obtain the overall value. The end result follows a rule of mixtures.

It can be seen from the table, that various composites compare modestly agaist metals, however when compared on a weight for weight basis, the advantage lies heavilly with the composite.

Material	Specific Gravity grammes/cc	Young's Modulus GPa	Tensile Strength GPa	Specific Youngs Modulus GPa/ Density	Specific Tensile Strength GPa/Density
E-Glass	2.55	72	2.4	28.24	0.94
Kevlar 49	1.49	124	2.8	83.22	1.88
Carbon (High Strength)	1.81	248	4.5	137.02	2.49
Carbon (High Modulus)	2.18	826	2.2	378.90	1.01
Polyester Resin	1.23	3.2	0.065	2.60	0.05
Epoxy Resin	1.2	3	0.05	2.50	0.04
E-Glass/Polyester (18% Fibre Random)	1.5	8	0.1	5.33	0.07
E-Glass/Epoxy (43% Fibre Uni-Direc.)	1.7	30.96	1.032	18.21	0.61
Carbon (HS)/Epoxy (62% Fibre Uni-Direc.)	1.6	153.76	2.79	96.10	1.74
Kevlar 49/Epoxy (62% Fibre Uni-Direct.)	1.4	76.88	1.736	54.91	1.24
Steel	7.85	207	0.413	26.37	0.05
Aluminum	2.7	72	0.07	26.67	0.03
NAB	8.7	120	0.44	13.79	0.05





Appendix 6

Propeller load calculation spreadsheets.

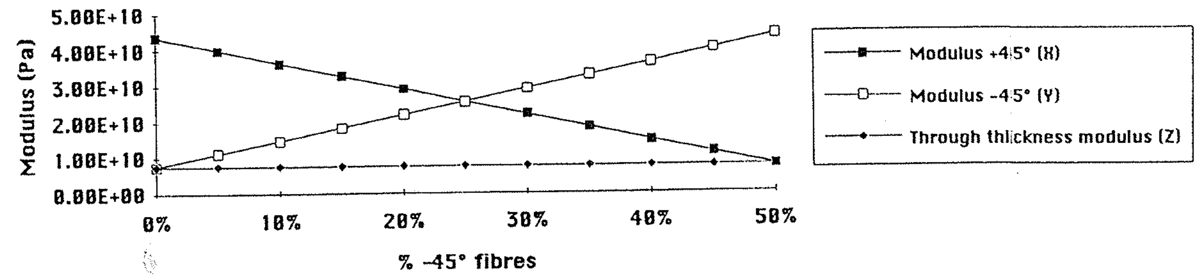
A	B	C	D	E	F	G	H	I	J	K	L	M
0.4r	2	3	4	5	6	7	8	9	10	11	12	13
Ord.	X	Yp coeff.	t coeff.	Max Thick	Yp	t	SM	t x SM	(2Yp + t)t	col 10xSM	[3Yp(Yp+t)+txt]t	col 12xSM
1	0	0.191	0.169	16.662	3.183	2.817	0.500	1.408657	25.869566	12.935	183.748	91.874
2	17.189	0.159	0.383	16.662	2.649	6.382	2.000	12.76339	74.540432	149.081	717.969	1435.937
3	34.378	0.128	0.574	16.662	2.133	9.564	1.000	9.564218	132.27114	132.271	1590.682	1590.682
4	51.567	0.096	0.765	16.662	1.600	12.747	2.000	25.49347	203.25839	406.517	2948.626	5897.252
5	68.756	0.064	0.893	16.662	1.066	14.880	1.000	14.87952	253.13507	253.135	4053.392	4053.392
6	85.945	0.000	0.989	16.662	0.000	16.479	2.000	32.95823	271.56119	543.122	4475.088	8950.175
7	103.13	0.000	1.000	16.662	0.000	16.662	1.000	16.6624	277.63557	277.636	4626.075	4626.075
8	120.32	0.000	0.989	16.662	0.000	16.479	2.000	32.95823	271.56119	543.122	4475.088	8950.175
9	137.51	0.000	0.893	16.662	0.000	14.880	1.000	14.87952	221.40021	221.400	3294.330	3294.330
10	154.7	0.064	0.638	16.662	1.066	10.631	2.000	21.26122	135.68273	271.365	1599.171	3198.341
11	171.89	0.244	0.000	16.662	4.057	0.000	0.500	0	0	0.000	0.000	0
								182.829		**2810.58**		**42088.2333**
0.6r	2	3	4	5	6	7	8	9	10	11	12	13
Ord.	X	Yp coeff.	t coeff.	Max Thick	Yp	t	SM	t x SM	(2Yp + t)t	col 10xSM	[3Yp(Yp+t)+txt]t	col 12xSM
1	0	0.051	0.169	12.294	0.627	2.079	0.500	1.039	6.9271842	3.464	19.559	9.780
2	18.786	0.000	0.304	12.294	0.000	3.737	2.000	7.475	13.967	27.934	52.198	104.397
3	37.572	0.000	0.521	12.294	0.000	6.405	1.000	6.405	41.024	41.024	262.755	262.755
4	56.358	0.000	0.694	12.294	0.000	8.532	2.000	17.064	72.791	145.582	621.034	1242.069
5	75.143	0.000	0.825	12.294	0.000	10.142	1.000	10.142	102.865	102.865	1043.276	1043.276
6	93.929	0.000	0.911	12.294	0.000	11.199	2.000	22.399	125.428	250.856	1404.728	2809.457
7	112.72	0.000	1.000	12.294	0.000	12.294	1.000	12.294	151.133	151.133	1857.964	1857.964
8	131.5	0.000	0.868	12.294	0.000	10.671	2.000	21.342	113.867	227.734	1215.056	2430.113
9	150.29	0.000	0.738	12.294	0.000	9.073	1.000	9.073	82.313	82.313	746.803	746.803
10	169.07	0.045	0.434	12.294	0.553	5.335	2.000	10.671	34.370	68.740	204.025	408.050
11	187.86	0.102	0.000	12.294	1.260	0.000	0.500	0.000	0.00	0.000	0.000	0
								117.902		**1101.64**		**10914.6625**
0.8r	2	3	4	5	6	7	8	9	10	11	12	13
Ord.	X	Yp coeff.	t coeff.	Max Thick	Yp	t	SM	t x SM	(2Yp + t)t	col 10xSM	[3Yp(Yp+t)+txt]t	col 12xSM
1	0	0.000	0.169	7.925	0.000	1.340	0.500	0.670	1.7954446	0.898	2.406	1.203
2	17.452	0.000	0.340	7.925	0.000	2.694	2.000	5.389	7.260	14.520	19.561	39.123
3	34.904	0.000	0.543	7.925	0.000	4.303	1.000	4.303	18.517	18.517	79.683	79.683
4	52.356	0.000	0.747	7.925	0.000	5.920	2.000	11.840	35.044	70.089	207.456	414.913
5	69.808	0.000	0.883	7.925	0.000	6.998	1.000	6.998	48.966	48.966	342.647	342.647
6	87.26	0.000	1.000	7.925	0.000	7.925	2.000	15.850	62.802	125.605	497.697	995.394
7	104.71	0.000	1.000	7.925	0.000	7.925	1.000	7.925	62.802	62.802	497.697	497.697
8	122.16	0.000	0.815	7.925	0.000	6.459	2.000	12.917	41.715	83.430	269.425	538.850
9	139.62	0.000	0.611	7.925	0.000	4.842	1.000	4.842	23.445	23.445	113.524	113.524
10	157.07	0.000	0.340	7.925	0.000	2.694	2.000	5.389	7.260	14.520	19.561	39.123
11	174.52	0.000	0.000	7.925	0.000	0.000	0.500	0.000	0.00	0.000	0.000	0
								76.122		**462.79**		**3062.15612**
1.0r	2	3	4	5	6	7	8	9	10	11	12	13
Ord.	X	Yp coeff.	t coeff.	Max Thick	Yp	t	SM	t x SM	(2Yp + t)t	col 10xSM	[3Yp(Yp+t)+txt]t	col 12xSM
1	0	0.000	0.000	0.000	0.000	0.000	0.500	0.000	0	0.000	0.000	0.000
2	0	0.000	0.000	0.000	0.000	0.000	2.000	0.000	0.000	0.000	0.000	0.000
3	0	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
4	0	0.000	0.000	0.000	0.000	0.000	2.000	0.000	0.000	0.000	0.000	0.000
5	0	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
6	0	0.000	0.000	0.000	0.000	0.000	2.000	0.000	0.000	0.000	0.000	0.000
7	0	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
8	0	0.000	0.000	0.000	0.000	0.000	2.000	0.000	0.000	0.000	0.000	0.000
9	0	0.000	0.000	0.000	0.000	0.000	1.000	0.000	0.000	0.000	0.000	0.000
10	0	0.000	0.000	0.000	0.000	0.000	2.000	0.000	0.000	0.000	0.000	0.000
11	0	0.000	0.000	0.000	0.000	0.000	0.500	0.000	0.00	0.000	0.000	0
								0.000		**0.00**		**0**

Glass Mod.	72000000000
Resin Mod.	5000000000

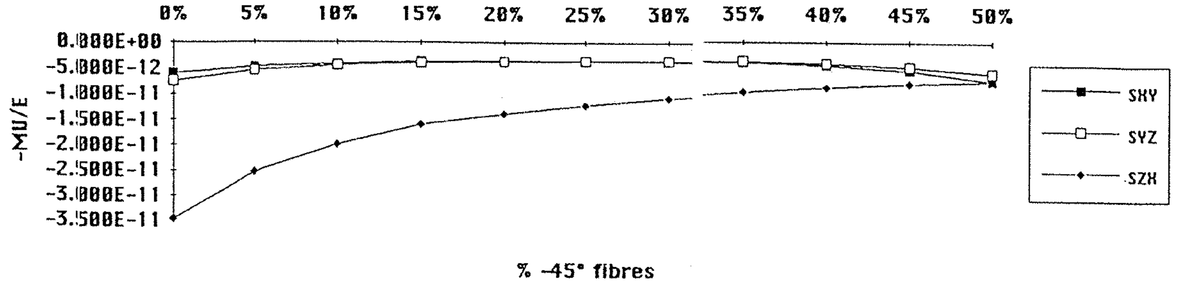
3D compliances from elastic

%FIBRE (@+45°)	%FIBRE (@-45°)	EX	EY	EZ	MUXY	MUYX	MUZY	SXY	SYZ	SZX	SXX	SYY	SZZ	SHXY	SHYZ	=P5
0.5	=0.5-B7	=($C$2*B7)+($C$3*1.5)	=($C$2*C7)+($C$3*1.5)	=$E$7	0.26	0.056	=G7	=-G7/D7	=-H7/E7	=-I7/F7	=1/D7	=1/E7	=1/F7	0.0000000002415	0.0000000003386	=P7
0.45	=0.5-B8	=($C$2*B8)+($C$3*1.5)	=($C$2*C8)+($C$3*1.5)	=$E$7	0.19	0.06	=G8	=-G8/D8	=-H8/E8	=-I8/F8	=1/D8	=1/E8	=1/F8	0.0000000002415	0.0000000003386	=P8
0.4	=0.5-B9	=($C$2*B9)+($C$3*1.5)	=($C$2*C9)+($C$3*1.5)	=$E$7	0.15	0.066	=G9	=-G9/D9	=-H9/E9	=-I9/F9	=1/D9	=1/E9	=1/F9	0.0000000002415	0.0000000003386	=P9
0.35	=0.5-B10	=($C$2*B10)+($C$3*1.5)	=($C$2*C10)+($C$3*1.5)	=$E$7	0.12	0.0729	=G10	=-G10/D10	=-H10/E10	=-I10/F10	=1/D10	=1/E10	=1/F10	0.0000000002415	0.0000000003386	=P10
0.3	=0.5-B11	=($C$2*B11)+($C$3*1.5)	=($C$2*C11)+($C$3*1.5)	=$E$7	0.105	0.0812	=G11	=-G11/D11	=-H11/E11	=-I11/F11	=1/D11	=1/E11	=1/F11	0.0000000002415	0.0000000003386	=P11
0.25	=0.5-B12	=($C$2*B12)+($C$3*1.5)	=($C$2*C12)+($C$3*1.5)	=$E$7	0.0918	0.0918	=G12	=-G12/D12	=-H12/E12	=-I12/F12	=1/D12	=1/E12	=1/F12	0.0000000002415	0.0000000003386	=P12
0.2	=0.5-B13	=($C$2*B13)+($C$3*1.5)	=($C$2*C13)+($C$3*1.5)	=$E$7	0.0812	0.105	=G13	=-G13/D13	=-H13/E13	=-I13/F13	=1/D13	=1/E13	=1/F13	0.0000000002415	0.0000000003386	=P13
0.15	=0.5-B14	=($C$2*B14)+($C$3*1.5)	=($C$2*C14)+($C$3*1.5)	=$E$7	0.0729	0.12	=G14	=-G14/D14	=-H14/E14	=-I14/F14	=1/D14	=1/E14	=1/F14	0.0000000002415	0.0000000003386	=P14
0.1	=0.5-B15	=($C$2*B15)+($C$3*1.5)	=($C$2*C15)+($C$3*1.5)	=$E$7	0.066	0.15	=G15	=-G15/D15	=-H15/E15	=-I15/F15	=1/D15	=1/E15	=1/F15	0.0000000002415	0.0000000003386	=P15
0.05	=0.5-B16	=($C$2*B16)+($C$3*1.5)	=($C$2*C16)+($C$3*1.5)	=$E$7	0.06	0.19	=G16	=-G16/D16	=-H16/E16	=-I16/F16	=1/D16	=1/E16	=1/F16	0.0000000002415	0.0000000003386	=P16
0	=0.5-B17	=($C$2*B17)+($C$3*1.5)	=($C$2*C17)+($C$3*1.5)	=$E$7	0.056	0.26	=G17	=-G17/D17	=-H17/E17	=-I17/F17	=1/D17	=1/E17	=1/F17	0.0000000002415	0.0000000003386	=P17

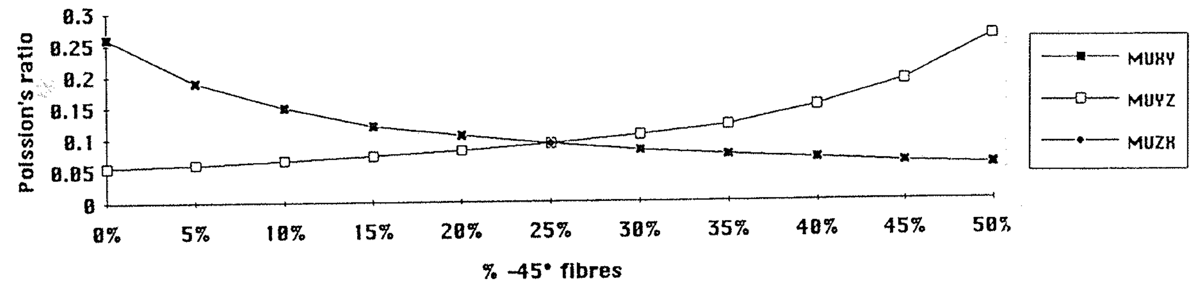
Modulus variation Figure 6.#



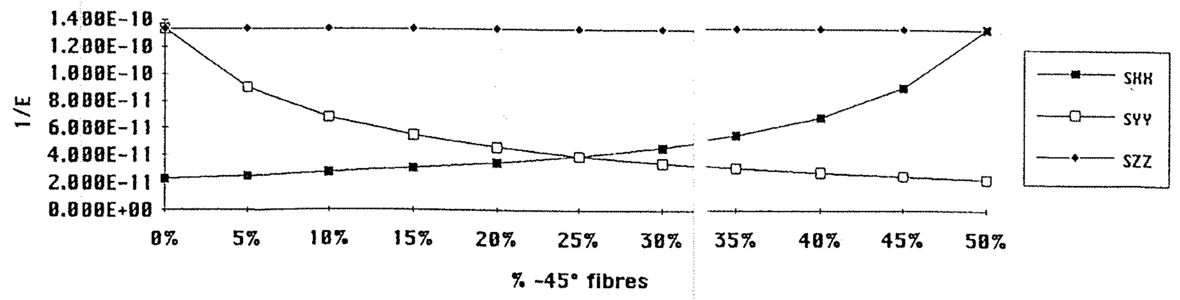
SXY, SYZ, SZX Figure 6.



Poission's ratio variation Figure 6.#



SXX, SYY, SZZ Figure 6.



A B C D E F G H I J K L M

Evaluation of Propeller Section Moduli, Test Beam Dimensions & Loads:
Prop: Pandora Composite

Bollard Pull RPM:	1450.00				BM (Nm)
Vessel Speed [knots]:	7	Stress Due to Thrust:	=E9*1000*E15*E16*(E23-E25)*(E13*12.5)*COS(RADIANS(D28))/(D29*E17*D35)	MPa	=K7*D35/1000
Engine RPM:	1750	Stress Due to Torque:	=E9*1000*E15*(E24-E25)*SIN(RADIANS(D28))/(2*PI()*((E8/E10)/60)*E24*4*D35)*1000	MPa	=K8*D35/1000
Engine Power [kW]:	31	Stress Due to Centrifugal Bending Moment:	=(K10*D34)/D35*E13*12.7*(E22-E25)*TAN(RADIANS(E18))*SIN(RADIANS(D28))	MPa	=K9*D35/1000
Gear Ratio:	1.85	Stress Due to Centrifugal Force (Direct stress:	=2*PI()*PI()*D30*E22*E13*0.0254*(E8/E10)/60*(E8/E10)/60/D34	MPa	
Taylor Wake Fraction:	0.2	Stress Due To Impact Loads:	0.00	MPa	
DAR:	0.5	**Maximum Tensile Stress Acting On Section:**	=SUM(K7..K11)	MPa	=M7+M8+M9
Prop.Diameter [in]:	20				(Total BM)
Prop. pitch [in]:	12				
Shaft Effic:	0.98				
Prop. Effic:	0.55				
Number of Blades:	3				
Rake Angle:	0				BM (Nm)
Skew Angle:	0	Stress Due to Thrust:	=E9*1000*E15*E16*(E23-E25)*(E13*12.5)*COS(RADIANS(D28))/(D36*E17*D35)	MPa	=K19*H29/1000
Beam Width:	50	Stress Due to Torque:	=E9*1000*E15*(E24-E25)*SIN(RADIANS(D28))/(2*PI()*((E6/E10)/60)*E24*4*D35)*1000	MPa	=K20*D35/1000
Material Density	2000	Stress Due to Centrifugal Bending Moment:	=(K22*D34)/D35*E13*12.7*(E22-E25)*TAN(RADIANS(E18))*SIN(RADIANS(D28))	MPa	=K21*D35/1000
Non-dim Blade CoG:	0.51	Stress Due to Centrifugal Force (Direct stress:	=2*PI()*PI()*D30*E22*E13*0.0254*(E6/E10)/60*(E6/E10)/60/D34	MPa	
Thrust Moment Arm [a]:	0.7	Stress Due To Impact Loads:	0.00	MPa	
Torque Moment Arm [b]:	0.6	**Maximum Tensile Stress Acting On Section:**	=SUM(K19..K23)	MPa	=M19+M20+M21
Non-dim. Stress Sec. Radius:	0.2				(Total BM)

	Mean Blade Thickness	=AVERAGE(G63..G73)/2	mm		**Beam**		**Max Blade**	
	Stress Sect. Pitch	=DEGREES(ATAN(E14/(PI()*E25*E13)))	deg	**Radius**	**Depth**	**z**	**Thickness**	**Area**
	Speed of Advance	=E7*0.515*(1-E11)	m/s	0.2	=SQRT(6*H29/E20)	=((2*(2*M74*B64/3)*J29)/(3*(2*K74*B64/3)))-(0.5*2*K74*B64/3)	=(1-F29)*D31*(((13-D33)*0.005)-0.007)+(0.007*D31)	=2*I74*B64/3
	Blade Mass	=0.75*D27/1000*(E12*PI()*(E13*0.0254)*(E13*0.0254))/(4*E17)*E21	kg	0.4	=SQRT(6*H30/E20)	=((2*(2*M88*B78/3)*J30)/(3*(2*K88*B78/3)))-(0.5*2*K88*B78/3)	=(1-F30)*D31*(((13-D33)*0.005)-0.007)+(0.007*D31)	=2*I88*B78/3
	Diameter	=E13*25.4	mm	0.6	=SQRT(6*H31/E20)	=((2*(2*M111*B101/3)*J31)/(3*(2*K111*B101/3)))-(0.5*2*K111*B101/3)	=(1-F31)*D31*(((13-D33)*0.005)-0.007)+(0.007*D31)	=2*I111*B101/3
	Ae/Ao	=E12	-	0.8	=SQRT(6*H32/E20)	=((2*(2*M125*B115/3)*J32)/(3*(2*K125*B115/3)))-(0.5*2*K125*B115/3)	=(1-F32)*D31*(((13-D33)*0.005)-0.007)+(0.007*D31)	=2*I125*B115/3
	No. Blades	=E17	-	1	=SQRT(6*H33/E20)+I33	0.000	=(1-F33)*D31*(((13-D33)*0.005)-0.007)+(0.007*D31)	0.000
mm^2	Section Area [A]	=J29						
mm^3	Section Modulus [Z]	=H29						
	Speed of water thru prop	=E14*0.0254*E6/(E10*60)	m/sec					

		Chord Length Coeff..	
No Blades	Coeff..	2,3 Blade	4,5,6,7, Bl..
2	=1.104*D32*D31	0.747	0.761
3	=0.7396*D32*D31	0.915	0.936
4	=0.5467*D32*D31	1.000	1.000
5	=0.4373*D32*D31	0.929	0.900
6	=0.3628*D32*D31	0.000	0.000
7	=0.3174*D32*D31		

0.2r	2	3	4	5	6	7	8	9	10	11	12	13
Ord.	X	Yp coeff.	t coeff.	Max Thick	Yp	t	SM	t x SM	(2Yp + t)t	col 10xSM	[3Yp(Yp+t)+txt]t	col 12xSM
1	0.000	0.300	=I33/I29	=I29	=C63*E63	=D63*E63	0.500	=G63*H63	=G63*(2*F63+G63)	=J63*H63	=G63*(3*F63*(F63+G63)+(G63*G63))	=L63*H63
2	=(IF(D33<4;F41;G41)/10)*IF(D33=2;E41;(IF(D33=3;E42;(IF(D33=4;E43;(IF(D33=5;E44;(IF(D33=6;E45;(IF(D33=7;E46;0))))))))))))	0.202	0.353	=E63	=C64*E64	=D64*E64	2.000	=G64*H64	=G64*(2*F64+G64)	=J64*H64	=G64*(3*F64*(F64+G64)+(G64*G64))	=L64*H64
3	=B64*2	0.126	0.504	=E64	=C65*E65	=D65*E65	1.000	=G65*H65	=G65*(2*F65+G65)	=J65*H65	=G65*(3*F65*(F65+G65)+(G65*G65))	=L65*H65
4	=B64*3	0.076	0.706	=E65	=C66*E66	=D66*E66	2.000	=G66*H66	=G66*(2*F66+G66)	=J66*H66	=G66*(3*F66*(F66+G66)+(G66*G66))	=L66*H66
5	=B64*4	0.025	0.857	=E66	=C67*E67	=D67*E67	1.000	=G67*H67	=G67*(2*F67+G67)	=J67*H67	=G67*(3*F67*(F67+G67)+(G67*G67))	=L67*H67
6	=B64*5	0.000	0.907	=E67	=C68*E68	=D68*E68	2.000	=G68*H68	=G68*(2*F68+G68)	=J68*H68	=G68*(3*F68*(F68+G68)+(G68*G68))	=L68*H68
7	=B64*6	0.000	0.958	=E68	=C69*E69	=D69*E69	1.000	=G69*H69	=G69*(2*F69+G69)	=J69*H69	=G69*(3*F69*(F69+G69)+(G69*G69))	=L69*H69
8	=B64*7	0.000	0.983	=E69	=C70*E70	=D70*E70	2.000	=G70*H70	=G70*(2*F70+G70)	=J70*H70	=G70*(3*F70*(F70+G70)+(G70*G70))	=L70*H70
9	=B64*8	0.050	0.907	=E70	=C71*E71	=D71*E71	1.000	=G71*H71	=G71*(2*F71+G71)	=J71*H71	=G71*(3*F71*(F71+G71)+(G71*G71))	=L71*H71
10	=B64*9	0.126	0.655	=E71	=C72*E72	=D72*E72	2.000	=G72*H72	=G72*(2*F72+G72)	=J72*H72	=G72*(3*F72*(F72+G72)+(G72*G72))	=L72*H72
11	=B64*10	0.368	=I2	=E72	=C73*E73	=D73*E73	0.500	=G73*H73	=G73*(2*F73+G73)	=J73*H73	=G73*(3*F73*(F73+G73)+(G73*G73))	=L73*H73
								=SUM(I63..I73)		=SUM(K63..K73)		=SUM(M63..M73)

Help:	This worksheet calcul
Vessel:	Aquatay
Sheet:	Load.XLS
Date:	33619

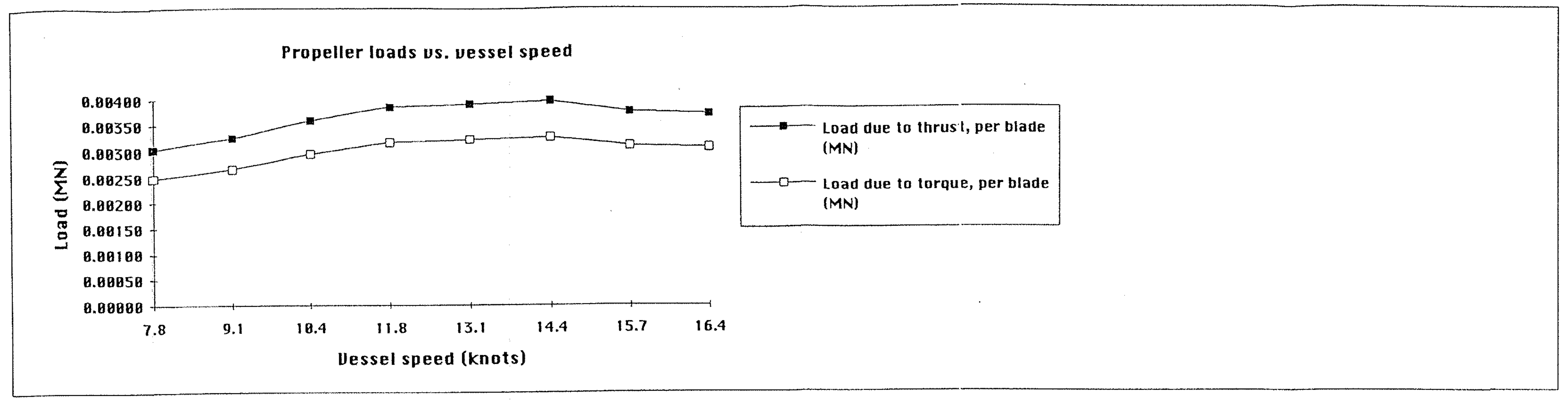
Propeller Parameters:	
No. Blades	3
Prop. Efficiency	0.55
Pitch (m)	0.558
Diameter (m)	0.62
DAR	0.7
Taylor Wake Fraction	0.93
Gear Ratio	1.93

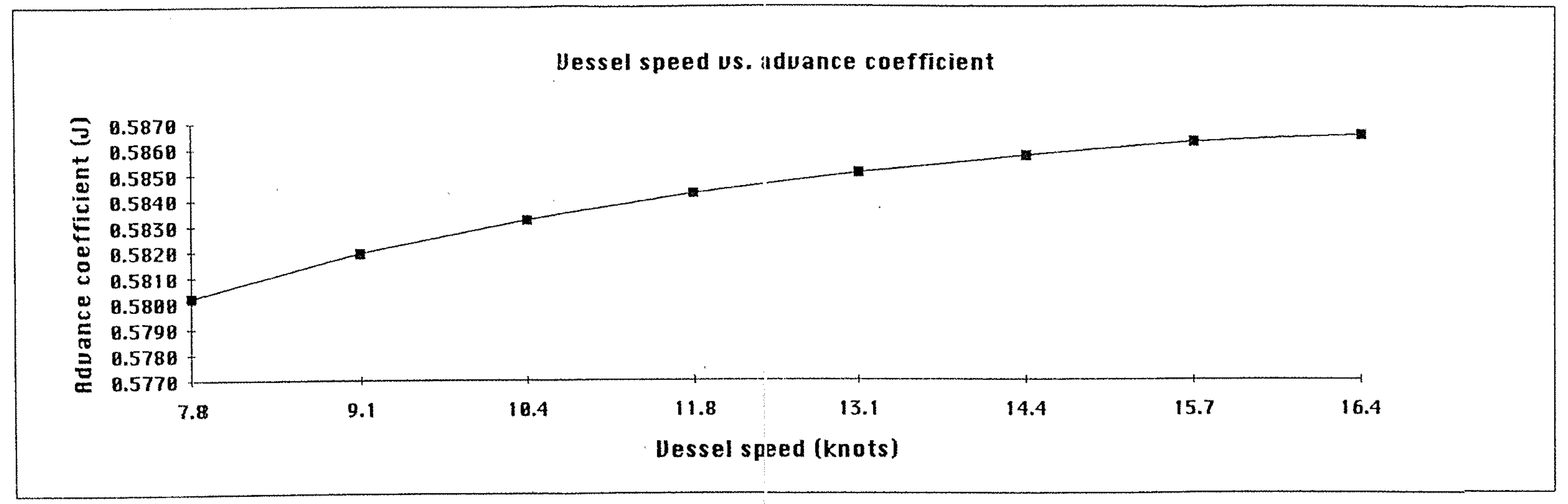
Vessel Operating Para

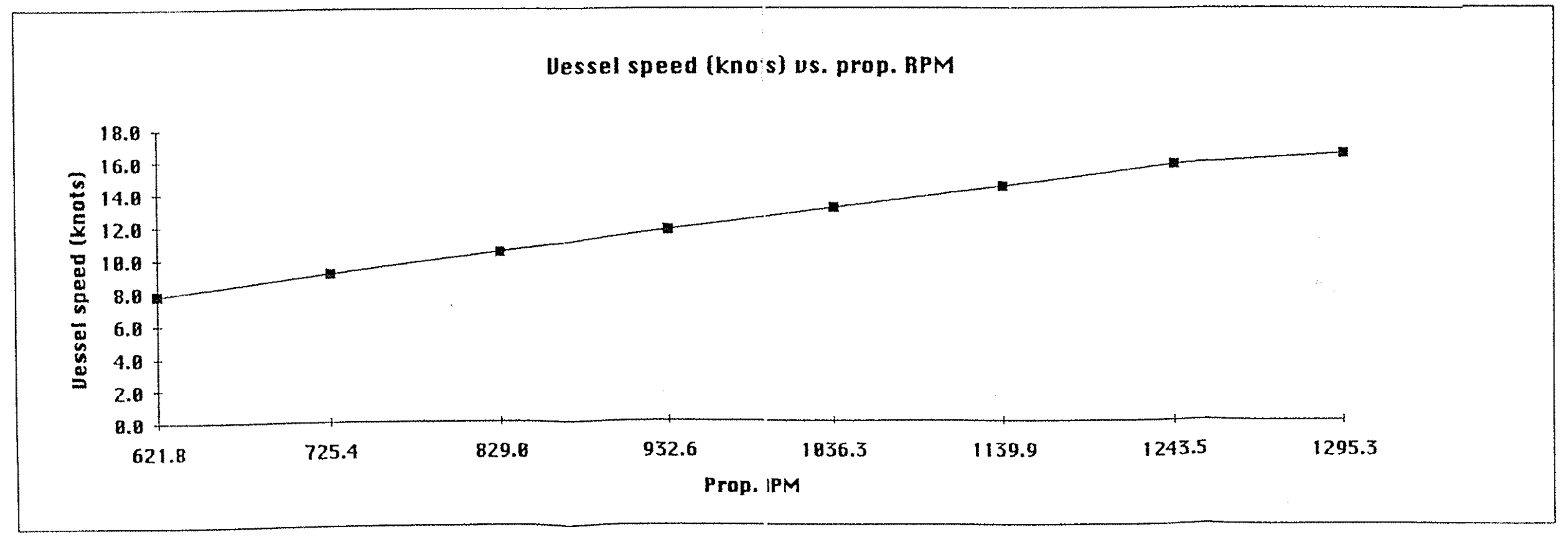
Pd (kw)	RPM (engine)	Boat Speed (Knots)	RPM (prop)	J	Total Load Thrust (MN)	Total Load Torque (MN)
60	1200	= - 0.16366+0.012796*E14	=C14/$H$9	=((D14*0.5144)*$H$8)/(((C14/$H$9)/60)*$H$6)	=(B14*1000*$H$4)/($H$3*(D14/2)*$H$8)/1000000	=(B14*1000*$H$4)/(PI()*2*($H$6*0.33)*(C14/($H$9*60)))/1000000
75	1400	= - 0.16366+0.012796*E15	=C15/$H$9	=((D15*0.5144)*$H$8)/(((C15/$H$9)/60)*$H$6)	=(B15*1000*$H$4)/($H$3*(D15/2)*$H$8)/1000000	=(B15*1000*$H$4)/(PI()*2*($H$6*0.33)*(C15/($H$9*60)))/1000000
95	1600	= - 0.16366+0.012796*E16	=C16/$H$9	=((D16*0.5144)*$H$8)/(((C16/$H$9)/60)*$H$6)	=(B16*1000*$H$4)/($H$3*(D16/2)*$H$8)/1000000	=(B16*1000*$H$4)/(PI()*2*($H$6*0.33)*(C16/($H$9*60)))/1000000
115	1800	= - 0.16366+0.012796*E17	=C17/$H$9	=((D17*0.5144)*$H$8)/(((C17/$H$9)/60)*$H$6)	=(B17*1000*$H$4)/($H$3*(D17/2)*$H$8)/1000000	=(B17*1000*$H$4)/(PI()*2*($H$6*0.33)*(C17/($H$9*60)))/1000000
130	2000	= - 0.16366+0.012796*E18	=C18/$H$9	=((D18*0.5144)*$H$8)/(((C18/$H$9)/60)*$H$6)	=(B18*1000*$H$4)/($H$3*(D18/2)*$H$8)/1000000	=(B18*1000*$H$4)/(PI()*2*($H$6*0.33)*(C18/($H$9*60)))/1000000
145	2200	= - 0.16366+0.012796*E19	=C19/$H$9	=((D19*0.5144)*$H$8)/(((C19/$H$9)/60)*$H$6)	=(B19*1000*$H$4)/($H$3*(D19/2)*$H$8)/1000000	=(B19*1000*$H$4)/(PI()*2*($H$6*0.33)*(C19/($H$9*60)))/1000000
150	2400	= - 0.16366+0.012796*E20	=C20/$H$9	=((D20*0.5144)*$H$8)/(((C20/$H$9)/60)*$H$6)	=(B20*1000*$H$4)/($H$3*(D20/2)*$H$8)/1000000	=(B20*1000*$H$4)/(PI()*2*($H$6*0.33)*(C20/($H$9*60)))/1000000
155	2500	= - 0.16366+0.012796*E21	=C21/$H$9	=((D21*0.5144)*$H$8)/(((C21/$H$9)/60)*$H$6)	=(B21*1000*$H$4)/($H$3*(D21/2)*$H$8)/1000000	=(B21*1000*$H$4)/(PI()*2*($H$6*0.33)*(C21/($H$9*60)))/1000000

Thrust	=F14	=F15	=F16	=F17	=F18	=F19	=F20	=F21
0	=$G$14*B24	=$G$15*B24	=$G$16*B24	=$G$17*B24	=$G$18*B24	=$G$19*B24	=$G$20*B24	=$G$21*B24
0.01	=$G$14*B25	=$G$15*B25	=$G$16*B25	=$G$17*B25	=$G$18*B25	=$G$19*B25	=$G$20*B25	=$G$21*B25
0.02	=$G$14*B26	=$G$15*B26	=$G$16*B26	=$G$17*B26	=$G$18*B26	=$G$19*B26	=$G$20*B26	=$G$21*B26
0.05	=$G$14*B27	=$G$15*B27	=$G$16*B27	=$G$17*B27	=$G$18*B27	=$G$19*B27	=$G$20*B27	=$G$21*B27
0.09	=$G$14*B28	=$G$15*B28	=$G$16*B28	=$G$17*B28	=$G$18*B28	=$G$19*B28	=$G$20*B28	=$G$21*B28
0.15	=$G$14*B29	=$G$15*B29	=$G$16*B29	=$G$17*B29	=$G$18*B29	=$G$19*B29	=$G$20*B29	=$G$21*B29
0.19	=$G$14*B30	=$G$15*B30	=$G$16*B30	=$G$17*B30	=$G$18*B30	=$G$19*B30	=$G$20*B30	=$G$21*B30
0.2	=$G$14*B31	=$G$15*B31	=$G$16*B31	=$G$17*B31	=$G$18*B31	=$G$19*B31	=$G$20*B31	=$G$21*B31
0.17	=$G$14*B32	=$G$15*B32	=$G$16*B32	=$G$17*B32	=$G$18*B32	=$G$19*B32	=$G$20*B32	=$G$21*B32
0.12	=$G$14*B33	=$G$15*B33	=$G$16*B33	=$G$17*B33	=$G$18*B33	=$G$19*B33	=$G$20*B33	=$G$21*B33
0	=$G$14*B34	=$G$15*B34	=$G$16*B34	=$G$17*B34	=$G$18*B34	=$G$19*B34	=$G$20*B34	=$G$21*B34
	=SUM(C24:C34)	=SUM(D24:D34)	=SUM(E24:E34)	=SUM(F24:F34)	=SUM(G24:G34)	=SUM(H24:H34)	=SUM(I24:I34)	=SUM(J24:J34)

Torque	=C23	=D23	=E23	=F23	=G23	=H23	=I23	=J23
0	=$H$14*B38	=$H$15*B38	=$H$16*B38	=$H$17*B38	=$H$18*B38	=$H$19*B38	=$H$20*B38	=$H$21*B38
0.01	=$H$14*B39	=$H$15*B39	=$H$16*B39	=$H$17*B39	=$H$18*B39	=$H$19*B39	=$H$20*B39	=$H$21*B39
0.02	=$H$14*B40	=$H$15*B40	=$H$16*B40	=$H$17*B40	=$H$18*B40	=$H$19*B40	=$H$20*B40	=$H$21*B40
0.05	=$H$14*B41	=$H$15*B41	=$H$16*B41	=$H$17*B41	=$H$18*B41	=$H$19*B41	=$H$20*B41	=$H$21*B41
0.09	=$H$14*B42	=$H$15*B42	=$H$16*B42	=$H$17*B42	=$H$18*B42	=$H$19*B42	=$H$20*B42	=$H$21*B42
0.15	=$H$14*B43	=$H$15*B43	=$H$16*B43	=$H$17*B43	=$H$18*B43	=$H$19*B43	=$H$20*B43	=$H$21*B43
0.19	=$H$14*B44	=$H$15*B44	=$H$16*B44	=$H$17*B44	=$H$18*B44	=$H$19*B44	=$H$20*B44	=$H$21*B44
0.2	=$H$14*B45	=$H$15*B45	=$H$16*B45	=$H$17*B45	=$H$18*B45	=$H$19*B45	=$H$20*B45	=$H$21*B45
0.17	=$H$14*B46	=$H$15*B46	=$H$16*B46	=$H$17*B46	=$H$18*B46	=$H$19*B46	=$H$20*B46	=$H$21*B46
0.12	=$H$14*B47	=$H$15*B47	=$H$16*B47	=$H$17*B47	=$H$18*B47	=$H$19*B47	=$H$20*B47	=$H$21*B47
0	=$H$14*B48	=$H$15*B48	=$H$16*B48	=$H$17*B48	=$H$18*B48	=$H$19*B48	=$H$20*B48	=$H$21*B48
	=SUM(C38:C48)	=SUM(D38:D48)	=SUM(E38:E48)	=SUM(F38:F48)	=SUM(G38:G48)	=SUM(H38:H48)	=SUM(I38:I48)	=SUM(J38:J48)







	Fibre	Resin
Modulus (GPa)	72	8
Tensile strength (MPa)	2400	85
Compressive strength (MPa)	1440	130
Shear inplane mod (GPa)	=E3*3/5	=F3*3/5
Shear inplane strength (MPa)	=E4*3/5	=F4*3/5

Orthotropic Epoxy/Glass Lamina at

% 0° Fibre	%90° Fibre	Ex	Ey	Gxy	Nuxy	X	X'	Y	Y'	Sxy	Fxy*
50	0	40	8	24	0.26	1242.5	785	85	130	51	-0.5
37.5	12.5	=J5*H6/50	14	24	0.13	=N5*H6/50	=O5*H6/50	354.6	=261.25	51	-0.5
25	25	=J5*25/50	20	24	0.0918	=N5*0.5	=O5*0.5	=N7	=O7	51	-0.5

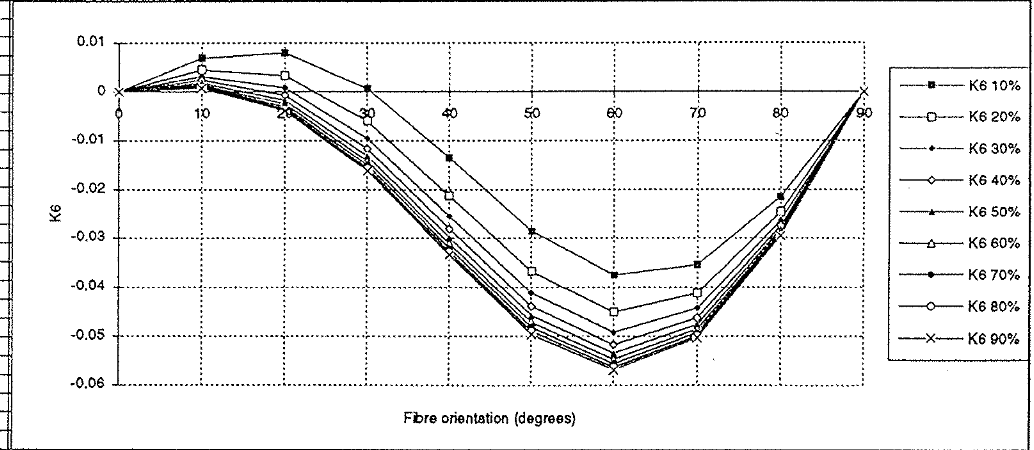
Laminate Properties Modified

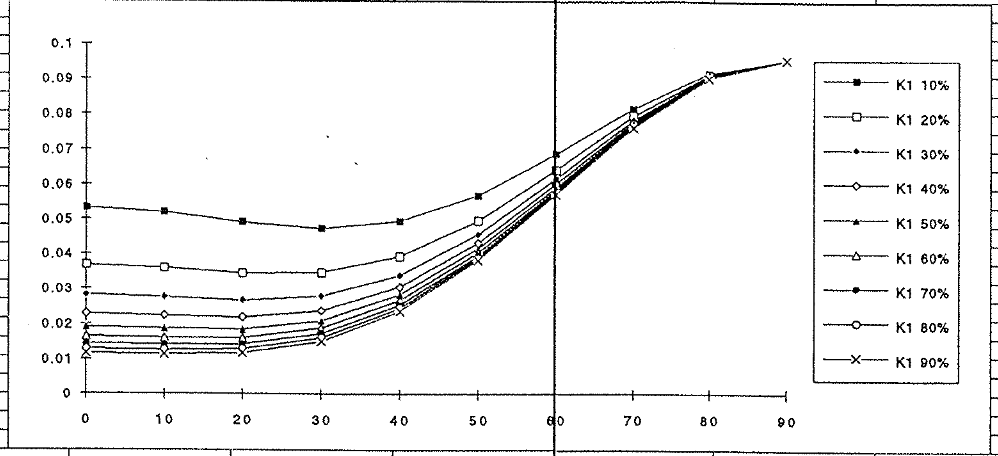
Volume Frac.	Ex	Ey	Gxy	Nuxy	X	X'	Y	Y'	Sxy	Fxy*
0	=$F$3*(1-B11)+($E$3*B11)	=$F$3	=$F$6*(1-B11)+($E$6*B11)	0.26	=$F$4*(1-B11)+($E$4*B11)	=$F$5*(1-B11)+($E$5*B11)	=$F$4	=$F$5	=$F$7	-0.5
=B11+0.1	=$F$3*(1-B12)+($E$3*B12)	=$F$3	=$F$6*(1-B12)+($E$6*B12)	0.26	=$F$4*(1-B12)+($E$4*B12)	=$F$5*(1-B12)+($E$5*B12)	=$F$4	=$F$5	=$F$7	-0.5
=B12+0.1	=$F$3*(1-B13)+($E$3*B13)	=$F$3	=$F$6*(1-B13)+($E$6*B13)	0.26	=$F$4*(1-B13)+($E$4*B13)	=$F$5*(1-B13)+($E$5*B13)	=$F$4	=$F$5	=$F$7	-0.5
=B13+0.1	=$F$3*(1-B14)+($E$3*B14)	=$F$3	=$F$6*(1-B14)+($E$6*B14)	0.26	=$F$4*(1-B14)+($E$4*B14)	=$F$5*(1-B14)+($E$5*B14)	=$F$4	=$F$5	=$F$7	-0.5
=B14+0.1	=$F$3*(1-B15)+($E$3*B15)	=$F$3	=$F$6*(1-B15)+($E$6*B15)	0.26	=$F$4*(1-B15)+($E$4*B15)	=$F$5*(1-B15)+($E$5*B15)	=$F$4	=$F$5	=$F$7	-0.5
=B15+0.1	=$F$3*(1-B16)+($E$3*B16)	=$F$3	=$F$6*(1-B16)+($E$6*B16)	0.26	=$F$4*(1-B16)+($E$4*B16)	=$F$5*(1-B16)+($E$5*B16)	=$F$4	=$F$5	=$F$7	-0.5
=B16+0.1	=$F$3*(1-B17)+($E$3*B17)	=$F$3	=$F$6*(1-B17)+($E$6*B17)	0.26	=$F$4*(1-B17)+($E$4*B17)	=$F$5*(1-B17)+($E$5*B17)	=$F$4	=$F$5	=$F$7	-0.5
=B17+0.1	=$F$3*(1-B18)+($E$3*B18)	=$F$3	=$F$6*(1-B18)+($E$6*B18)	0.26	=$F$4*(1-B18)+($E$4*B18)	=$F$5*(1-B18)+($E$5*B18)	=$F$4	=$F$5	=$F$7	-0.5
=B18+0.1	=$F$3*(1-B19)+($E$3*B19)	=$F$3	=$F$6*(1-B19)+($E$6*B19)	0.26	=$F$4*(1-B19)+($E$4*B19)	=$F$5*(1-B19)+($E$5*B19)	=$F$4	=$F$5	=$F$7	-0.5
=B19+0.1	=$F$3*(1-B20)+($E$3*B20)	=$F$3	=$F$6*(1-B20)+($E$6*B20)	0.26	=$F$4*(1-B20)+($E$4*B20)	=$F$5*(1-B20)+($E$5*B20)	=$F$4	=$F$5	=$F$7	-0.5
=B20+0.1	=$F$3*(1-B21)+($E$3*B21)	=$F$3	=$F$6*(1-B21)+($E$6*B21)	0.26	=$F$4*(1-B21)+($E$4*B21)	=$F$5*(1-B21)+($E$5*B21)	=$F$4	=$F$5	=$F$7	-0.5

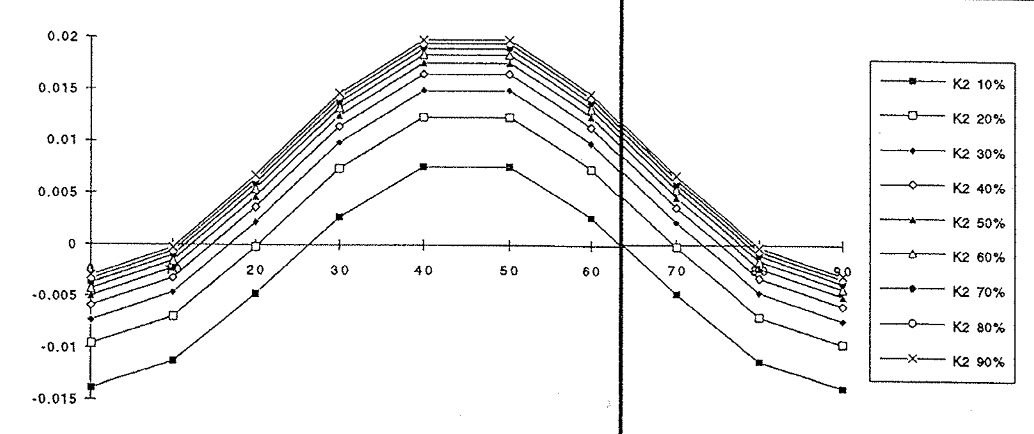
K1 70%	K2 70%	K6 70%	K1 80%	K2 80%	K6 80%	K1 90%	K2 90%	K6 90%
0.01455	-0.00378	0	0.01297	-0.00337	0	0.01171	-0.00304	0
0.01426	-0.00104	0.00115	0.01273	-0.00062	0.00092	0.01149	-0.00029	0.00074
0.01438	0.00591	-0.00307	0.01297	0.00635	-0.00352	0.01183	0.0067	-0.00388
0.01731	0.01381	-0.01495	0.01609	0.01427	-0.01558	0.0151	0.01463	-0.01609
0.02544	0.01897	-0.03208	0.02446	0.01944	-0.03284	0.02368	0.01982	-0.03344
0.03959	0.01897	-0.04813	0.03888	0.01944	-0.04893	0.03831	0.01982	-0.04957
0.05804	0.01381	-0.05559	0.0576	0.01427	-0.05632	0.05725	0.01463	-0.05691
0.07678	0.00591	-0.04928	0.07657	0.00635	-0.04985	0.0764	0.00669	-0.0503
0.0908	-0.00104	-0.02901	0.09075	-0.00062	-0.02932	0.0907	-0.00029	-0.02957
0.096	-0.00378	0	0.096	-0.00337	0	0.096	-0.00304	0

Fibre Angle	K1 10%	K2 10%	K6 10%	K1 20%	K2 20%	K6 20%	K1 30%	K2 30%	K6 30%
0	0.05333	-0.01387	0	0.03692	-0.0096	0	0.02823	-0.00734	0
=B26+10	0.05204	-0.01129	0.00687	0.03605	-0.00695	0.00445	0.02759	-0.00465	0.00317
=B27+10	0.04922	-0.00476	0.008	0.03448	-0.00024	0.00332	0.02667	0.00215	0.00084
=B28+10	0.04747	0.00267	0.00062	0.03471	0.00738	-0.00597	0.02795	0.00988	-0.00947
=B29+10	0.04958	0.00751	-0.01347	0.03937	0.01236	-0.02134	0.03396	0.01493	-0.02551
=B30+10	0.05699	0.00751	-0.02855	0.04963	0.01236	-0.03683	0.04573	0.01493	-0.04122
=B31+10	0.0688	0.00267	-0.03757	0.06425	0.00738	-0.04519	0.06183	0.00988	-0.04923
=B32+10	0.0819	-0.00476	-0.03542	0.07973	-0.00024	-0.04129	0.07858	0.00215	-0.04439
=B33+10	0.09213	-0.01129	-0.02147	0.09157	-0.00695	-0.02466	0.09127	-0.00465	-0.02635
=B34+10	0.096	-0.01387	0	0.096	-0.0096	0	0.096	-0.00734	0

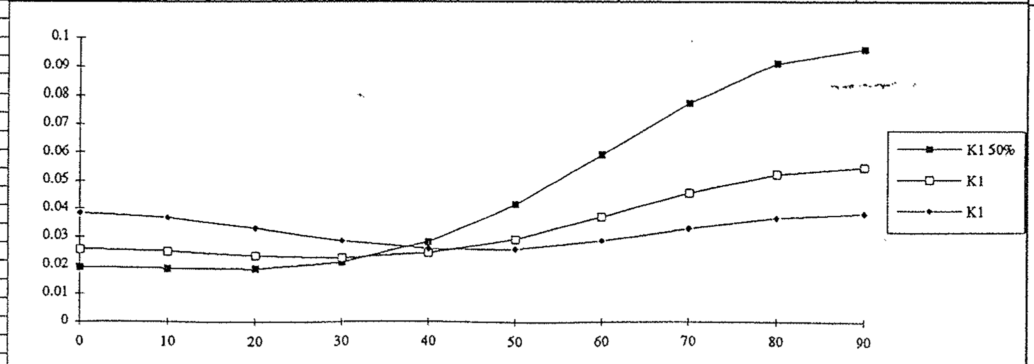
Fibre Angle	K1 40%	K2 40%	K6 40%	K1 50%	K2 50%	K6 50%	K1 60%	K2 60%	K6 60%
0	0.02286	-0.00594	0	0.0192	-0.00499	0	0.01655	-0.0043	0
=B26+10	0.02235	-0.00323	0.00238	0.01879	-0.00227	0.00184	0.01621	-0.00157	0.00145
=B27+10	0.02184	0.00363	-0.0007	0.01856	0.00463	-0.00174	0.01618	0.00536	-0.0025
=B28+10	0.02377	0.01143	-0.01161	0.02093	0.01248	-0.01308	0.01887	0.01324	-0.01414
=B29+10	0.03062	0.01652	-0.02809	0.02834	0.0176	-0.02985	0.02669	0.01838	-0.03112
=B30+10	0.04332	0.01652	-0.04394	0.04167	0.0176	-0.04578	0.04049	0.01838	-0.04712
=B31+10	0.06034	0.01143	-0.05173	0.05933	0.01248	-0.05343	0.05859	0.01324	-0.05466
=B32+10	0.07787	0.00363	-0.04632	0.07739	0.00463	-0.04763	0.07704	0.00536	-0.04857
=B33+10	0.09109	-0.00323	-0.0274	0.09096	-0.00227	-0.02811	0.09087	-0.00157	-0.02862
=B34+10	0.096	-0.00594	0	0.096	-0.00499	0	0.096	-0.0043	0

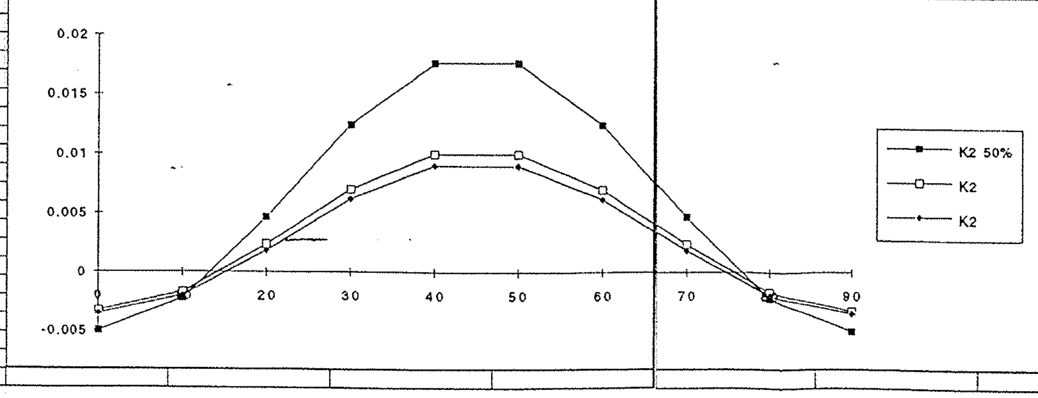


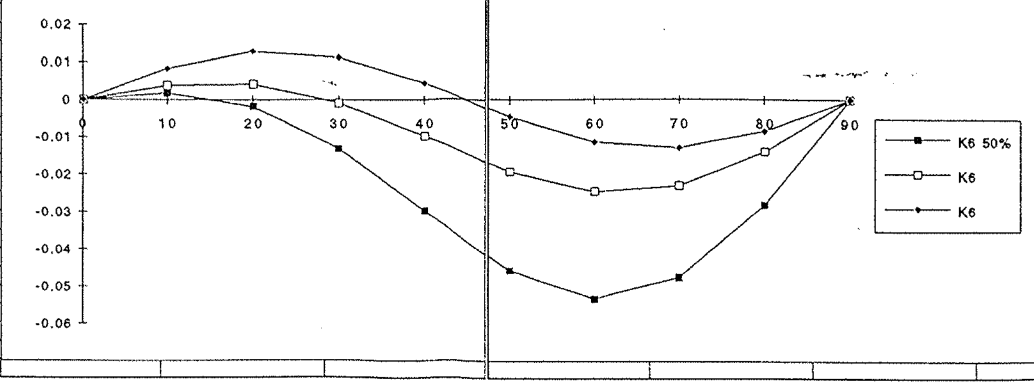




				37.5:12.5			25:25		
Fibre Angle	K1 50%	K2 50%	K6 50%	K1	K2	K6	K1	K2	K6
0	0.0192	-0.00499	0	0.0256	-0.0033	0	0.0384	-0.00353	0
=B77+10	0.01879	-0.00227	0.00184	0.02487	-0.00172	0.00385	0.03688	-0.00201	0.00833
=B78+10	0.01856	0.00463	-0.00174	0.02333	0.00236	0.00417	0.03304	0.00183	0.01277
=B79+10	0.02093	0.01248	-0.01308	0.02258	0.00701	-0.00074	0.02868	0.0062	0.01123
=B80+10	0.02834	0.0176	-0.02985	0.02433	0.01003	-0.00969	0.02585	0.00905	0.00443
=B81+10	0.04167	0.0176	-0.04578	0.02941	0.01003	-0.01912	0.02583	0.00905	-0.00443
=B82+10	0.05933	0.01248	-0.05343	0.03721	0.00701	-0.0246	0.02868	0.0062	-0.01123
=B83+10	0.07739	0.00463	-0.04763	0.04574	0.00236	-0.02297	0.03304	0.00183	-0.01277
=B84+10	0.09096	-0.00227	-0.02811	0.05236	-0.00172	-0.01386	0.03688	-0.00201	-0.00833
=B85+10	0.096	-0.00499	0	0.05486	-0.00333	0	0.0384	-0.00353	0



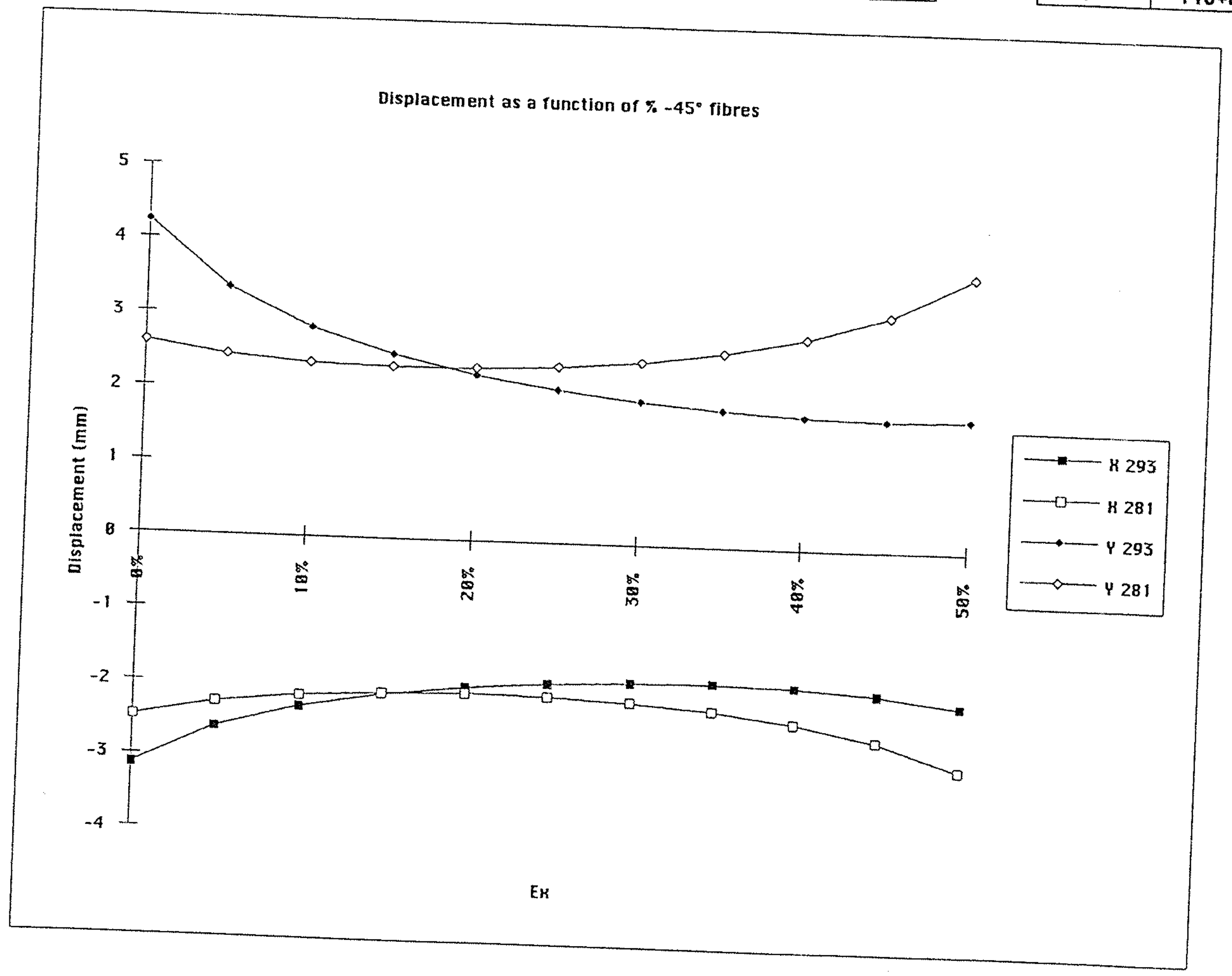


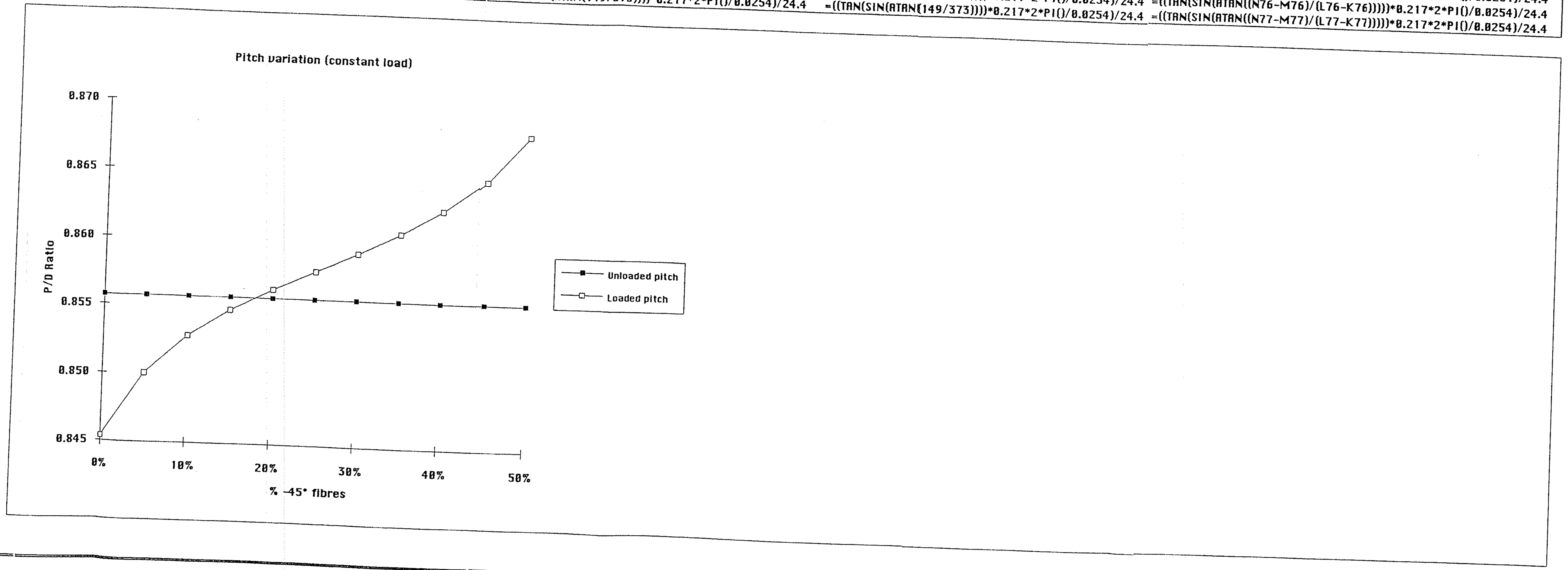


% -45°	X 293	X 281	Y 293	Y 281	Z 293	Z 281
0	-3.1268	-2.4753	4.2436	2.5976	-0.3113	3.4229
0.05	-2.6052	-2.2677	3.343	2.4333	-0.345	3.1326
0.1	-2.3047	-2.1522	2.8251	2.3508	-0.3643	2.9703
0.15	-2.1167	-2.0953	2.4911	2.3261	-0.3818	2.8888
0.2	-1.9869	-2.0708	2.2491	2.3339	-0.3995	2.8521
0.25	-1.9049	-2.0832	2.0755	2.3848	-0.421	2.8657
0.3	-1.8585	-2.1292	1.9478	2.478	-0.4478	2.925
0.35	-1.8448	-2.2145	1.8563	2.6232	-0.4822	3.0371
0.4	-1.867	-2.3526	1.7978	2.8418	-0.5282	3.2204
0.45	-1.9365	-2.5724	1.7757	3.177	-0.5931	3.5133
0.5	-2.0798	-2.939	1.8011	3.727	-0.6917	4.0033

% -45°	X' 293	X' 281	Y' 293	Y' 281	Z' 293	Z' 281
=B67	=-148+C67	=225+D67	=-117+E67	=32+F67	=217+G67	=217+H67
=B68	=-148+C68	=225+D68	=-117+E68	=32+F68	=217+G68	=217+H68
=B69	=-148+C69	=225+D69	=-117+E69	=32+F69	=217+G69	=217+H69
=B70	=-148+C70	=225+D70	=-117+E70	=32+F70	=217+G70	=217+H70
=B71	=-148+C71	=225+D71	=-117+E71	=32+F71	=217+G71	=217+H71
=B72	=-148+C72	=225+D72	=-117+E72	=32+F72	=217+G72	=217+H72
=B73	=-148+C73	=225+D73	=-117+E73	=32+F73	=217+G73	=217+H73
=B74	=-148+C74	=225+D74	=-117+E74	=32+F74	=217+G74	=217+H74
=B75	=-148+C75	=225+D75	=-117+E75	=32+F75	=217+G75	=217+H75
=B76	=-148+C76	=225+D76	=-117+E76	=32+F76	=217+G76	=217+H76
=B77	=-148+C77	=225+D77	=-117+E77	=32+F77	=217+G77	=217+H77

% -45° Fibre	• Unloaded Pitch (in)	NAB Loaded Pitch (in)	FRP Loaded Pitch (in)
=0	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N67-M67)/(L67-K67)))))*0.217*2*PI()/0.0254)/24.4
=R67+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N68-M68)/(L68-K68)))))*0.217*2*PI()/0.0254)/24.4
=R68+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N69-M69)/(L69-K69)))))*0.217*2*PI()/0.0254)/24.4
=R69+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N70-M70)/(L70-K70)))))*0.217*2*PI()/0.0254)/24.4
=R70+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N71-M71)/(L71-K71)))))*0.217*2*PI()/0.0254)/24.4
=R71+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N72-M72)/(L72-K72)))))*0.217*2*PI()/0.0254)/24.4
=R72+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N73-M73)/(L73-K73)))))*0.217*2*PI()/0.0254)/24.4
=R73+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N74-M74)/(L74-K74)))))*0.217*2*PI()/0.0254)/24.4
=R74+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N75-M75)/(L75-K75)))))*0.217*2*PI()/0.0254)/24.4
=R75+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N76-M76)/(L76-K76)))))*0.217*2*PI()/0.0254)/24.4
=R76+0.05	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N77-M77)/(L77-K77)))))*0.217*2*PI()/0.0254)/24.4



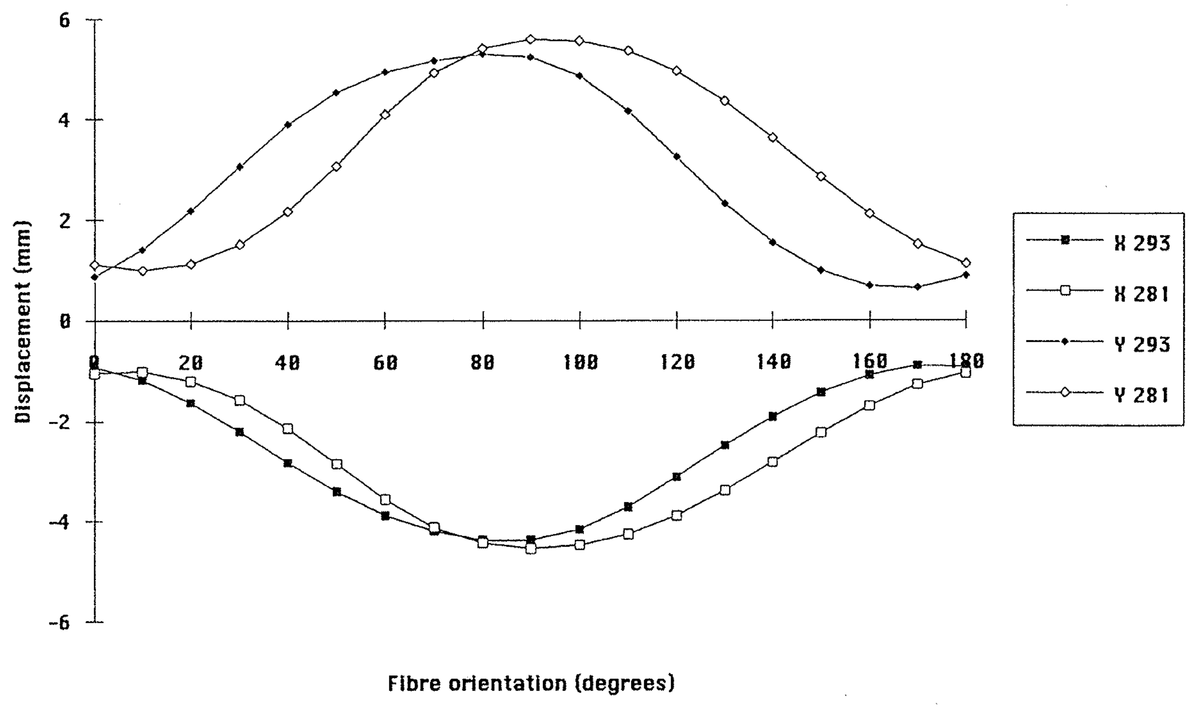


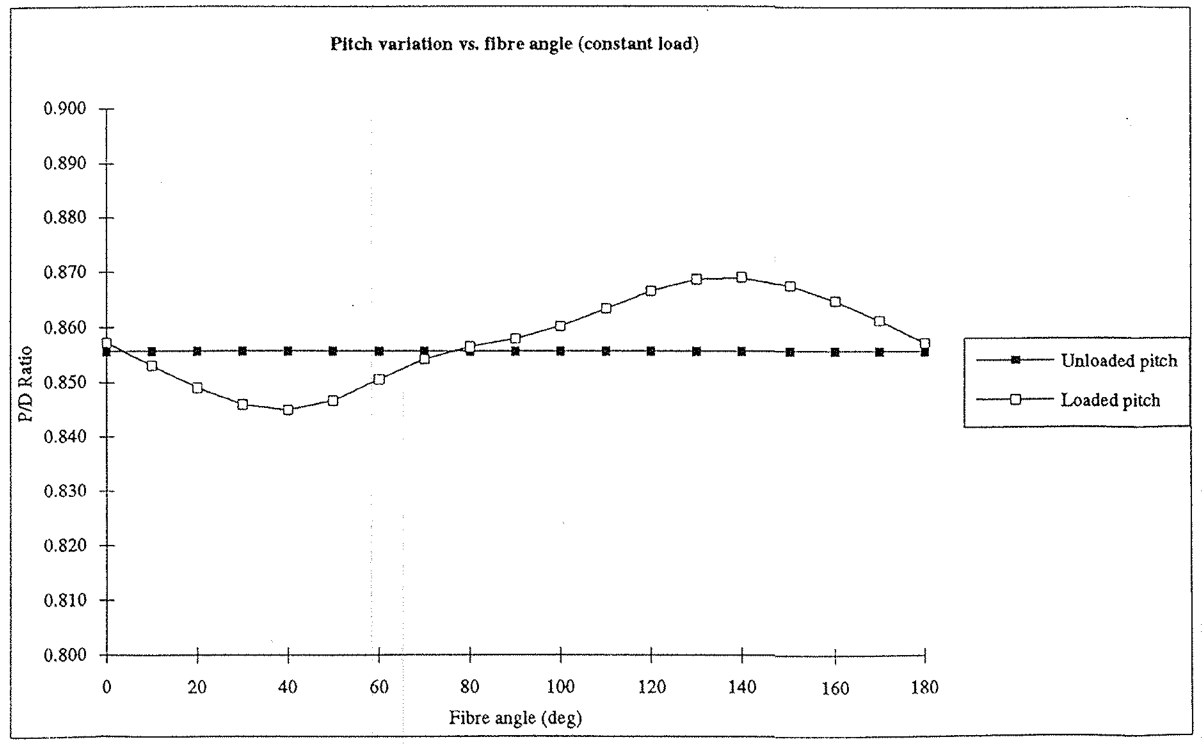
Displacements at Nodes 293 and 281

Degrees	X 293	X 281	Y 293	Y 281	Z 293	Z 281
0	-0.9198	-1.0283	0.873	1.1191	-0.2586	1.3918
=B6+10	-1.1711	-1.0007	1.4096	0.9925	-0.1978	1.3473
=B7+10	-1.6211	-1.1826	2.1871	1.1234	-0.1661	1.5644
=B8+10	-2.1985	-1.5641	3.0652	1.5144	-0.1785	2.1333
=B9+10	-2.8236	-2.1325	3.8918	2.1711	-0.2515	2.9424
=B10+10	-3.4082	-2.8418	4.5362	3.0785	-0.3836	3.929
=B11+10	-3.8708	-3.562	4.9346	4.0909	-0.545	4.9042
=B12+10	-4.1867	-4.1182	5.1606	4.9218	-0.6843	5.643
=B13+10	-4.3615	-4.4278	5.2878	5.4027	-0.7695	6.0461
=B14+10	-4.3629	-4.5252	5.2261	5.5796	-0.8109	6.1697
=B15+10	-4.1493	-4.4644	4.8528	5.5547	-0.8295	6.087
=B16+10	-3.7134	-4.2502	4.1542	5.3493	-0.8287	5.7984
=B17+10	-3.1147	-3.8787	3.2417	4.9414	-0.8029	5.2947
=B18+10	-2.4777	-3.3859	2.3154	4.3442	-0.7479	4.6226
=B19+10	-1.9044	-2.8244	1.5402	3.6187	-0.6652	3.8541
=B20+10	-1.4265	-2.2367	0.9826	2.8389	-0.561	3.049
=B21+10	-1.0751	-1.6903	0.6734	2.0986	-0.4486	2.3015
=B22+10	-0.8946	-1.2675	0.6321	1.4995	-0.3439	1.7229
=B23+10	-0.9198	-1.0283	0.873	1.1191	-0.2586	1.3918

Degrees	X' 293	X' 281	Y' 293	Y' 281	Z' 293	Z' 281
0	=-148+C6	=225+D6	=-117+E6	=32+F6	=217+G6	=217+H6
=J6+10	=-148+C7	=225+D7	=-117+E7	=32+F7	=217+G7	=217+H7
=J7+10	=-148+C8	=225+D8	=-117+E8	=32+F8	=217+G8	=217+H8
=J8+10	=-148+C9	=225+D9	=-117+E9	=32+F9	=217+G9	=217+H9
=J9+10	=-148+C10	=225+D10	=-117+E10	=32+F10	=217+G10	=217+H10
=J10+10	=-148+C11	=225+D11	=-117+E11	=32+F11	=217+G11	=217+H11
=J11+10	=-148+C12	=225+D12	=-117+E12	=32+F12	=217+G12	=217+H12
=J12+10	=-148+C13	=225+D13	=-117+E13	=32+F13	=217+G13	=217+H13
=J13+10	=-148+C14	=225+D14	=-117+E14	=32+F14	=217+G14	=217+H14
=J14+10	=-148+C15	=225+D15	=-117+E15	=32+F15	=217+G15	=217+H15
=J15+10	=-148+C16	=225+D16	=-117+E16	=32+F16	=217+G16	=217+H16
=J16+10	=-148+C17	=225+D17	=-117+E17	=32+F17	=217+G17	=217+H17
=J17+10	=-148+C18	=225+D18	=-117+E18	=32+F18	=217+G18	=217+H18
=J18+10	=-148+C19	=225+D19	=-117+E19	=32+F19	=217+G19	=217+H19
=J19+10	=-148+C20	=225+D20	=-117+E20	=32+F20	=217+G20	=217+H20
=J20+10	=-148+C21	=225+D21	=-117+E21	=32+F21	=217+G21	=217+H21
=J21+10	=-148+C22	=225+D22	=-117+E22	=32+F22	=217+G22	=217+H22
=J22+10	=-148+C23	=225+D23	=-117+E23	=32+F23	=217+G23	=217+H23
=J23+10	=-148+C24	=225+D24	=-117+E24	=32+F24	=217+G24	=217+H24

	•	NAB	FRP
	Unloaded	Loaded	Loaded
Degrees	Pitch (in)	Pitch (in)	Pitch (in)
0	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N6-M6)/(L6-K6)))))*0.217*2*PI()/0.0254)/24.4
=R6+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N7-M7)/(L7-K7)))))*0.217*2*PI()/0.0254)/24.4
=R7+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N8-M8)/(L8-K8)))))*0.217*2*PI()/0.0254)/24.4
=R8+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N9-M9)/(L9-K9)))))*0.217*2*PI()/0.0254)/24.4
=R9+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N10-M10)/(L10-K10)))))*0.217*2*PI()/0.0254)/24.4
=R10+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N11-M11)/(L11-K11)))))*0.217*2*PI()/0.0254)/24.4
=R11+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N12-M12)/(L12-K12)))))*0.217*2*PI()/0.0254)/24.4
=R12+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N13-M13)/(L13-K13)))))*0.217*2*PI()/0.0254)/24.4
=R13+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N14-M14)/(L14-K14)))))*0.217*2*PI()/0.0254)/24.4
=R14+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N15-M15)/(L15-K15)))))*0.217*2*PI()/0.0254)/24.4
=R15+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N16-M16)/(L16-K16)))))*0.217*2*PI()/0.0254)/24.4
=R16+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N17-M17)/(L17-K17)))))*0.217*2*PI()/0.0254)/24.4
=R17+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N18-M18)/(L18-K18)))))*0.217*2*PI()/0.0254)/24.4
=R18+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N19-M19)/(L19-K19)))))*0.217*2*PI()/0.0254)/24.4
=R19+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N20-M20)/(L20-K20)))))*0.217*2*PI()/0.0254)/24.4
=R20+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N21-M21)/(L21-K21)))))*0.217*2*PI()/0.0254)/24.4
=R21+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N22-M22)/(L22-K22)))))*0.217*2*PI()/0.0254)/24.4
=R22+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N23-M23)/(L23-K23)))))*0.217*2*PI()/0.0254)/24.4
=R23+10	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN(149/373))))*0.217*2*PI()/0.0254)/24.4	=((TAN(SIN(ATAN((N24-M24)/(L24-K24)))))*0.217*2*PI()/0.0254)/24.4





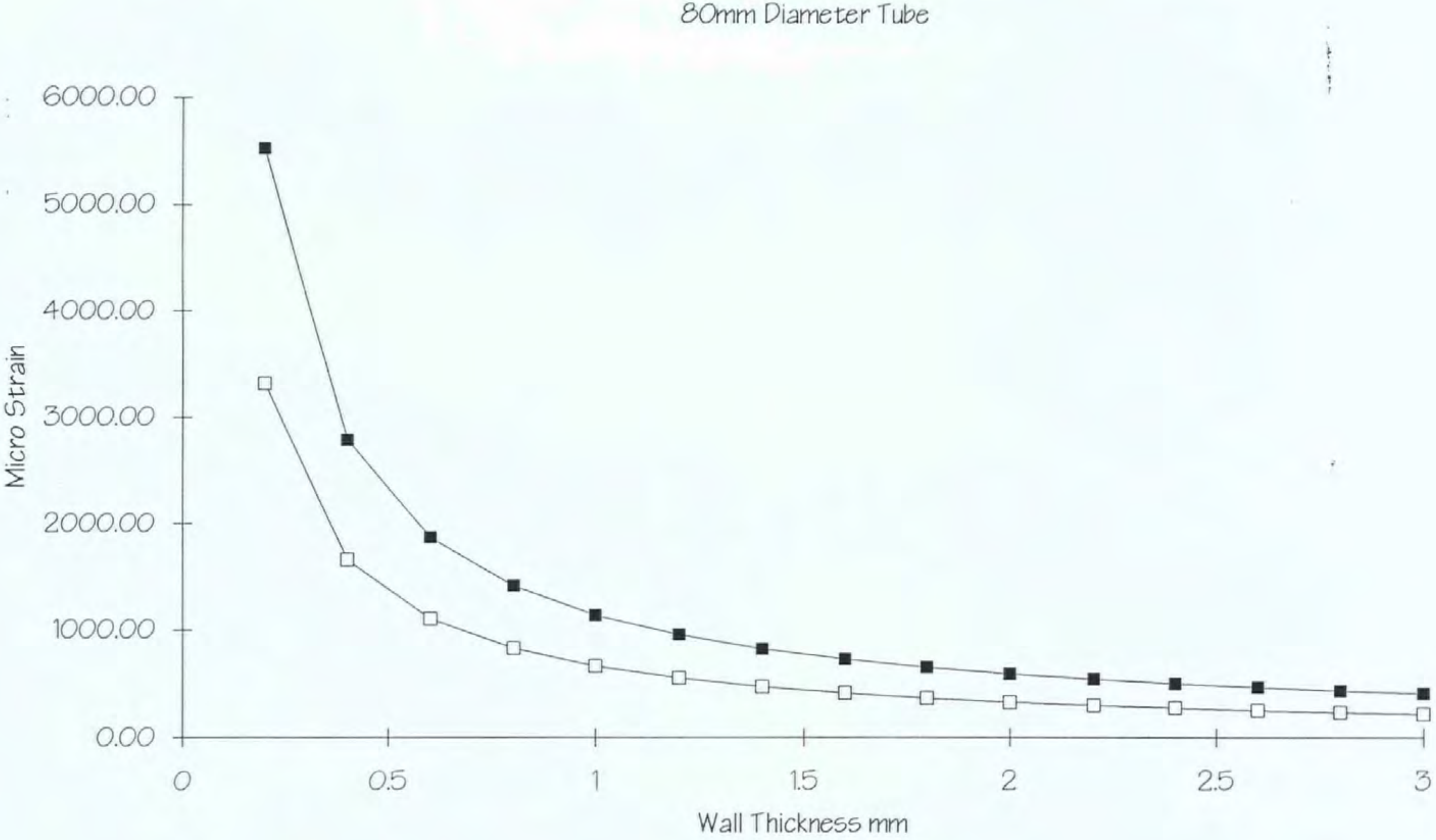
Appendix 6a

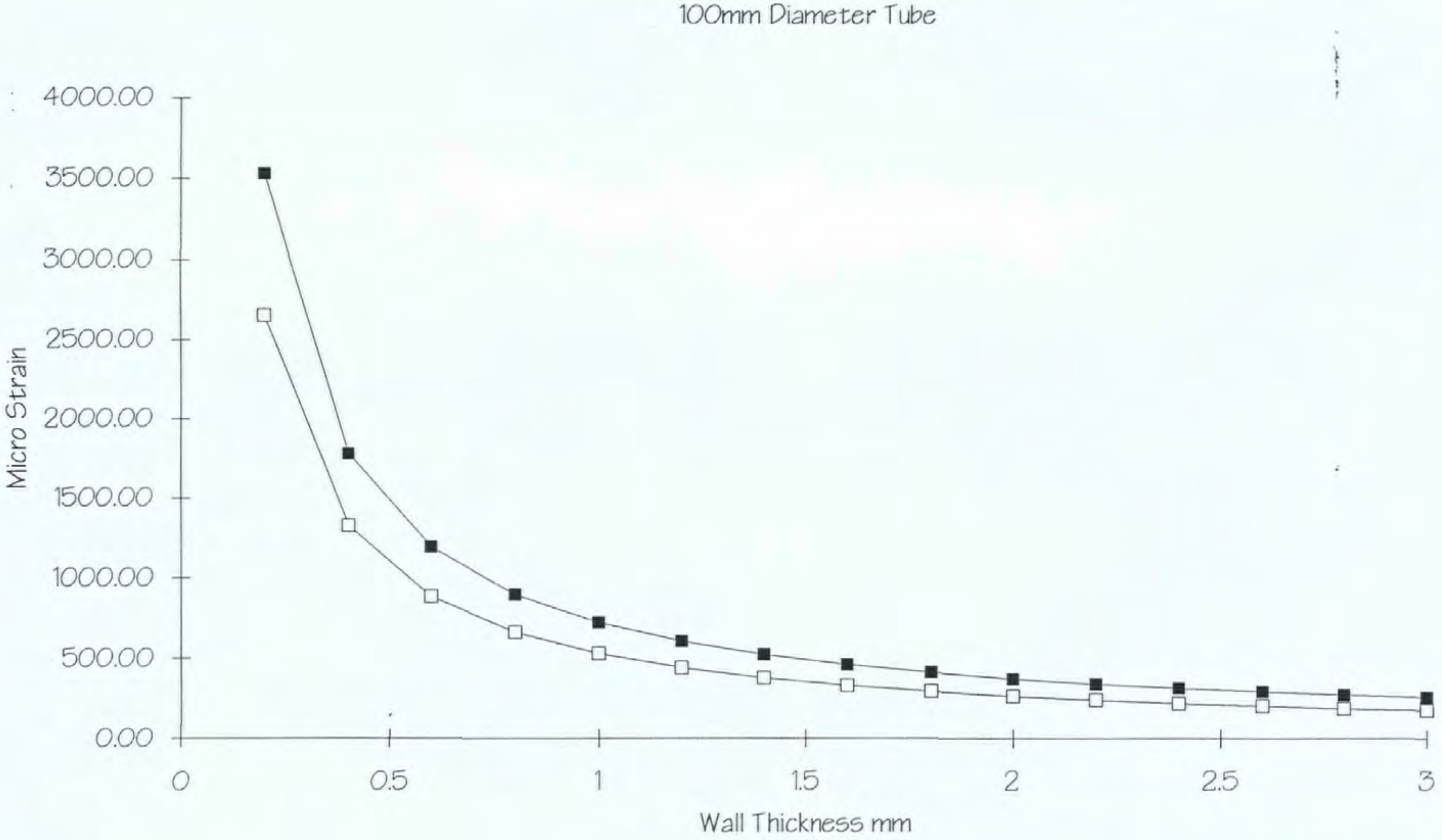
Load cell.

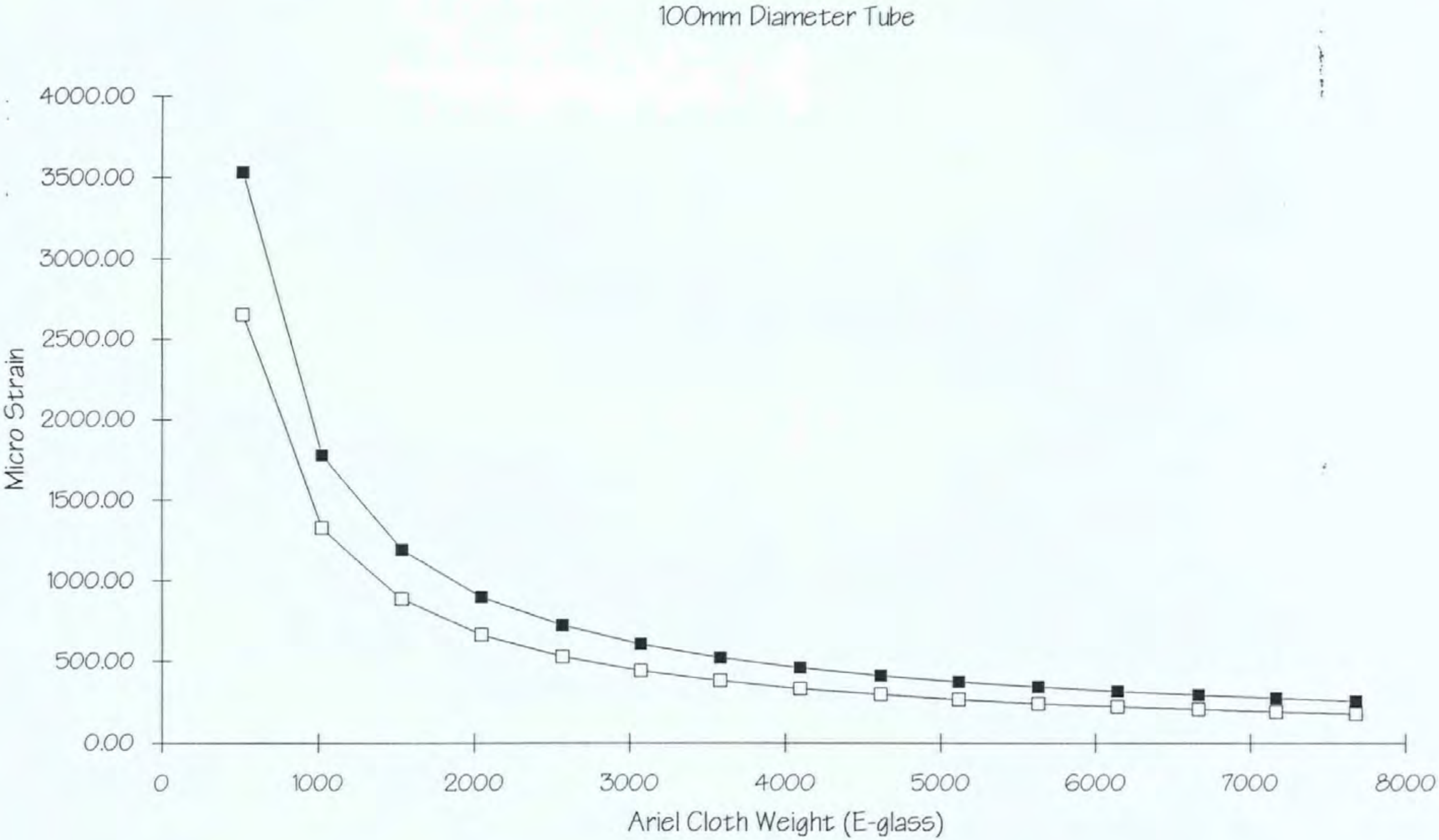
Final
Dynomometer
Design

Max Torque [Nmm]	300781.62	Poissons Ratio	0.32					
Max Thrust [N]	3000							
Modulus +/- 45	36000		Modulus 0/90	18000				
Wall Thickness [mm]	80	90	100	110	120	130	80	90
0.2	5526.52	4362.99	3531.66	2917.14	2450.09	2086.85	3315.73	2947.31
0.4	2784.09	2196.10	1776.47	1466.55	1231.19	1048.26	1657.86	1473.66
0.6	1870.06	1473.88	1191.45	983.06	824.91	702.07	1105.24	982.44
0.8	1413.13	1112.82	898.98	741.33	621.79	529.00	828.93	736.83
1	1139.05	896.23	723.52	596.32	499.93	425.16	663.15	589.46
1.2	956.38	751.88	606.58	499.66	418.71	355.94	552.62	491.22
1.4	825.96	648.80	523.07	430.63	360.70	306.51	473.68	421.04
1.6	728.19	571.51	460.45	378.87	317.20	269.44	414.47	368.41
1.8	652.18	511.43	411.77	338.63	283.37	240.62	368.41	327.48
2	591.42	463.39	372.83	306.44	256.32	217.56	331.57	294.73
2.2	541.73	424.10	340.99	280.11	234.19	198.70	301.43	267.94
2.4	500.36	391.38	314.47	258.19	215.76	182.99	276.31	245.61
2.6	465.38	363.71	292.04	239.64	200.17	169.70	255.06	226.72
2.8	435.42	340.01	272.83	223.75	186.81	158.31	236.84	210.52
3	409.49	319.48	256.18	209.98	175.23	148.45	221.05	196.49

100	110	120	130
2652.58	2411.44	2210.49	2040.45
1326.29	1205.72	1105.24	1020.22
884.19	803.81	736.83	680.15
663.15	602.86	552.62	510.11
530.52	482.29	442.10	408.09
442.10	401.91	368.41	340.07
378.94	344.49	315.78	291.49
331.57	301.43	276.31	255.06
294.73	267.94	245.61	226.72
265.26	241.14	221.05	204.04
241.14	219.22	200.95	185.50
221.05	200.95	184.21	170.04
204.04	185.50	170.04	156.96
189.47	172.25	157.89	145.75
176.84	160.76	147.37	136.03

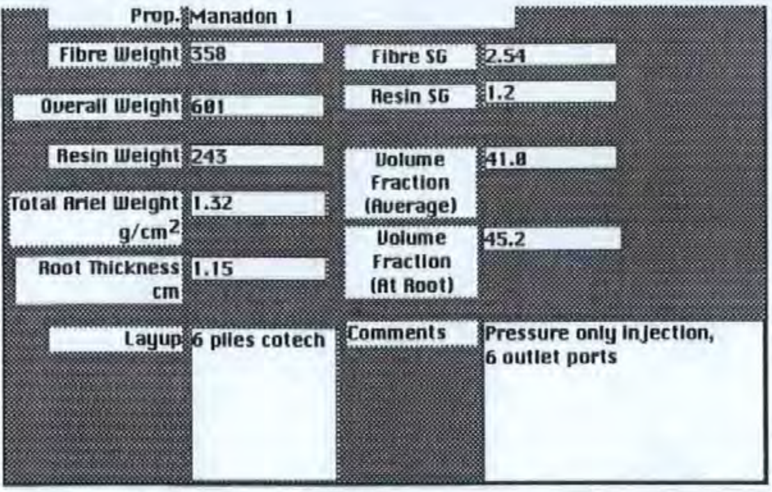

80mm Diameter Tube
6000.00
5000.00
4000.00
3000.00
2000.00
1000.00
0.00
Micro Strain
0
0.5
1
1.5
2
2.5
3
Wall Thickness mm


100mm Diameter Tube
Micro Strain
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
0
0.5
1
1.5
2
2.5
3
Wall Thickness mm


100mm Diameter Tube
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
Micro Strain
0
1000
2000
3000
4000
5000
6000
7000
8000
Ariel Cloth Weight (E-glass)

Appendix 7

Composite propellers manufactured for this project.



Prop. Manadon 1

Fibre Weight 358

Overall Weight 601

Resin Weight 243

Total Ariel Weight g/cm² 1.32

Root Thickness cm 1.15

Layup 6 plies cotech

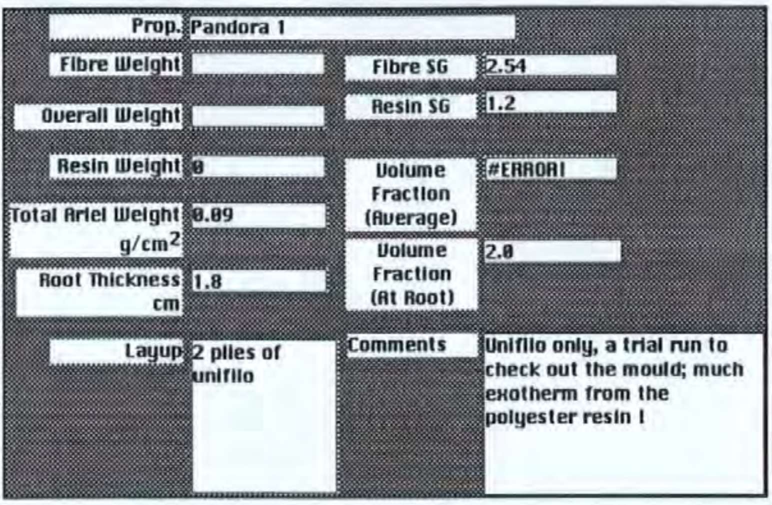
Fibre SG 2.54

Resin SG 1.2

Volume Fraction (Average) 41.8

Volume Fraction (At Root) 45.2

Comments Pressure only injection,
6 outlet ports



Prop. Pandora 1

Fibre Weight

Overall Weight

Resin Weight 0

Total Ariel Weight g/cm² 0.09

Root Thickness cm 1.8

Layup 2 plies of unifilo

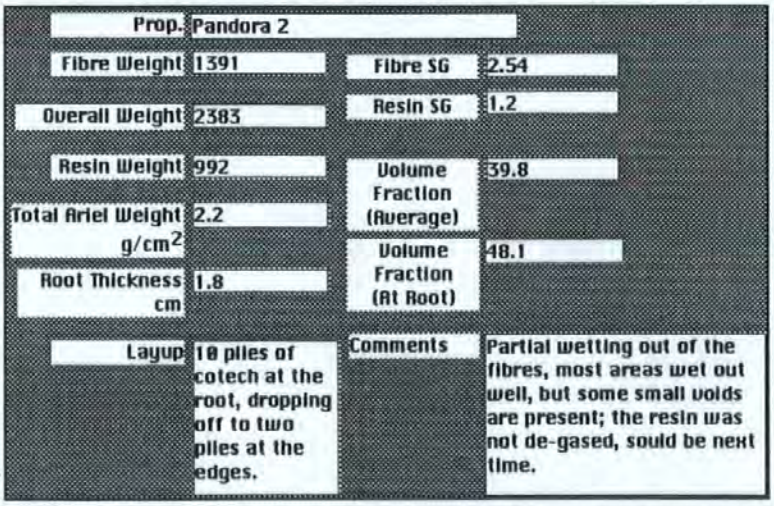
Fibre SG 2.54

Resin SG 1.2

Volume Fraction (Average) #ERROR!

Volume Fraction (At Root) 2.0

Comments Unifilo only, a trial run to check out the mould; much exotherm from the polyester resin !



Prop. Pandora 2

Fibre Weight 1391

Overall Weight 2383

Resin Weight 992

Total Ariel Weight g/cm² 2.2

Root Thickness cm 1.8

Layup 10 plies of cotech at the root, dropping off to two plies at the edges.

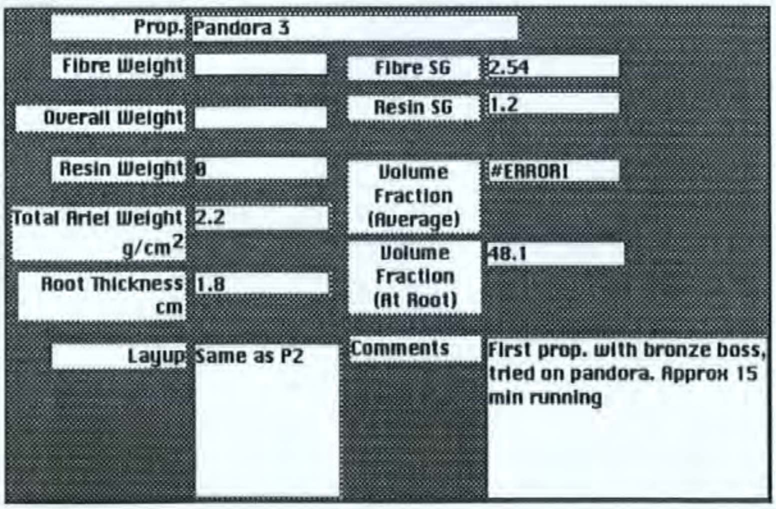
Fibre SG 2.54

Resin SG 1.2

Volume Fraction (Average) 39.8

Volume Fraction (At Root) 48.1

Comments Partial wetting out of the fibres, most areas wet out well, but some small voids are present; the resin was not de-gased, sould be next time.



Prop. Pandora 3

Fibre Weight

Overall Weight

Resin Weight 0

Total Ariel Weight g/cm² 2.2

Root Thickness cm 1.8

Layup Same as P2

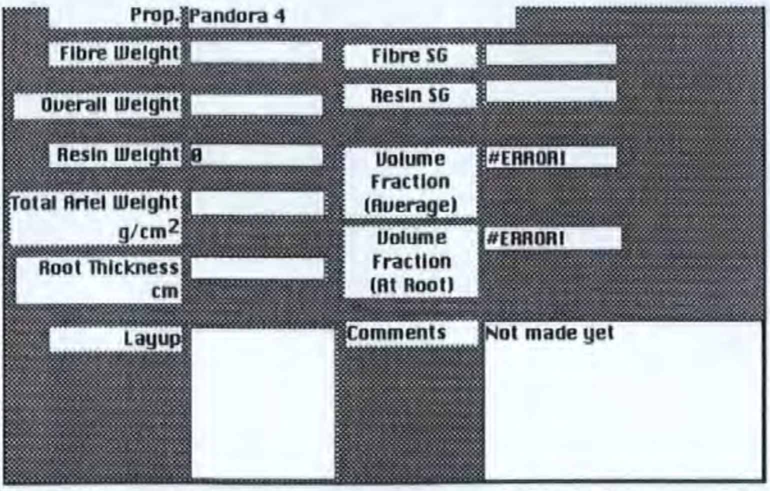
Fibre SG 2.54

Resin SG 1.2

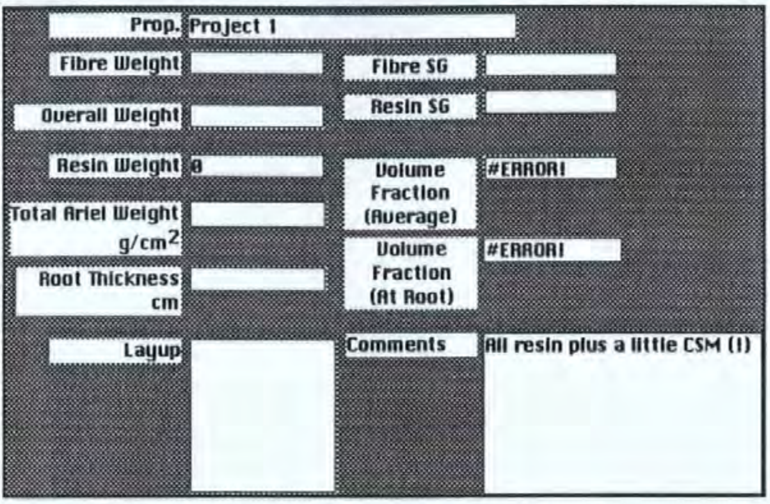
Volume Fraction (Average) #ERROR!

Volume Fraction (At Root) 48.1

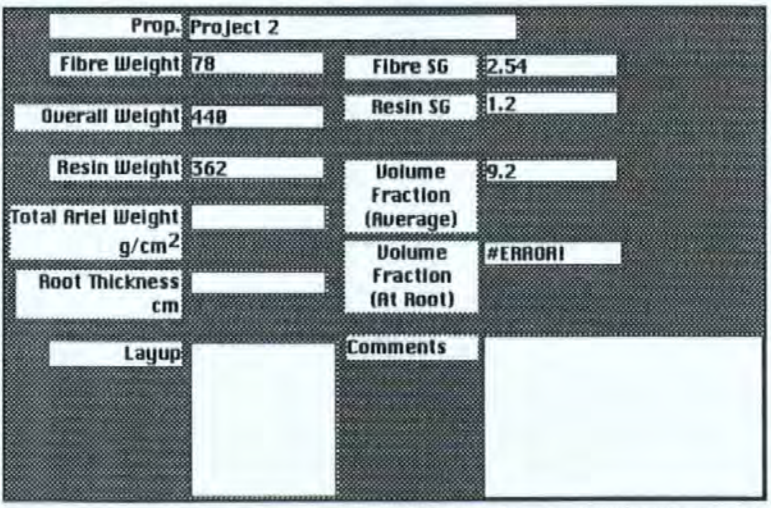
Comments First prop. with bronze boss, tried on pandora. Approx 15 min running



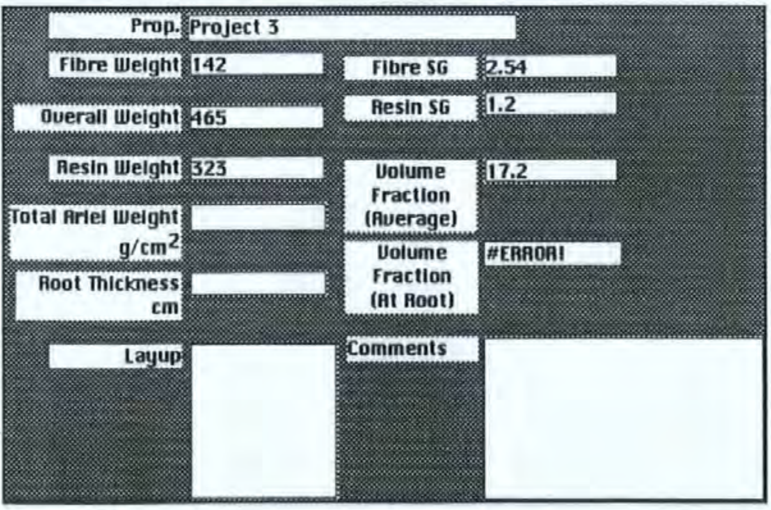
Prop.	Pandora 4		
Fibre Weight		Fibre SG	
Overall Weight		Resin SG	
Resin Weight	0	Volume Fraction (Average)	#ERROR!
Total Ariel Weight g/cm^2		Volume Fraction (At Root)	#ERROR!
Root Thickness cm			
Layup		Comments	Not made yet



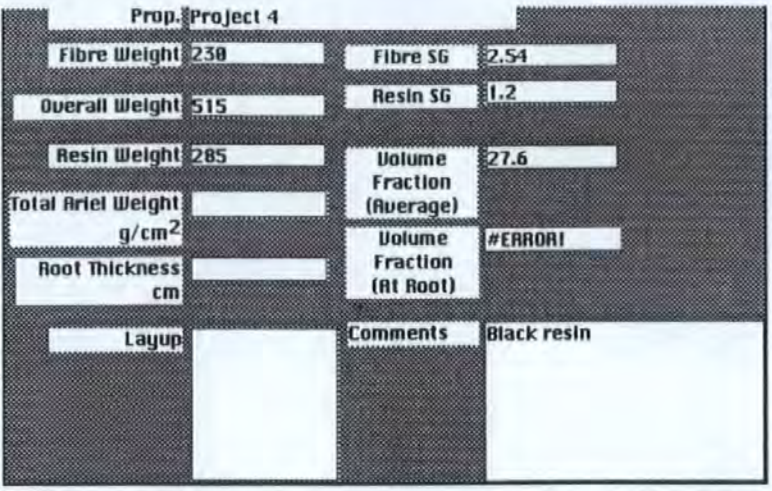
Prop.	Project 1		
Fibre Weight		Fibre SG	
Overall Weight		Resin SG	
Resin Weight	0	Volume Fraction (Average)	#ERROR!
Total Ariel Weight g/cm^2		Volume Fraction (At Root)	#ERROR!
Root Thickness cm			
Layup		Comments	All resin plus a little CSM (!)



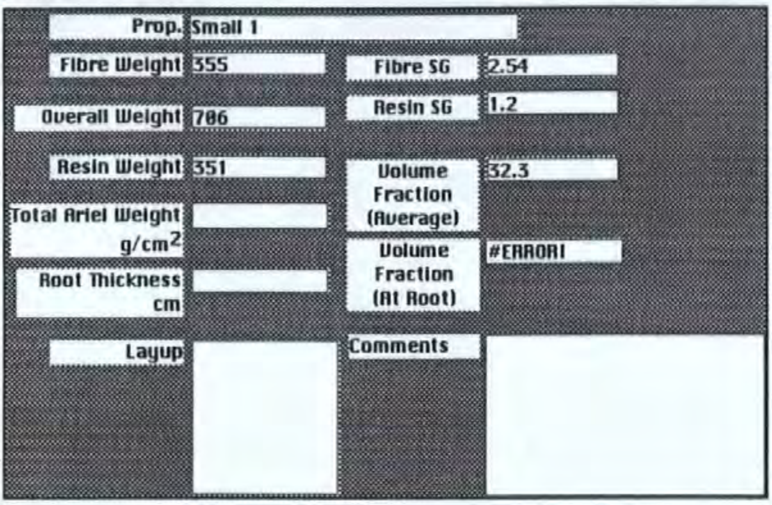
Prop.	Project 2		
Fibre Weight	78	Fibre SG	2.54
Overall Weight	440	Resin SG	1.2
Resin Weight	362	Volume Fraction (Average)	9.2
Total Ariel Weight g/cm^2		Volume Fraction (At Root)	#ERROR!
Root Thickness cm			
Layup		Comments	



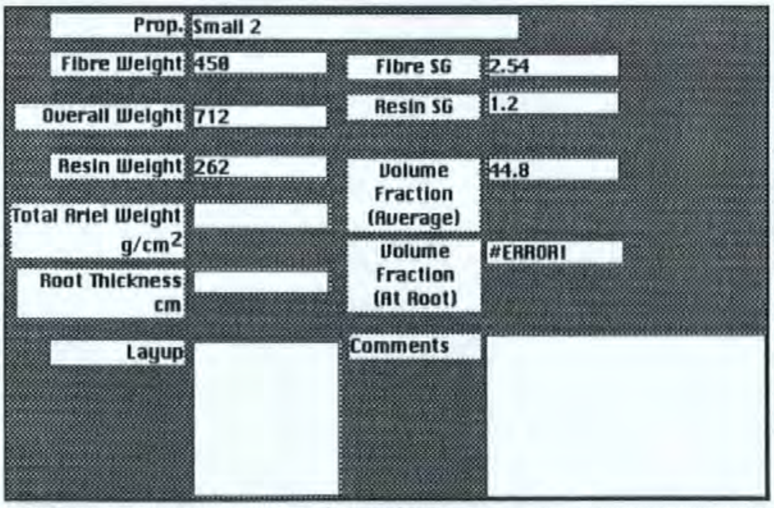
Prop.	Project 3		
Fibre Weight	142	Fibre SG	2.54
Overall Weight	465	Resin SG	1.2
Resin Weight	323	Volume Fraction (Average)	17.2
Total Ariel Weight g/cm^2		Volume Fraction (At Root)	#ERROR!
Root Thickness cm			
Layup		Comments	



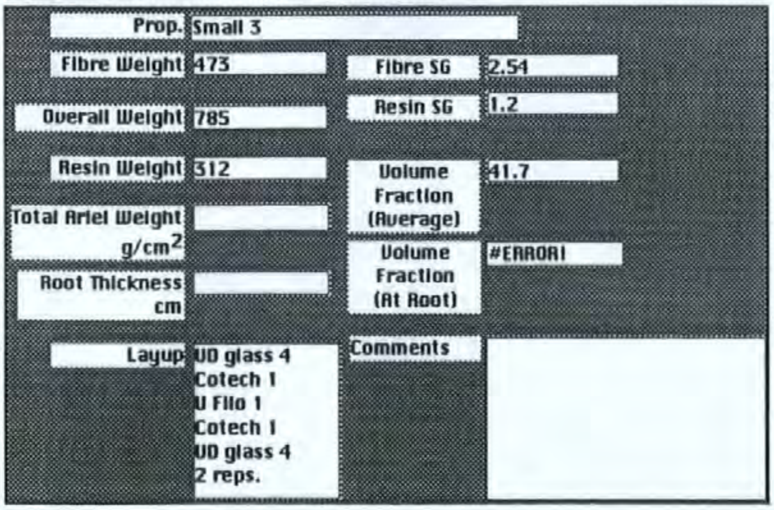
Prop.	Project 4		
Fibre Weight	230	Fibre SG	2.54
Overall Weight	515	Resin SG	1.2
Resin Weight	285	Volume Fraction (Average)	27.6
Total Ariel Weight g/cm^2		Volume Fraction (At Root)	#ERROR!
Root Thickness cm			
Layup		Comments	Black resin



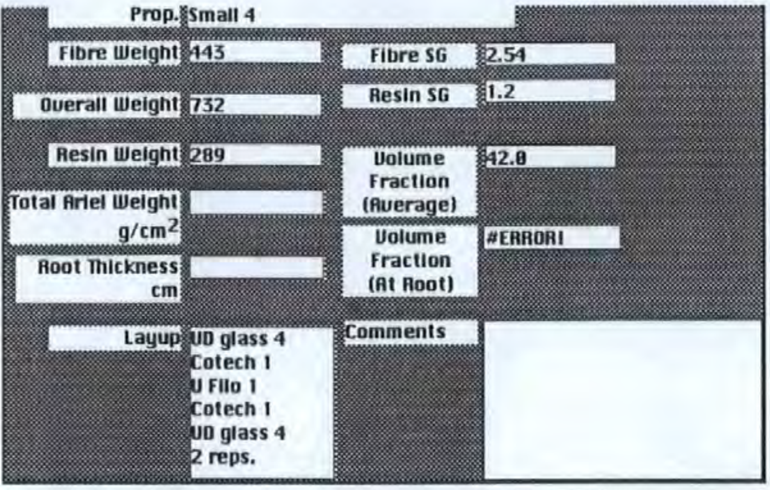
Prop.	Small 1		
Fibre Weight	355	Fibre SG	2.54
Overall Weight	706	Resin SG	1.2
Resin Weight	351	Volume Fraction (Average)	32.3
Total Ariel Weight g/cm^2		Volume Fraction (At Root)	#ERROR!
Root Thickness cm			
Layup		Comments	



Prop.	Small 2		
Fibre Weight	450	Fibre SG	2.54
Overall Weight	712	Resin SG	1.2
Resin Weight	262	Volume Fraction (Average)	44.8
Total Ariel Weight g/cm^2		Volume Fraction (At Root)	#ERROR!
Root Thickness cm			
Layup		Comments	



Prop.	Small 3		
Fibre Weight	473	Fibre SG	2.54
Overall Weight	785	Resin SG	1.2
Resin Weight	312	Volume Fraction (Average)	41.7
Total Ariel Weight g/cm^2		Volume Fraction (At Root)	#ERROR!
Root Thickness cm			
Layup	UD glass 4 Cotech 1 U Filo 1 Cotech 1 UD glass 4 2 reps.	Comments	



Prop. Small 4

Fibre Weight 443

Overall Weight 732

Resin Weight 289

Total Ariel Weight g/cm^2

Root Thickness cm

Fibre SG 2.54

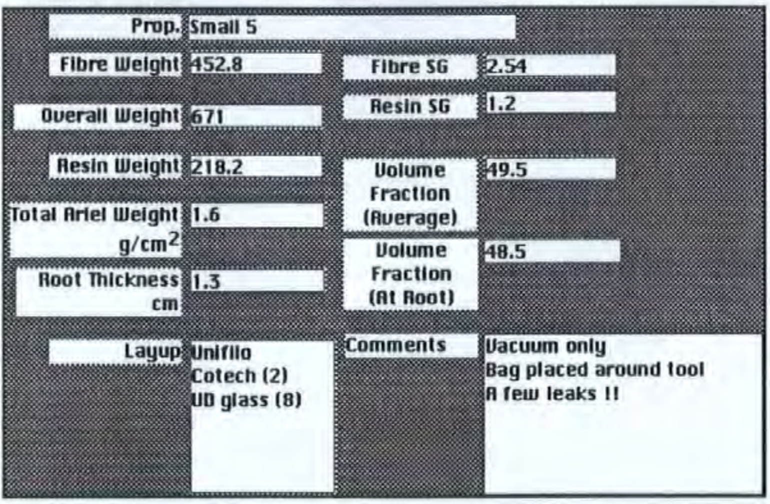
Resin SG 1.2

Volume Fraction (Average) 42.8

Volume Fraction (At Root) #ERROR!

Layup
UD glass 4
Cotech 1
U Filo 1
Cotech 1
UD glass 4
2 reps.

Comments



Prop. Small 5

Fibre Weight 452.8

Overall Weight 671

Resin Weight 218.2

Total Ariel Weight g/cm^2 1.6

Root Thickness cm 1.3

Fibre SG 2.54

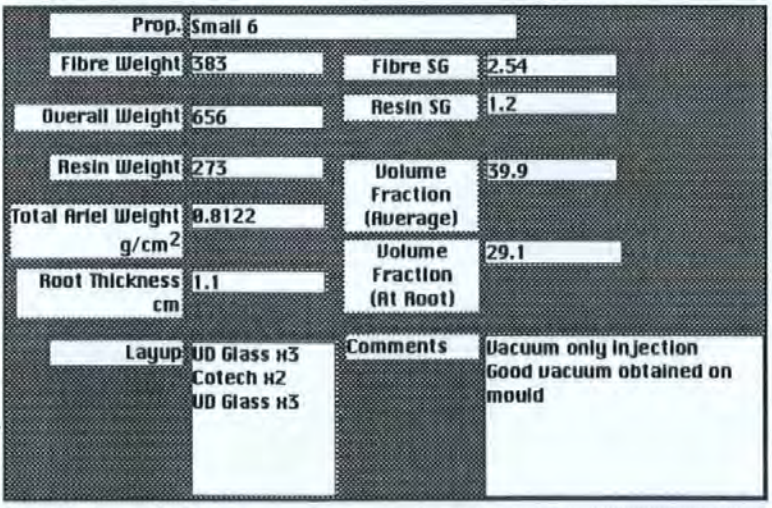
Resin SG 1.2

Volume Fraction (Average) 49.5

Volume Fraction (At Root) 48.5

Layup
Unifilo
Cotech (2)
UD glass (8)

Comments
Vacuum only
Bag placed around tool
A few leaks !!



Prop. Small 6

Fibre Weight 383

Overall Weight 656

Resin Weight 273

Total Ariel Weight g/cm^2 0.8122

Root Thickness cm 1.1

Fibre SG 2.54

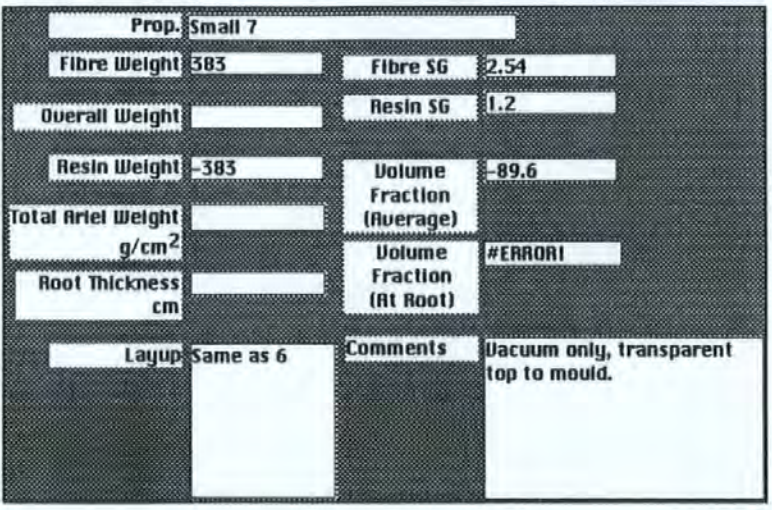
Resin SG 1.2

Volume Fraction (Average) 39.9

Volume Fraction (At Root) 29.1

Layup
UD Glass x3
Cotech x2
UD Glass x3

Comments
Vacuum only injection
Good vacuum obtained on mould



Prop. Small 7

Fibre Weight 383

Overall Weight

Resin Weight -383

Total Ariel Weight g/cm^2

Root Thickness cm

Fibre SG 2.54

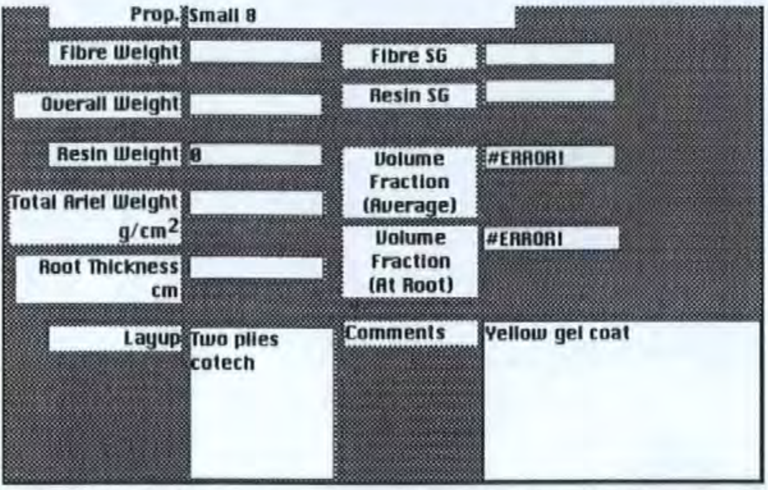
Resin SG 1.2

Volume Fraction (Average) -89.6

Volume Fraction (At Root) #ERROR!

Layup
Same as 6

Comments
Vacuum only, transparent top to mould.



Prop. Small 0

Fibre Weight

Overall Weight

Resin Weight 0

Total Ariel Weight g/cm²

Root Thickness cm

Layup Two plies cotech

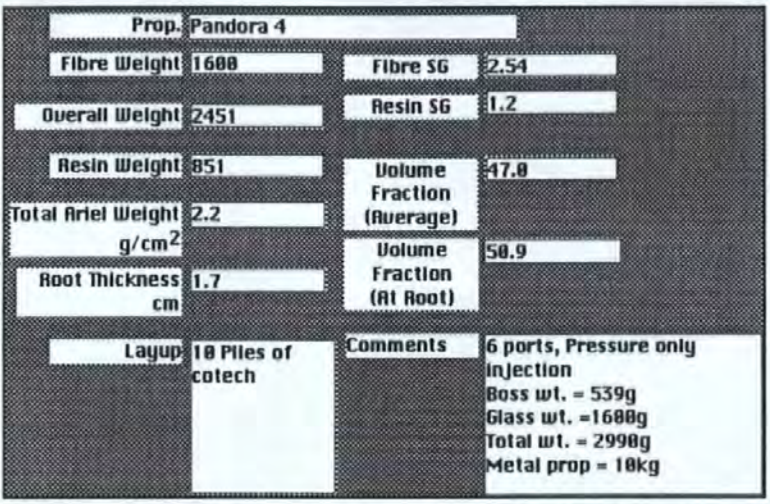
Fibre SG

Resin SG

Volume Fraction (Average) #ERROR!

Volume Fraction (At Root) #ERROR!

Comments Yellow gel coat



Prop. Pandora 4

Fibre Weight 1600

Overall Weight 2451

Resin Weight 851

Total Ariel Weight g/cm² 2.2

Root Thickness cm 1.7

Layup 10 Plies of cotech

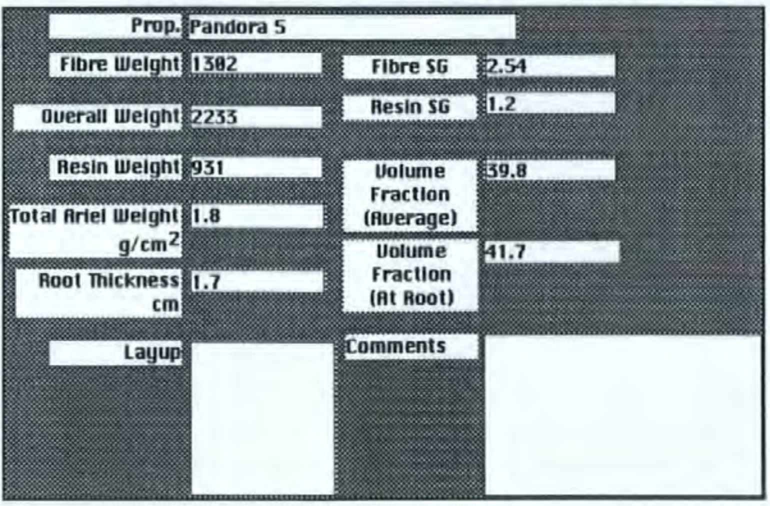
Fibre SG 2.54

Resin SG 1.2

Volume Fraction (Average) 47.0

Volume Fraction (At Root) 50.9

Comments 6 ports, Pressure only injection
Boss wt. = 539g
Glass wt. =1600g
Total wt. = 2990g
Metal prop = 10kg



Prop. Pandora 5

Fibre Weight 1302

Overall Weight 2233

Resin Weight 931

Total Ariel Weight g/cm² 1.8

Root Thickness cm 1.7

Layup

Fibre SG 2.54

Resin SG 1.2

Volume Fraction (Average) 39.8

Volume Fraction (At Root) 41.7

Comments

Appendix 7a

Cavitation data.

	Advance	Bronze Effic. @ 3 m/s	Bronze Effic. @ 4 m/s	Composite Effic. @ 3 m/s	Composite Effic. @ 4 m/s
1	1.100	0.866		0.843	
2	1.051	0.832		0.795	
3	1.000	0.790		0.771	
4	0.950	0.757		0.727	
5	0.901	0.717		0.695	
6	0.850	0.687		0.666	
7	0.801	0.655		0.635	
8	0.749	0.630		0.600	
9	0.700	0.596		0.561	
10	0.651	0.548		0.515	
11	0.600	0.504		0.470	
12	0.550	0.451		0.425	
13	0.500	0.398			
14	0.450	0.350			
15					
16	1.099		0.702		0.624
17	1.050		0.698		0.696
18	1.000		0.678		0.673
19	0.950		0.671		0.674
20	0.900		0.648		0.650
21	0.851		0.632		0.617
22	0.800		0.595		0.588
23	0.750		0.570		0.560
24	0.699		0.526		0.515
25	0.650		0.487		
26	0.599		0.446		
27	0.562		0.413		

	Advance Coefficient	Bronze Kt @ 3 m/s	Bronze Kq @ 3 m/s	Bronze Kt @ 4 m/s	Bronze Kq @ 4 m/s	Composite Kt @ 3 m/s	Composite Kq @ 3 m/s
1	1.100	0.212	0.042			0.200	0.041
2	1.051	0.231	0.046			0.215	0.045
3	1.000	0.260	0.052			0.243	0.049
4	0.950	0.283	0.056			0.261	0.054
5	0.901	0.305	0.060			0.283	0.058
6	0.850	0.330	0.064			0.308	0.062
7	0.801	0.355	0.068			0.330	0.065
8	0.749	0.382	0.071			0.356	0.070
9	0.700	0.413	0.076			0.387	0.076
10	0.651	0.434	0.081			0.413	0.082
11	0.600	0.462	0.086			0.446	0.089
12	0.550	0.486	0.093			0.477	0.097
13	0.500	0.507	0.100				
14	0.450	0.526	0.106				
15							
16	1.099			0.191	0.047		
17	1.050			0.214	0.051		
18	1.000			0.237	0.055		
19	0.950			0.268	0.059		
20	0.900			0.295	0.064		
21	0.851			0.323	0.068		
22	0.800			0.348	0.073		
23	0.750			0.379	0.078		
24	0.699			0.403	0.084		
25	0.650			0.430	0.090		
26	0.599			0.452	0.095		
27	0.562			0.463	0.099		

	Composite Kt @ 4 m/s	Composite Kq @ 4 m/s
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		
12		
13		
14		
15		
16	0.179	0.049
17	0.203	0.048
18	0.224	0.052
19	0.253	0.056
20	0.277	0.060
21	0.302	0.065
22	0.334	0.071
23	0.365	0.077
24	0.396	0.084
25		
26		
27		

Appendix 8

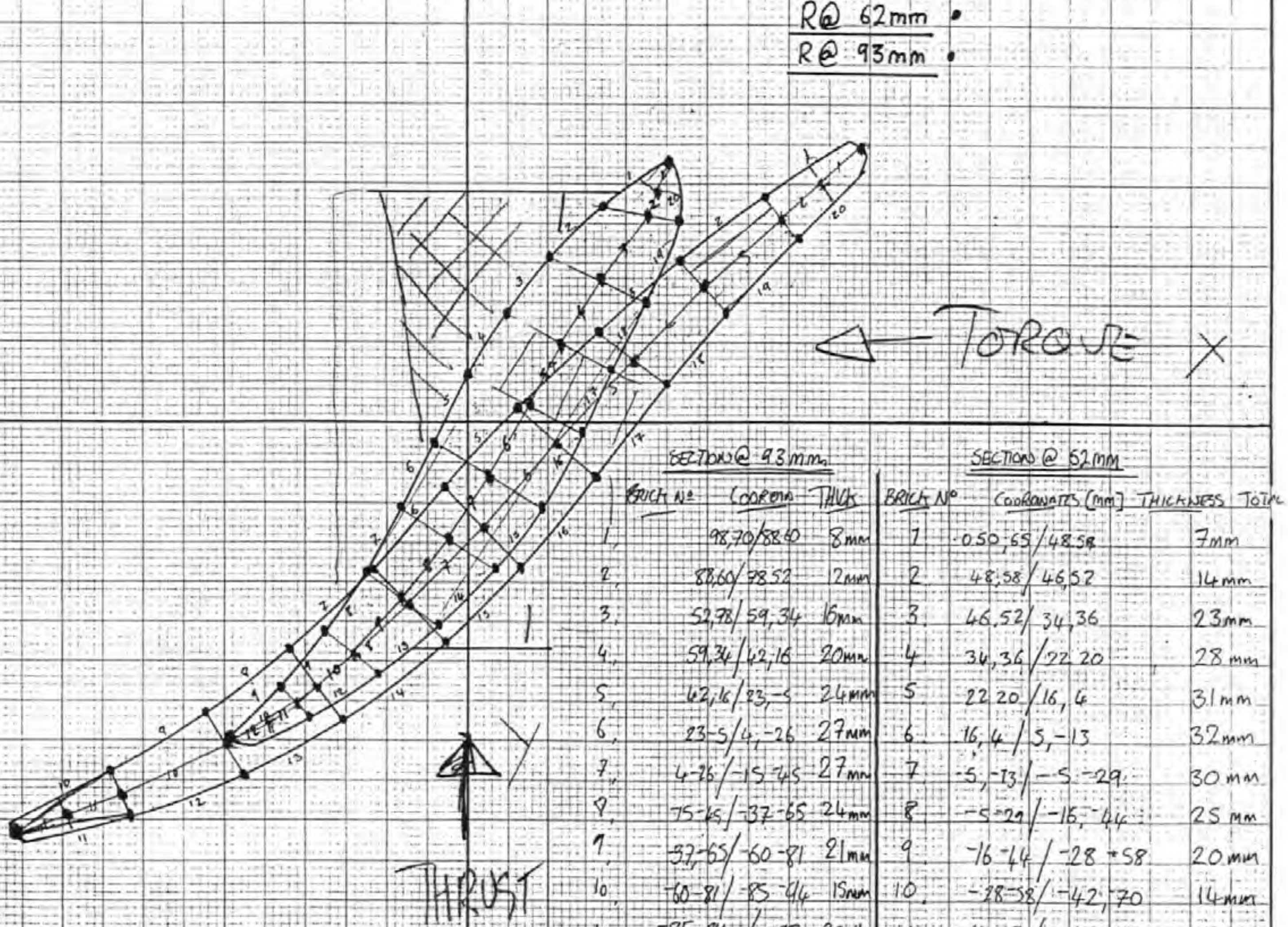
FEA modelling data.

ORTHOTROPIC.MATERIAL

ORTHOTROPIC.MATERIAL

NUMBER	SXX	SYY	SZZ	SXY	SYZ	SZX	SHXY	
SHYZ	SHZX	RO	ALX	ALY	ALZ	MU	KX	KY
KZ	SH							

NUMBER	Referred to from the ORTHOTROPIC.MATERIAL.NUMBER entry in the LAMINATES module, or, for three dimensional elements, from the PROPERTY entry in the ELEMENTS module. *No default*
SXX,SYY,SZZ	Material compliances in the principal directions for the material. For example, SXX gives the strain in the X direction when the stress in the X direction is unity and all other stresses are zero. *No default*
SXY,SYZ,SZX	Cross compliances. SXY gives the strain in the X direction when the Y stress is unity and all other stresses are zero. *No default*
SHXY,SHYZ,SHZX	Shear compliances. SHXY gives the engineering shear strain γ_{xy} when the shear stress σ_{xy} is unity. *No default*
RO	Density *Default = 0.0*
ALX,ALY,ALZ	Coefficients of thermal expansion in the principal axes of the material. *Default = 0.0*
MU	Hysteretic damping. *Default = 0.0*
KX,KY,KZ	Thermal conductivities in the principal directions of the material. *Default = 0.0*



SECTION @ 93mm

BRICK No	COORDINATES	THICK
1,	98,70/88,60	8mm
2,	88,60/78,52	12mm
3,	52,78/59,34	16mm
4,	59,34/42,16	20mm
5,	42,16/23,-5	24mm
6,	23-5/4,-26	27mm
7,	4-26/-15-45	27mm
8,	15-45/-37-65	24mm
9,	-37-65/-60-81	21mm
10,	-60-81/-85-94	15mm
11,	-85-94,/-98-99	11mm
12	-98,-99/-112-101	7mm

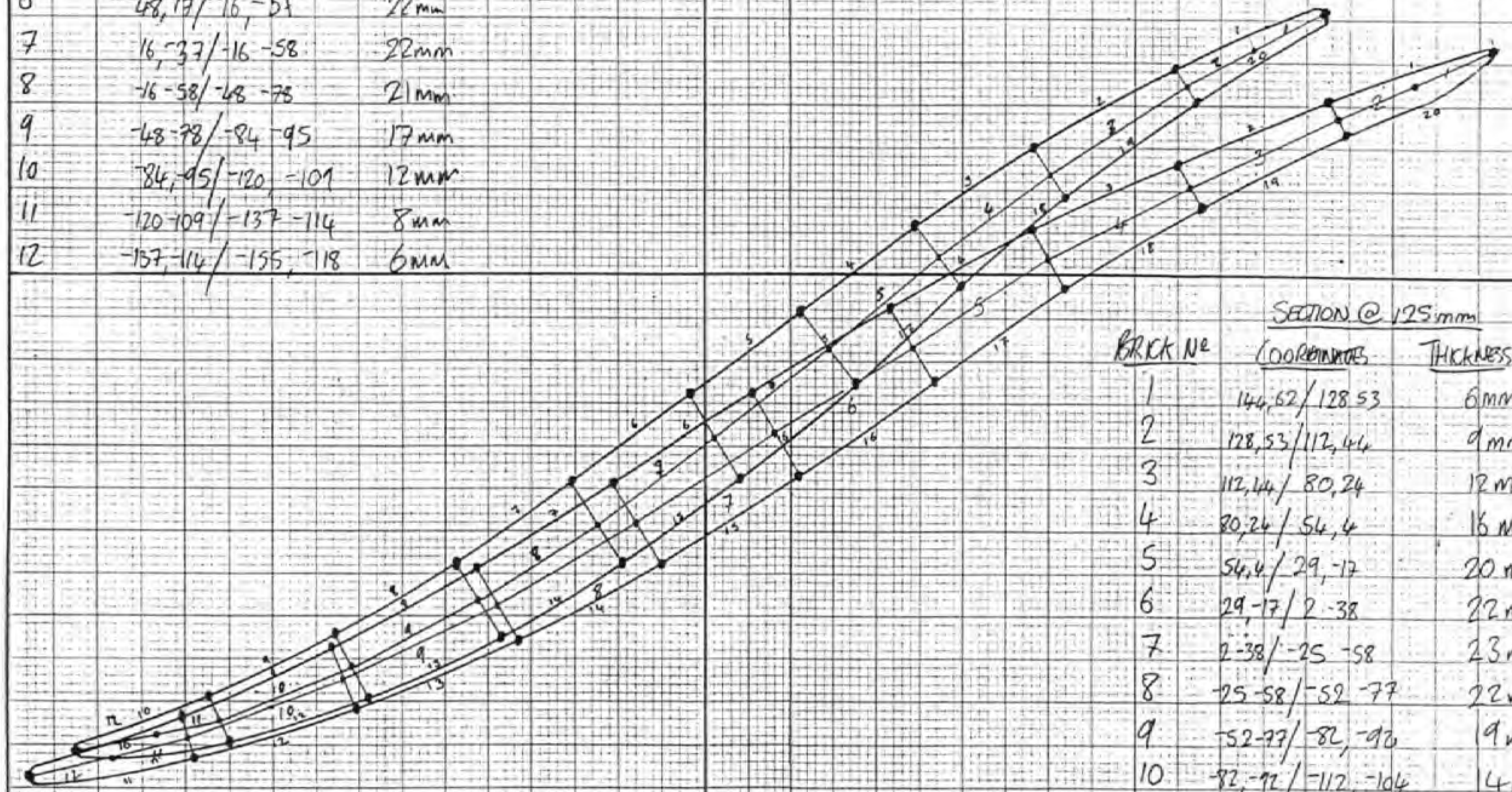
SECTION @ 62MM

BRICK No	COORDINATES (mm)	THICKNESS TOTAL
1	0.50,65/48,58	7mm
2	48,58/46,52	14mm
3	46,52/34,36	23mm
4	34,36/22,20	28 mm
5	22,20/16,4	31mm
6	16,4/5,-13	32mm
7	-5,-13/-5-29	30 mm
8	-5-29/-16,-44	25 mm
9	-16-44/-28-58	20mm
10	-28-58/-42,-70	14mm
11	-42-70/-49,-76	10 mm
12	-49,-76/-59,-80	5 MM

SECTION @ 155 mm

BRICK Nº	COORDINATES	THICKNESS
1	183,53/ 165,45	5MM
2	165,45/ 147, 37	8mm
3	147,37/ 113, 21	10mm
4	113,21 / 80, 4	14mm
5	80,4/ 48,-17	18mm
6	48,-17/ 16,-37	22mm
7	16,-37/-16 -58	22mm
8	-16 -58/-48 -78	21mm
9	-48-78/-84 -95	17mm
10	-84,-95/-120, -107	12mm
11	-120-109/-137 -114	8mm
12	-137,-114/ -155, -118	6MM

R@ 124mm •
R@ 155 mm •



SECTION @ 125mm

BRICK Nº	COORDINATES	THICKNESS
1	144,62/ 128 53	6mm
2	128,53/112,44	9mm
3	112,44/ 80,24	12mm
4	80,24 / 54,4	16 mm
5	54,4/ 29,-17	20 mm
6	29,-17/ 2 -38	22 mm
7	2 -38/ -25 -58	23mm
8	-25-58/ -52 -77	22mm
9	-52-77/ -82, -92	19mm
10	-82,-92 / -112, -104	4mm
11	-112-104 / -128, -108	10 mm
12	-128, -108/ -145, -112	5mm

SECTION @ 217 mm

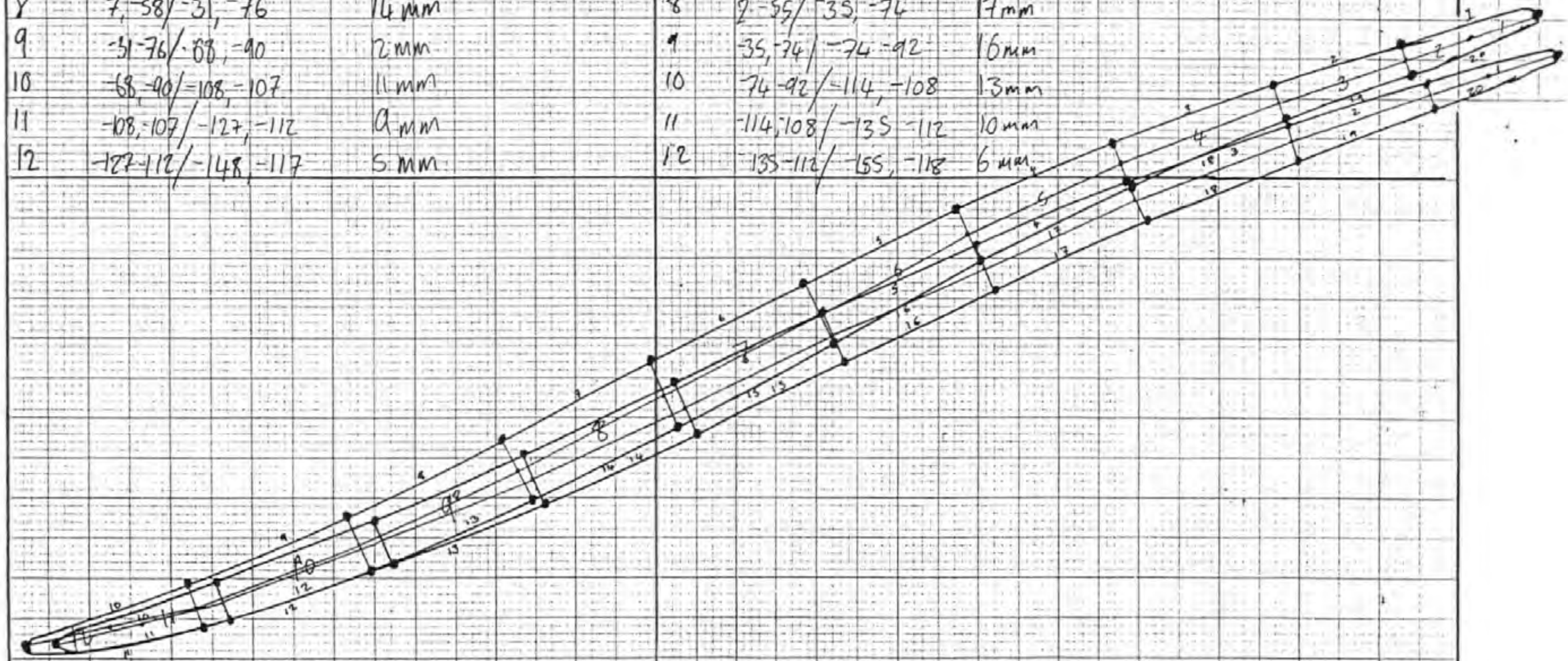
BRICK No	COORDINATES	THICKNESS (MM)
1	225, 32/208, 26	5mm
2	208, 26/193, 21	6mm
3	193, 21/158, 9	8mm
4	158, 9/119, -6	10mm
5	119-6/82, -23	12mm
6	82, -23/44, -39	13mm
7	44-39/7, -58	14mm
8	7, -58/-31, -76	14mm
9	-31-76/-68, -90	12mm
10	-68, -90/-108, -107	11mm
11	-108, -107/-127, -112	9mm
12	-127-112/-148, -117	5 mm

SECTION @ 186 mm

BRICK No		
1	220, 42/203, 35	5mm
2	203, 35/186 30	8mm
3	186 30/155 19	8mm
4	155, 19/116, 4	11mm
5	116 4/78, -14	13mm
6	78 14/41 -34	15mm
7	41-34/2, -55	18mm
8	2-55/-35, -74	17mm
9	-35, -74/-74 -92	16mm
10	-74-92/-114, -108	13mm
11	-114, 108/-135 -112	10mm
12	-135-112/-155, -118	6mm

R@ 186 mm •

R@ 217 mm •



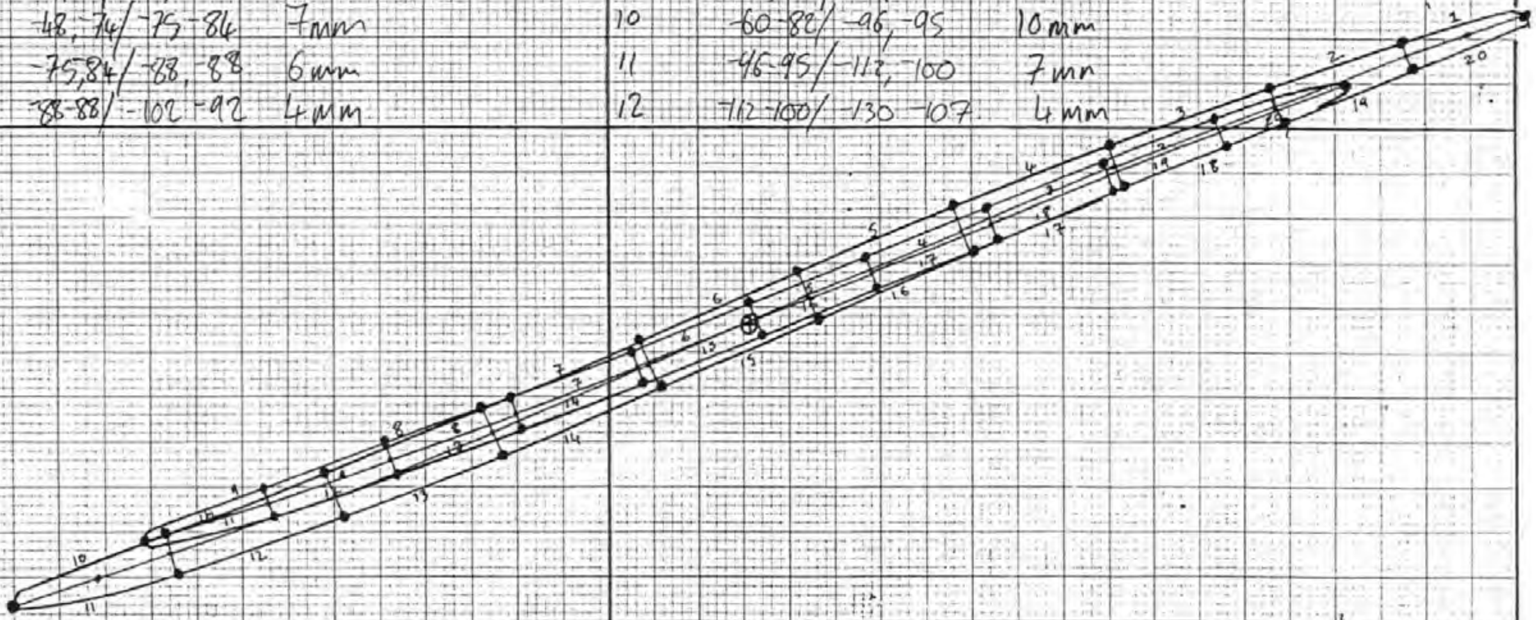
SECTION @ 279mm

BRCK Nº	COORDINATES	THICKNESS mm
1	162, 10/146, 5	5mm
2	146,5/ 134, -1	6mm
3	134-1/ 110, -11	7mm
4	110,-11/ 84, -22	7mm
5	84-22/ 58, -32	8mm
6	58,-32/ 32, -43	8mm
7	32,-43/ 6, -54	8mm
8	6,-54/-20, -64	7mm
9	-20, -64/ -48, -74	7mm
10	-48, -74/ -75 -84	7mm
11	-75,84/ -88, -88	6mm
12	-88-88/ -102 -92	4mm

SECTION @ 248mm

BRICK Nº	COORDINATES	THICKNESS MM
1	201, 25/ 189, 21	5mm
2	189, 21/ 176, 16	6mm
3	176, 16/ 147, 5	8mm
4	147,5 / 111, -8	10mm
5	111-8/ 77, -23	11mm
6	77, -23/ 43, -35	12mm
7	43-35/ 8, -53	11mm
8	8-53/ -26, -68	11mm
9	-26, -68/ -60, -82	11mm
10	-60-82/ -96, -95	10mm
11	-96-95/ -112, -100	7mm
12	-112-100/ -130 -107	4mm

R@ 248mm ●
R@ 279mm ●
R@ 310 mm ⊗



	Fibre	Resin
Modulus (GPa)	72	8
Tensile strength (MPa)	2400	85
Compressive strength (MPa)	1440	130
Shear inplane mod (GPa)	43.2	4.8
Shear inplane strength (MPa)	1440	51

Orthotropic Epoxy/Glass Lamina at 50% Fibre Volume Fraction

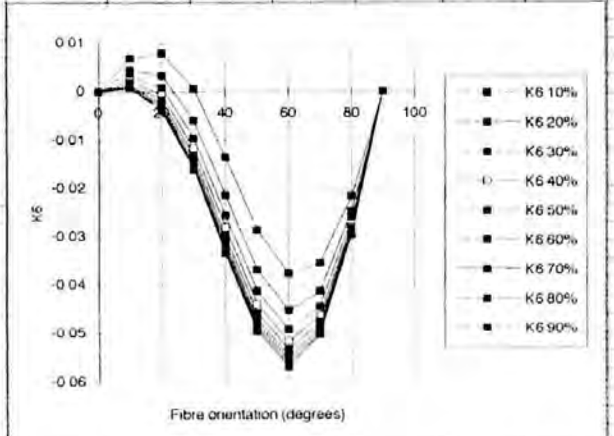
% 0° Fibre	%90° Fibre	Ex	Ey	Gxy	Nuxy	X	X'	Y	Y'	Sxy	Fxy*
50	0	40	8	24	0.26	1242.5	785	85	130	51	-0.5
37.5	12.5	30	14	24	0.13	931.875	588.75	354.6	261.25	51	-0.5
25	25	20	20	24	0.0918	621.25	392.5	621.25	392.5	51	-0.5

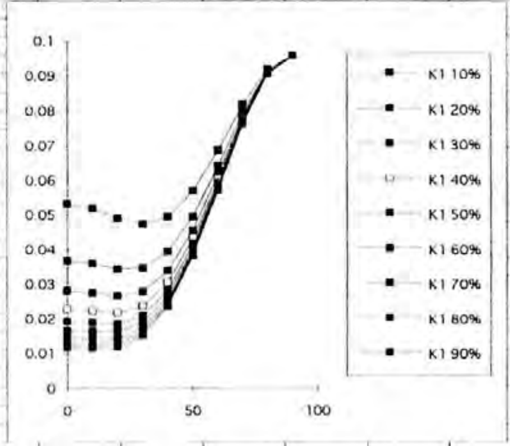
Laminate Properties Modified Scotchply

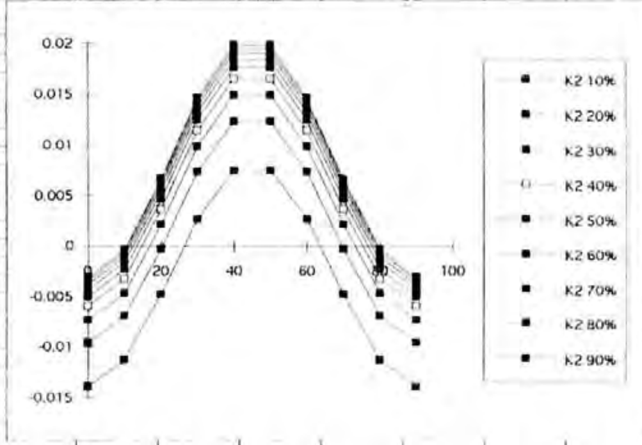
Volume Frac.	Ex	Ey	Gxy	Nuxy	X	X'	Y	Y'	Sxy	Fxy*
0	8	8	4.8	0.26	85	130	85	130	51	-0.5
0.1	14.4	8	8.64	0.26	316.5	261	85	130	51	-0.5
0.2	20.8	8	12.48	0.26	548	392	85	130	51	-0.5
0.3	27.2	8	16.32	0.26	779.5	523	85	130	51	-0.5
0.4	33.6	8	20.16	0.26	1011	654	85	130	51	-0.5
0.5	40	8	24	0.26	1242.5	785	85	130	51	-0.5
0.6	46.4	8	27.84	0.26	1474	916	85	130	51	-0.5
0.7	52.8	8	31.68	0.26	1705.5	1047	85	130	51	-0.5
0.8	59.2	8	35.52	0.26	1937	1178	85	130	51	-0.5
0.9	65.6	8	39.36	0.26	2168.5	1309	85	130	51	-0.5
1	72	8	43.2	0.26	2400	1440	85	130	51	-0.5

K1 70%	K2 70%	K6 70%	K1 80%	K2 80%	K6 80%	K1 90%	K2 90%	K6 90%
0.01455	-0.00378	0	0.01297	-0.00337	0	0.01171	-0.00304	0
0.01426	-0.00104	0.00115	0.01273	-0.00062	0.00092	0.01149	-0.00029	0.00074
0.01438	0.00591	-0.00307	0.01297	0.00635	-0.00352	0.01183	0.0067	-0.00388
0.01731	0.01381	-0.01495	0.01609	0.01427	-0.01558	0.0151	0.01463	-0.01609
0.02544	0.01897	-0.03208	0.02446	0.01944	-0.03284	0.02368	0.01982	-0.03344
0.03959	0.01897	-0.04813	0.03888	0.01944	-0.04893	0.03831	0.01982	-0.04957
0.05804	0.01381	-0.05559	0.0576	0.01427	-0.05632	0.05725	0.01463	-0.05691
0.07678	0.00591	-0.04928	0.07657	0.00635	-0.04985	0.0764	0.00669	-0.0503
0.0908	-0.00104	-0.02901	0.09075	-0.00062	-0.02932	0.0907	-0.00029	-0.02957
0.096	-0.00378	0	0.096	-0.00337	0	0.096	-0.00304	0

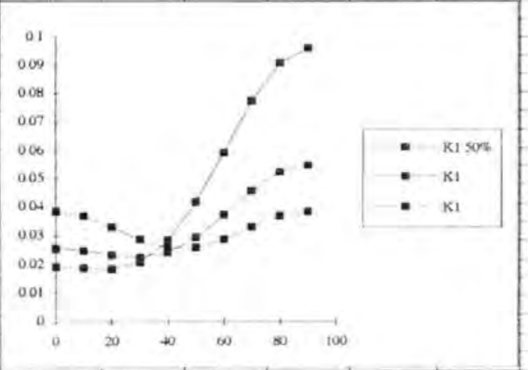
Fibre Angle	K1 10%	K2 10%	K6 10%	K1 20%	K2 20%	K6 20%	K1 30%	K2 30%	K6 30%	K1 40%	K2 40%	K6 40%	K1 50%	K2 50%	K6 50%	K1 60%	K2 60%	K6 60%
0	0.05333	-0.01387	0	0.03692	-0.0096	0	0.02823	-0.00734	0	0.02286	-0.00594	0	0.0192	-0.00499	0	0.01655	-0.0043	0
10	0.05204	-0.01129	0.00687	0.03605	-0.00695	0.00445	0.02759	-0.00465	0.00317	0.02235	-0.00323	0.00238	0.01879	-0.00227	0.00184	0.01621	-0.00157	0.00145
20	0.04922	-0.00476	0.008	0.03448	-0.00024	0.00332	0.02667	0.00215	0.00084	0.02184	0.00363	-0.0007	0.01856	0.00463	-0.00174	0.01618	0.00536	-0.0025
30	0.04747	0.00267	0.00062	0.03471	0.00738	-0.00597	0.02795	0.00988	-0.00947	0.02377	0.01143	-0.01161	0.02093	0.01248	-0.01308	0.01887	0.01324	-0.01414
40	0.04958	0.00751	-0.01347	0.03937	0.01236	-0.02134	0.03396	0.01493	-0.02551	0.03062	0.01652	-0.02809	0.02834	0.0176	-0.02985	0.02669	0.01838	-0.03112
50	0.05699	0.00751	-0.02855	0.04963	0.01236	-0.03683	0.04573	0.01493	-0.04122	0.04332	0.01652	-0.04394	0.04167	0.0176	-0.04578	0.04049	0.01838	-0.04712
60	0.0688	0.00267	-0.03757	0.06425	0.00738	-0.04519	0.06183	0.00988	-0.04923	0.06034	0.01143	-0.05173	0.05933	0.01248	-0.05343	0.05859	0.01324	-0.05466
70	0.0819	-0.00476	-0.03542	0.07973	-0.00024	-0.04129	0.07858	0.00215	-0.04439	0.07787	0.00363	-0.04632	0.07739	0.00463	-0.04763	0.07704	0.00536	-0.04857
80	0.09213	-0.01129	-0.02147	0.09157	-0.00695	-0.02466	0.09127	-0.00465	-0.02635	0.09109	-0.00323	-0.0274	0.09096	-0.00227	-0.02811	0.09087	-0.00157	-0.02862
90	0.096	-0.01387	0	0.096	-0.0096	0	0.096	-0.00734	0	0.096	-0.00594	0	0.096	-0.00499	0	0.096	-0.0043	0

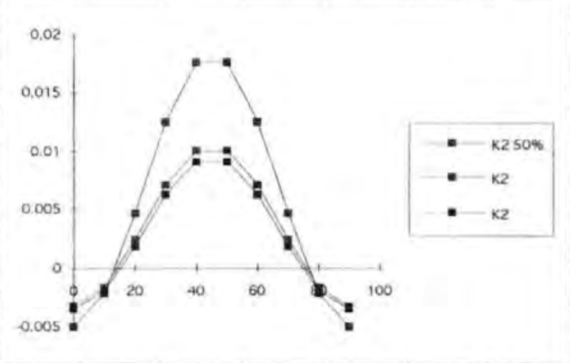


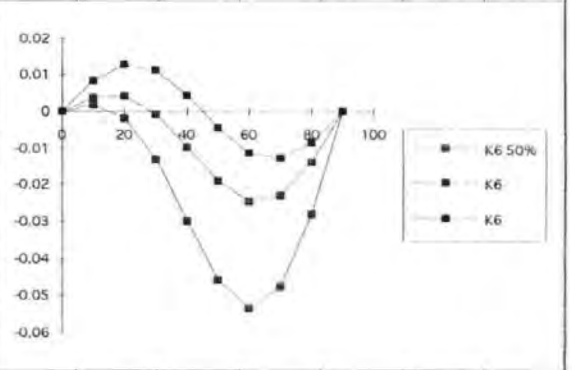




				37.5:12.5			25:25		
Fibre Angle	K1 50%	K2 50%	K6 50%	K1	K2	K6	K1	K2	K6
0	0.0192	-0.00499	0	0.0256	-0.0033	0	0.0384	-0.00353	0
10	0.01879	-0.00227	0.00184	0.02487	-0.00172	0.00385	0.03688	-0.00201	0.00833
20	0.01856	0.00463	-0.00174	0.02333	0.00236	0.00417	0.03304	0.00183	0.01277
30	0.02093	0.01248	-0.01308	0.02258	0.00701	-0.00074	0.02868	0.0062	0.01123
40	0.02834	0.0176	-0.02985	0.02433	0.01003	-0.00969	0.02585	0.00905	0.00443
50	0.04167	0.0176	-0.04578	0.02941	0.01003	-0.01912	0.02583	0.00905	-0.00443
60	0.05933	0.01248	-0.05343	0.03721	0.00701	-0.0246	0.02868	0.0062	-0.01123
70	0.07739	0.00463	-0.04763	0.04574	0.00236	-0.02297	0.03304	0.00183	-0.01277
80	0.09096	-0.00227	-0.02811	0.05236	-0.00172	-0.01386	0.03688	-0.00201	-0.00833
90	0.096	-0.00499	0	0.05486	-0.00333	0	0.0384	-0.00353	0







BRONZE PROP

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67      0.0377  -0.0261  -0.0358          5.112    *    -1.794             0.0581
68        *        *        *               *    1.706   0.463               *
69        *        *        *               *      *     0.112               *
70      0.0065  -0.0037  -0.0064            *    2.864   1.384             0.0098
71      0.0111  -0.0029  -0.0189          2.960  1.149     *               0.0221
72      0.0170  -0.0093  -0.0197          2.372  1.268     *               0.0276
73      0.0254  -0.0108  -0.0373          4.077  1.549     *               0.0464

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------------------------------------------------------------------------------
E  1           TRANSLATIONS                     ROTATIONS              RESULTAN

 F1║Editing: AQTH.007    L 516  C 1                                    I A
E  1           TRANSLATIONS                     ROTATIONS              RESULTAN
DE          MULTIPLIED BY 1E 3            MULTIPLIED BY 1E 3           MULTIPL
BER        UX        UY        UZ          PHIX    PHIY    PHIZ           U
------------------------------------------------------------------------------


74        *        *        *             0.458  0.823     *                 *
75        *        *        *               *      *     0.179               *
76      0.0028   0.0001  -0.0061          1.692  1.160     *               0.0067
77      0.0038   0.0058  -0.0148          2.965 -0.131     *               0.0163
78     -0.0036   0.0228  -0.0207          5.828  0.474     *               0.0310
79        *        *        *               *      *     0.132               *
80     -0.0078   0.0104  -0.0021          1.619 -0.323     *               0.0132
81      0.9576  -1.1365  -1.3090          12.33  8.610   0.228             1.9804
93      0.8748  -0.9576   0.1967          11.37  6.955  -2.507             1.3119
94      1.2312  -1.5161  -1.1830          15.24    *     0.910             2.2834
06      1.1774  -1.3752   0.1564          16.08    *    -2.268             1.8171
07      1.5127  -1.9121  -1.0212          12.27  8.576   1.115             2.6433
19      1.5191  -1.8843   0.0940          13.85  9.664  -3.604             2.4222
20      1.9149  -2.5889  -0.5116          17.03  4.779   1.222             3.2605
21      0.8191  -0.9481  -1.2259          15.85    *    -3.056             1.7529
22      0.9896  -1.2181  -0.5739          13.36  10.72   0.783             1.6711
23      0.7451  -0.7880   0.2199          13.38    *    -2.548             1.1065
24      1.0950  -1.3278  -1.2458          15.59    *     0.881             2.1246

 F1║Editing: AQTH.007    L 539  C 1                                    I A
24      1.0950  -1.3278  -1.2458          15.59    *     0.881             2.1246
25      1.2904  -1.6626  -0.5231          18.41    *     2.073             2.1686
26      1.0230  -1.1584   0.1759          15.32    *    -2.012             1.5554
30      0.6825  -0.7084   0.2310          12.95    *    -2.624             1.0104
31      0.7499  -0.8540  -1.1843          15.93    *    -3.066             1.6414
32      0.8419  -1.0088  -0.5152          17.06    *    -1.699             1.4114
33      0.8091  -0.8710   0.2085          13.78    *    -2.932             1.2070
34      0.8883  -1.0423  -1.2674          15.81    *    -3.085             1.8660
35      0.7763  -0.8637   0.0735          14.63    *    -2.677             1.1636
36      0.7110  -0.7769   0.0881          14.02    *    -2.526             1.0568
37      0.7611  -0.8272   0.1466          13.94    *    -2.564             1.1336
38      0.8033  -0.9272  -0.0738          15.67    *    -2.688             1.2290
39      0.7352  -0.8339  -0.0555          15.11    *    -2.509             1.1131
40      0.7903  -0.8970  -0.0001          15.10    *    -2.637             1.1955
41      0.8273  -0.9809  -0.2226          16.77    *    -2.747             1.3024
42      0.7561  -0.8804  -0.2003          16.25    *    -2.653             1.1777
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E  1         TRANSLATIONS                     ROTATIONS                RESULTAN
DE        MULTIPLIED BY 1E 3            MULTIPLIED BY 1E 3             MULTIPL
BER     UX        UY        UZ          PHIX   PHIY   PHIZ                U
------------------------------------------------------------------------------

 F1‖Editing: AQTH.007   L 447  C 1                                       I A
------------------------------------------------------------------------------


20         *         *         *            *      *    0.609             *
21     -0.0113    0.0205   -0.0067      4.472 -0.127     *           0.0244
22      0.0197   -0.0152    0.0223      5.925     *    1.579         0.0334
23      0.0104    0.0018    0.0483      9.179     *    1.864         0.0494
24      0.0116   -0.0072    0.0232      5.630     *    0.813         0.0269
25      0.0402   -0.0300    0.0434      7.348     *    1.430         0.0663
26         *         *         *            *  1.587 -0.610             *
27     -0.0067    0.0047    0.0052      2.925  0.988     *           0.0097
28         *         *         *            *      *   -0.260             *
29      0.0058   -0.0047    0.0068          *  4.041 -1.817          0.0101
30      0.0277   -0.0228    0.0175      6.112     *    1.263         0.0399
31      0.0247   -0.0199    0.0200      5.469     *    1.305         0.0375
32      0.0517   -0.0431    0.0323      7.039     *    1.155         0.0746
33         *         *         *            *  2.380 -0.299             *
34         *         *         *            *      *   -0.477             *
35      0.0091   -0.0074    0.0060          *  4.940 -1.531          0.0132
36      0.0305   -0.0256    0.0112      5.245     *    0.574         0.0414
37      0.0300   -0.0251    0.0149      5.666     *    0.937         0.0419
38      0.0552   -0.0473    0.0198      6.301     *    0.547         0.0754
39         *         *         *            *  2.303  0.387             *
40         *         *         *            *      *   -0.171             *

 F1‖Editing: AQTH.007   L 470  C 1                                       I A
40         *         *         *            *      *   -0.171             *
41      0.0115   -0.0094    0.0044          *  4.139 -0.544          0.0155
42      0.0283   -0.0233    0.0037      3.729     *    0.168         0.0368
43      0.0302   -0.0252    0.0076      4.846     *    0.452         0.0401
44      0.0521   -0.0441    0.0062      5.138     *    0.100         0.0685
45         *         *         *            *  1.892  0.518             *
46         *         *         *            *      *    0.245             *
47      0.0107   -0.0087    0.0016          *  2.687  0.270          0.0139
48      0.0226   -0.0174   -0.0025      2.922     *    0.173         0.0286
49      0.0260   -0.0210    0.0003      3.993     *    0.179         0.0335
50      0.0446   -0.0360   -0.0056      4.568     *   -0.076         0.0576
51         *         *         *            *      *    0.436             *
52      0.0069   -0.0051   -0.0006          *  1.597  0.634          0.0087
53      0.0203   -0.0147   -0.0076      3.523     *   -0.552         0.0261
54      0.0210   -0.0156   -0.0050      3.912     *   -0.294         0.0267
55      0.0405   -0.0310   -0.0154      5.026     *   -0.841         0.0533
56         *         *         *            *  2.075  0.395             *
57         *         *         *            *      *    0.108             *
58      0.0068   -0.0046   -0.0024          *  2.625  0.821          0.0086
59      0.0207   -0.0144   -0.0134      3.542     *   -1.070         0.0286
60      0.0204   -0.0144   -0.0103      4.059     *   -1.139         0.0270
61      0.0404   -0.0301   -0.0263      4.979     *   -1.540         0.0568
62         *         *         *            *  1.892  0.474             *
63         *         *         *            *      *    0.040             *

 F1‖Editing: AQTH.007   L 493  C 1                                       I A
63         *         *         *            *      *    0.040             *
64      0.0069   -0.0044   -0.0045          *  2.770  0.899          0.0094
65      0.0194   -0.0124   -0.0187      3.888     *   -1.479         0.0296
66      0.0206   -0.0141   -0.0163      3.961     *   -1.549         0.0298
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72      0.1331  -0.1151  -0.0904          8.272     *   -2.991            0.1979
73      0.1401  -0.1236  -0.0410          7.622     *   -1.382            0.1913
74      0.1808  -0.1648  -0.0606          8.886     *   -1.696            0.2520
75      0.1371  -0.1202  -0.0576          8.316     *   -2.117            0.1912
76      0.1481  -0.1330  -0.0064          7.308     *   -0.889            0.1991
77      0.1876  -0.1727  -0.0161          8.532     *   -1.156            0.2555
78      0.1444  -0.1287  -0.0241          7.426     *   -1.135            0.1950
79      0.1525  -0.1380   0.0303          7.745     *   -0.544            0.2079
80      0.1917  -0.1769   0.0302          8.762     *   -0.670            0.2626
81      0.1510  -0.1365   0.0117          7.261     *   -0.707            0.2039
82      0.1504  -0.1335   0.0681          8.456     *   -0.140            0.2123
83      0.1905  -0.1732   0.0780          9.234     *   -0.172            0.2690
84      0.1526  -0.1373   0.0490          7.818     *   -0.328            0.2110
85      0.1373  -0.1143   0.1068          9.534     *    0.343            0.2081
86      0.1795  -0.1551   0.1281         10.07      *    0.277            0.2696
87      0.1452  -0.1256   0.0873          8.828     *   -0.000            0.2109
88      0.1598  -0.1250   0.1800         10.82      *    0.906            0.2712
89      0.1273  -0.1003   0.1264          9.842     *    0.581            0.2055

 F1‖Editing: AQTH.007    L 401  C 1                                       I A
89      0.1273  -0.1003   0.1264          9.842     *    0.581            0.2055
90      0.0446  -0.0245  -0.0610          3.379  4.006   2.090            0.0794
91      0.0395  -0.0003  -0.0882          7.212  2.151     *              0.0966
92      0.0721  -0.0444  -0.1016          5.593  2.729     *              0.1322
93      0.0301  -0.0067  -0.0551          4.321  2.790   2.265            0.0632
94      0.0605  -0.0446  -0.0570          3.422  3.421   0.556            0.0944
95      0.0893  -0.0685  -0.0922          7.205     *   -3.240            0.1455
96      0.0544  -0.0367  -0.0609          3.219  3.332   1.347            0.0895
97      0.0653  -0.0513  -0.0427          3.854  2.946  -0.237            0.0934
98      0.0957  -0.0784  -0.0718          7.302     *   -3.026            0.1430
99      0.0639  -0.0492  -0.0506          3.326  3.163   0.267            0.0952
00      0.0665  -0.0536  -0.0258          3.592  3.437   0.239            0.0892
01      0.0982  -0.0822  -0.0479          7.395     *   -2.278            0.1367
02      0.0658  -0.0523  -0.0341          3.449  3.218   0.024            0.0907
03      0.1040  -0.0891  -0.0241          6.870     *   -1.191            0.1391
04      0.0683  -0.0559  -0.0177          2.959  3.839   0.527            0.0900
05      0.0805  -0.0698   0.0086          4.405  2.242   0.006            0.1069
06      0.1128  -0.0995   0.0016          6.846     *   -0.777            0.1504
07      0.0765  -0.0655  -0.0011          3.802  2.572   0.138            0.1007
08      0.0842  -0.0735   0.0293          5.430  2.030   0.044            0.1155
09      0.1172  -0.1042   0.0298          7.455     *   -0.336            0.1596
10      0.0833  -0.0728   0.0188          5.172  1.537  -0.090            0.1122
11      0.0802  -0.0677   0.0496          5.702  2.544   0.040            0.1161
12      0.1139  -0.0988   0.0587          8.122     *    0.096            0.1618

 F1‖Editing: AQTH.007    L 424  C 1                                       I A
12      0.1139  -0.0988   0.0587          8.122     *    0.096            0.1618
13      0.0834  -0.0720   0.0395          5.243  2.245  -0.075            0.1171
14      0.0652  -0.0483   0.0685          6.462  2.434  -0.261            0.1062
15      0.0990  -0.0785   0.0869          8.995     *    0.317            0.1533
16      0.0747  -0.0602   0.0593          5.123  2.971  -0.540            0.1128
17      0.0747  -0.0472   0.1137         10.13      *    1.184            0.1440
18      0.0514  -0.0320   0.0764          6.822  2.675  -0.615            0.0975
19     -0.0048   0.0076   0.0211          7.446     *    1.509            0.0229

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35       0.2040  -0.1787  -0.2353          11.19     *    -4.360             0.3591
36       0.2533  -0.2333  -0.2976          12.32     *    -4.781             0.4551
37       0.1970  -0.1665  -0.2562          11.01     *    -4.470             0.3635
38       0.2149  -0.1977  -0.1897          10.65     *    -3.777             0.3482

 F1║Editing: AQTH.007    L 332  C 1                                         I A
38       0.2149  -0.1977  -0.1897          10.65     *    -3.777             0.3482
39       0.2629  -0.2507  -0.2419          11.64     *    -4.143             0.4365
40       0.2100  -0.1892  -0.2130          10.38     *    -3.852             0.3540
41       0.2213  -0.2077  -0.1382          10.24     *    -3.229             0.3335
42       0.2690  -0.2606  -0.1815          11.07     *    -3.667             0.4161
43       0.2187  -0.2040  -0.1648          10.13     *    -3.457             0.3415
44       0.2734  -0.2657  -0.1181          10.86     *    -3.005             0.3991
45       0.2237  -0.2106  -0.1110          10.01     *    -2.821             0.3267
46       0.2316  -0.2191  -0.0275          5.328  6.949   0.523             0.3200
47       0.2772  -0.2691  -0.0534          10.31     *    -2.579             0.3901
48       0.2291  -0.2165  -0.0556          4.874  7.805   1.091             0.3201
49       0.2351  -0.2221   0.0295          6.308  5.371  -0.196             0.3247
50       0.2797  -0.2705   0.0116          10.16     *    -2.062             0.3892
51       0.2338  -0.2212   0.0008          5.794  5.887   0.130             0.3218
52       0.2345  -0.2185   0.0882          6.855  5.060  -0.468             0.3324
53       0.2793  -0.2672   0.0779          10.33     *    -1.670             0.3943
54       0.2356  -0.2215   0.0584          6.382  5.095  -0.246             0.3286
55       0.2251  -0.2005   0.1506          7.116  5.669  -0.832             0.3369
56       0.2708  -0.2504   0.1481          10.72     *    -1.575             0.3974
57       0.2310  -0.2113   0.1189          6.760  5.309  -0.669             0.3349
58       0.2527  -0.2179   0.2216          10.95     *    -1.409             0.4006
59       0.2169  -0.1862   0.1829          6.845  6.090  -1.108             0.3393
60       0.1041  -0.0699  -0.1486          6.392  3.007      *               0.1944
61       0.1171  -0.0654  -0.2193          9.243  4.354      *               0.2571

 F1║Editing: AQTH.007    L 355  C 1                                         I A
61       0.1171  -0.0654  -0.2193          9.243  4.354      *               0.2571
62       0.1426  -0.1052  -0.2061          7.705  4.366      *               0.2718
63       0.0905  -0.0500  -0.1500          7.271  2.688      *               0.1822
64       0.1217  -0.0968  -0.1320          7.881     *    -3.257             0.2040
65       0.1595  -0.1326  -0.1791          9.742     *    -3.866             0.2740

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-------------------------------------------------------------------------------
E  1            TRANSLATIONS                       ROTATIONS              RESULTAN
DE           MULTIPLIED BY 1E 3             MULTIPLIED BY 1E 3            MULTIPL
BER         UX          UY         UZ          PHIX   PHIY   PHIZ             U
-------------------------------------------------------------------------------


66       0.1143  -0.0851  -0.1416          5.581  2.861      *               0.2009

 F1║Editing: AQTH.007    L 378  C 1                                         I A
66       0.1143  -0.0851  -0.1416          5.581  2.861      *               0.2009
67       0.1306  -0.1112  -0.1057          8.216     *    -3.160             0.2015
68       0.1703  -0.1507  -0.1450          9.492     *    -3.422             0.2697
69       0.1271  -0.1055  -0.1197          7.525     *    -3.047             0.2040
70       0.1350  -0.1177  -0.0743          8.305     *    -2.556             0.1939
71       0.1762  -0.1597  -0.1045          9.281     *    -2.775             0.2598
```

```
95        0.4304  -0.4440  -0.0057            12.43     *    -2.071            0.6184
96        0.4178  -0.4160   0.1389            11.56     *    -1.732            0.6057
97        0.4725  -0.4804   0.1302            11.90     *    -1.758            0.6863
98        0.4243  -0.4299   0.0896            11.77     *    -1.770            0.6106
99        0.4510  -0.4344   0.2403            11.43     *    -1.568            0.6707
00        0.4087  -0.3972   0.1891            11.33     *    -1.687            0.6005
01        0.2965  -0.2760  -0.4305            13.94     *    -5.912            0.5912
02        0.3435  -0.3248  -0.5873            15.50     *    -6.878            0.7539
03        0.3561  -0.3484  -0.5170            14.65     *    -6.110            0.7180
04        0.2892  -0.2629  -0.4597            14.23     *    -6.086            0.6034
05        0.3073  -0.2960  -0.3665            13.27     *    -5.159            0.5625
06        0.3651  -0.3658  -0.4408            14.06     *    -5.457            0.6793
07        0.3024  -0.2867  -0.3990            13.33     *    -5.481            0.5769
08        0.3150  -0.3108  -0.2991            12.50     *    -4.412            0.5341
09        0.3710  -0.3778  -0.3612            13.48     *    -4.757            0.6410
10        0.3116  -0.3041  -0.3331            12.65     *    -4.759            0.5482

 F1║Editing: AQTH.007    L 286   C 1                                           I A
10        0.3116  -0.3041  -0.3331            12.65     *    -4.759            0.5482
11        0.3198  -0.3190  -0.2282            11.82     *    -3.768            0.5061

**************************************************
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----------------------------------------------------------------------------
E  1             TRANSLATIONS                    ROTATIONS              RESULTAN
DE            MULTIPLIED BY 1E 3            MULTIPLIED BY 1E 3          MULTIPL
BER         UX        UY         UZ         PHIX    PHIY    PHIZ            U
----------------------------------------------------------------------------


12        0.3744  -0.3842  -0.2792            12.99     *    -4.126            0.6048
13        0.3179  -0.3159  -0.2642            11.95     *    -4.076            0.5202
14        0.3236  -0.3234  -0.1556            11.57     *    -3.121            0.4832
15        0.3775  -0.3878  -0.1964            12.77     *    -3.385            0.5757

 F1║Editing: AQTH.007    L 309   C 1                                           I A
15        0.3775  -0.3878  -0.1964            12.77     *    -3.385            0.5757
16        0.3216  -0.3213  -0.1920            11.49     *    -3.491            0.4934
17        0.3262  -0.3248  -0.0817            11.01     *    -2.735            0.4675
18        0.3789  -0.3873  -0.1127            12.22     *    -3.027            0.5534
19        0.3254  -0.3251  -0.1190            11.26     *    -2.906            0.4751
20        0.3270  -0.3235  -0.0077            10.71     *    -2.173            0.4600
21        0.3777  -0.3824  -0.0289            11.78     *    -2.401            0.5383
22        0.3267  -0.3242  -0.0447            10.83     *    -2.356            0.4624
23        0.3265  -0.3200   0.0668            10.76     *    -1.719            0.4620
24        0.3762  -0.3771   0.0546            11.43     *    -1.830            0.5354
25        0.3272  -0.3224   0.0292            10.73     *    -1.790            0.4603
26        0.3182  -0.3029   0.1454            10.95     *    -1.623            0.4628
27        0.3673  -0.3583   0.1423            11.26     *    -1.731            0.5324
28        0.3237  -0.3137   0.1054            10.91     *    -1.610            0.4629
29        0.3480  -0.3203   0.2338            11.12     *    -1.665            0.5276
30        0.3103  -0.2879   0.1862            10.93     *    -1.501            0.4624
31        0.1888  -0.1526  -0.2760            12.05     *    -5.116            0.3676
32        0.2218  -0.1780  -0.3922            10.87   6.053      *              0.4845
33        0.2404  -0.2104  -0.3498            13.12     *    -5.440            0.4737
34        0.1785  -0.1355  -0.2922            9.291   4.891      *              0.3682
```

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**************************************************

 F1║Editing: AQTH.007   L 217  C 1                                 I A
**************************************************
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----------------------------------------------------------------------------
E  1          TRANSLATIONS                      ROTATIONS              RESULTAN
DE         MULTIPLIED BY 1E 3             MULTIPLIED BY 1E 3           MULTIPL
BER        UX        UY        UZ         PHIX    PHIY   PHIZ             U
----------------------------------------------------------------------------


58       0.5583  -0.6139  -0.1706         14.85     *    -3.158         0.8471
59       0.6690  -0.7450  -0.0378         14.48     *    -2.480         1.0020
60       0.5437  -0.5815   0.0038         13.28     *    -2.167         0.7961
61       0.6781  -0.7656  -0.1082         15.15     *    -2.600         1.0284
62       0.6052  -0.6607  -0.0165         13.91     *    -2.444         0.8961
63       0.5490  -0.5934  -0.0542         13.93     *    -2.427         0.8102
64       0.6478  -0.6949   0.1021         13.37     *    -2.300         0.9554

 F1║Editing: AQTH.007   L 240  C 1                                  I A
64       0.6478  -0.6949   0.1021         13.37     *    -2.300         0.9554
65       0.5287  -0.5475   0.1213         12.22     *    -1.890         0.7708
66       0.6590  -0.7215   0.0321         13.93     *    -2.303         0.9777
67       0.5870  -0.6186   0.1119         12.83     *    -2.094         0.8601
68       0.5371  -0.5665   0.0622         12.59     *    -1.921         0.7832
69       0.6354  -0.6651   0.1717         12.91     *    -2.095         0.9357
70       0.5628  -0.5624   0.2412         12.11     *    -1.741         0.8314
71       0.5184  -0.5242   0.1807         11.69     *    -1.753         0.7591
72       0.4185  -0.4262  -0.6081         15.16     *    -6.465         0.8524
73       0.4749  -0.4914  -0.8018         16.04     *    -7.531         1.0536
74       0.4834  -0.5088  -0.7044         15.53     *    -6.665         0.9944
75       0.4135  -0.4165  -0.6506         15.34     *    -6.697         0.8762
76       0.4260  -0.4413  -0.5195         14.67     *    -5.739         0.8038
77       0.4897  -0.5220  -0.6037         15.13     *    -5.912         0.9364
78       0.4226  -0.4343  -0.5642         14.72     *    -5.996         0.8280
79       0.4305  -0.4513  -0.4279         14.28     *    -5.008         0.7564
80       0.4934  -0.5309  -0.5005         14.89     *    -5.123         0.8808
81       0.4286  -0.4469  -0.4739         14.23     *    -5.306         0.7797
82       0.4330  -0.4567  -0.3346         13.94     *    -4.351         0.7127
83       0.4954  -0.5361  -0.3960         14.68     *    -4.452         0.8305
84       0.4320  -0.4547  -0.3815         13.88     *    -4.638         0.7341
85       0.4973  -0.5393  -0.2917         14.62     *    -3.667         0.7895
86       0.4339  -0.4580  -0.2876         13.70     *    -3.936         0.6933
87       0.4356  -0.4574  -0.1468         13.24     *    -3.212         0.6485

 F1║Editing: AQTH.007   L 263  C 1                                  I A
87       0.4356  -0.4574  -0.1468         13.24     *    -3.212         0.6485
88       0.4971  -0.5363  -0.1868         14.13     *    -3.311         0.7547
89       0.4363  -0.4603  -0.1944         13.45     *    -3.354         0.6634
90       0.4321  -0.4484  -0.0523         12.69     *    -2.562         0.6249
91       0.4913  -0.5228  -0.0813         13.55     *    -2.694         0.7220
92       0.4340  -0.4530  -0.0994         13.09     *    -2.840         0.6351
93       0.4284  -0.4388   0.0415         12.06     *    -1.904         0.6146
94       0.4848  -0.5077   0.0231         12.68     *    -1.995         0.7023
```

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BER        UX        UY        UZ                PHIX    PHIY    PHIZ            U
-----------------------------------------------------------------------------------


 1          *         *         *                0.276   0.201     *              *
 2          *         *         *                0.442   0.473     *              *
 3       0.0116    0.0159   -0.0424              4.439   3.867   3.236        0.0468
 4       0.0369   -0.0147    0.0836              5.515   5.292  -1.472        0.0926
 5       0.1665   -0.1155   -0.3050              10.22   5.414     *          0.3662
 6       0.2065   -0.1687    0.2156              7.240   6.208  -1.231        0.3429
 7       0.4082   -0.4062   -0.6921              15.81     *    -7.275        0.9003
 8       0.3970   -0.3737    0.2399              11.22     *    -1.628        0.5957
12       0.0719   -0.0603   -0.0098              3.406   3.129   0.429        0.0943
13       0.2261   -0.2132   -0.0833              5.245   7.836   1.294        0.3218

 F1║Editing: AQTH.007    L 171   C 1                                          I A
13       0.2261   -0.2132   -0.0833              5.245   7.836   1.294        0.3218
14       0.1156   -0.0841    0.1458              10.49     *     1.080        0.2042
15       0.0744   -0.0267   -0.1465              8.199   3.331     *          0.1665
16       0.4352   -0.4596   -0.2410              13.78     *    -3.569        0.6773
17       0.2998   -0.2683    0.2277              11.00     *    -1.521        0.4623
18       0.2811   -0.2483   -0.4869              15.01     *    -6.673        0.6146
19       0.6806   -0.7599   -1.1428              12.34   8.617   0.289        1.5319
20       0.6216   -0.6320    0.2418              12.52     *    -2.162        0.9189
21       0.6989   -0.8092   -0.4588              12.03   9.990   0.562        1.1635
22       0.5061   -0.4968    0.2407              11.61     *    -1.787        0.7489
23       0.5428   -0.5794   -0.9141              16.13     *    -7.379        1.2108
24       0.6865   -0.7738   -1.0075              12.16   8.631   0.259        1.4440
25       0.5501   -0.5950   -0.8037              15.80     *    -6.656        1.1413
26       0.6837   -0.7671   -1.0753              12.17   8.669   0.328        1.4873
27       0.6115   -0.6691   -1.0280              16.10     *    -7.389        1.3705
28       0.6179   -0.6837   -0.9050              15.87     *    -6.620        1.2916
29       0.5466   -0.5875   -0.8592              15.85     *    -6.915        1.1757
30       0.6906   -0.7845   -0.8706              12.05   8.675   0.179        1.3603
31       0.5553   -0.6065   -0.6905              15.42     *    -5.910        1.0738
32       0.6888   -0.7797   -0.9393              11.99   8.744   0.267        1.4016
33       0.6224   -0.6942   -0.7797              15.69     *    -5.926        1.2154
34       0.5529   -0.6012   -0.7473              15.45     *    -6.217        1.1071
35       0.6934   -0.7925   -0.7331              12.08   8.739   0.280        1.2830
36       0.5584   -0.6148   -0.5758              15.31     *    -5.130        1.0106

 F1║Editing: AQTH.007    L 194   C 1                                          I A
36       0.5584   -0.6148   -0.5758              15.31     *    -5.130        1.0106
37       0.6919   -0.7882   -0.8015              11.91   8.801   0.209        1.3200
38       0.6252   -0.7022   -0.6535              15.64     *    -5.083        1.1450
39       0.5570   -0.6107   -0.6330              15.06     *    -5.475        1.0411
40       0.6962   -0.8011   -0.5960              11.87   9.523   0.498        1.2173
41       0.5605   -0.6207   -0.4606              15.26     *    -4.488        0.9548
42       0.6950   -0.7972   -0.6647              11.88   9.053   0.352        1.2491
43       0.6277   -0.7095   -0.5275              15.65     *    -4.443        1.0842
44       0.5598   -0.6185   -0.5185              15.10     *    -4.787        0.9822
45       0.5622   -0.6245   -0.3451              15.27     *    -3.710        0.9084
46       0.6976   -0.8053   -0.5274              11.87   9.814   0.556        1.1888
47       0.6295   -0.7148   -0.4009              15.87     *    -3.719        1.0334
48       0.5613   -0.6226   -0.4027              15.18     *    -4.090        0.9300
49       0.6993   -0.8105   -0.3203              12.68   8.603  -0.469        1.1174
50       0.5617   -0.6216   -0.2291              14.90     *    -3.393        0.8686
51       0.7000   -0.8123   -0.3900              12.33   9.597   0.214        1.1410
52       0.6290   -0.7130   -0.2736              15.70     *    -3.441        0.9894
53       0.5628   -0.6251   -0.2876              15.02     *    -3.473        0.8889
54       0.6863   -0.7838   -0.1786              15.62     *    -2.847        1.0570
55       0.5537   -0.6040   -0.1121              14.32     *    -2.863        0.8270
56       0.6940   -0.8000   -0.2497              13.52   6.305  -1.394        1.0881
57       0.6189   -0.6911   -0.1446              15.01     *    -3.017        0.9389
```

```
 F1║Editing: AQTH.007    L 102  C 1                                          I A
DE       PHIX            NODE       PHIY             NODE       PHIZ
----------------      ------------------        -------------------
46      0.0195037         322      0.0107206          73      -0.0075311
31      0.0193089         375      0.0105605          27      -0.0073890
50      0.0193028         378      0.0103812          23      -0.0073791
48      0.0192983         491      0.0103267           7      -0.0072750
39      0.0192146         503      0.0102192          29      -0.0069153
40      0.0190526         497      0.0101094         102      -0.0068778
47      0.0190363         498      0.0100816          75      -0.0066970
23      0.0189726         504      0.0100716          18      -0.0066730
82      0.0189697         376      0.0100091          74      -0.0066652
84      0.0189535         371      0.0099917          25      -0.0066557
----------------      ------------------        -------------------

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 F1║Editing: AQTH.007    L 125  C 1                                          I A



PLACEMENTS AT NODES
-------------------




E - (2) THE  HISTOGRAM  INDICATES  THE  MAGNITUDE  OF THE
        RESULTANT TRANSLATION AT  EACH NODE.  EACH STAR *
        REPRESENTS 0.3261E-03 UNITS
    (3) A STAR * IN A DISPLACEMENT  COLUMN INDICATES THAT
        A CONSTRAINT HAS BEEN APPLIED.
    (4) ONLY  STRUCTURAL  NODES  ARE  GIVEN  IN THE TABLE
        BELOW
    (5) ROTATIONS ARE GIVEN IN RADIANS.

**************************************************
                ** NOTICE **                    **
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 F1║Editing: AQTH.007    L 148  C 1                                          I A
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---------------------------------------------------------------------------
E  1            TRANSLATIONS                     ROTATIONS              RESULTAN
DE           MULTIPLIED BY 1E 3            MULTIPLIED BY 1E 3           MULTIPL
```

```
43      0.8156  -0.9552  -0.1481          16.11     *    -2.719           1.2647
44      0.8448  -1.0174  -0.3712          17.43     *    -2.134           1.3735
45      0.7712  -0.9120  -0.3454          16.97     *    -2.153           1.2433
46      0.8377  -1.0031  -0.2973          17.14     *    -2.648           1.3402
47      0.7698  -0.9078  -0.4867          16.72     *    -1.743           1.2859
48      0.8445  -1.0159  -0.4437          17.28     *    -1.750           1.3936
49      0.8363  -0.9930  -0.6571          16.43     *    -1.947           1.4550
50      0.7658  -0.8961  -0.6263          16.21     *    -1.996           1.3348

 F1‖Editing: AQTH.007   L 562  C 1                                        I A
50      0.7658  -0.8961  -0.6263          16.21     *    -1.996           1.3348
51      0.8390  -1.0006  -0.5862          16.66     *    -1.796           1.4314
52      0.8317  -0.9804  -0.7991          16.06     *    -2.238           1.5137
53      0.7622  -0.8857  -0.7659          15.95     *    -2.260           1.3972
54      0.8339  -0.9865  -0.7280          16.13     *    -2.131           1.4827
55      0.8282  -0.9709  -0.9417          15.86     *    -2.611           1.5860
56      0.7593  -0.8772  -0.9060          15.81     *    -2.634           1.4720
57      0.8298  -0.9752  -0.8702          15.92     *    -2.503           1.5482
58      0.8242  -0.9606  -1.0843          15.79     *    -2.819           1.6666
59      0.7552  -0.8671  -1.0458          15.82     *    -2.820           1.5543
60      0.8264  -0.9661  -1.0131          15.78     *    -2.738           1.6256
61      0.8217  -0.9546  -1.1552          15.80     *    -2.964           1.7091
62      0.9117  -1.0486   0.0432          12.39  7.490 -2.269           1.3902
53      0.8433  -0.9545   0.0585          15.02     *    -2.896           1.2750

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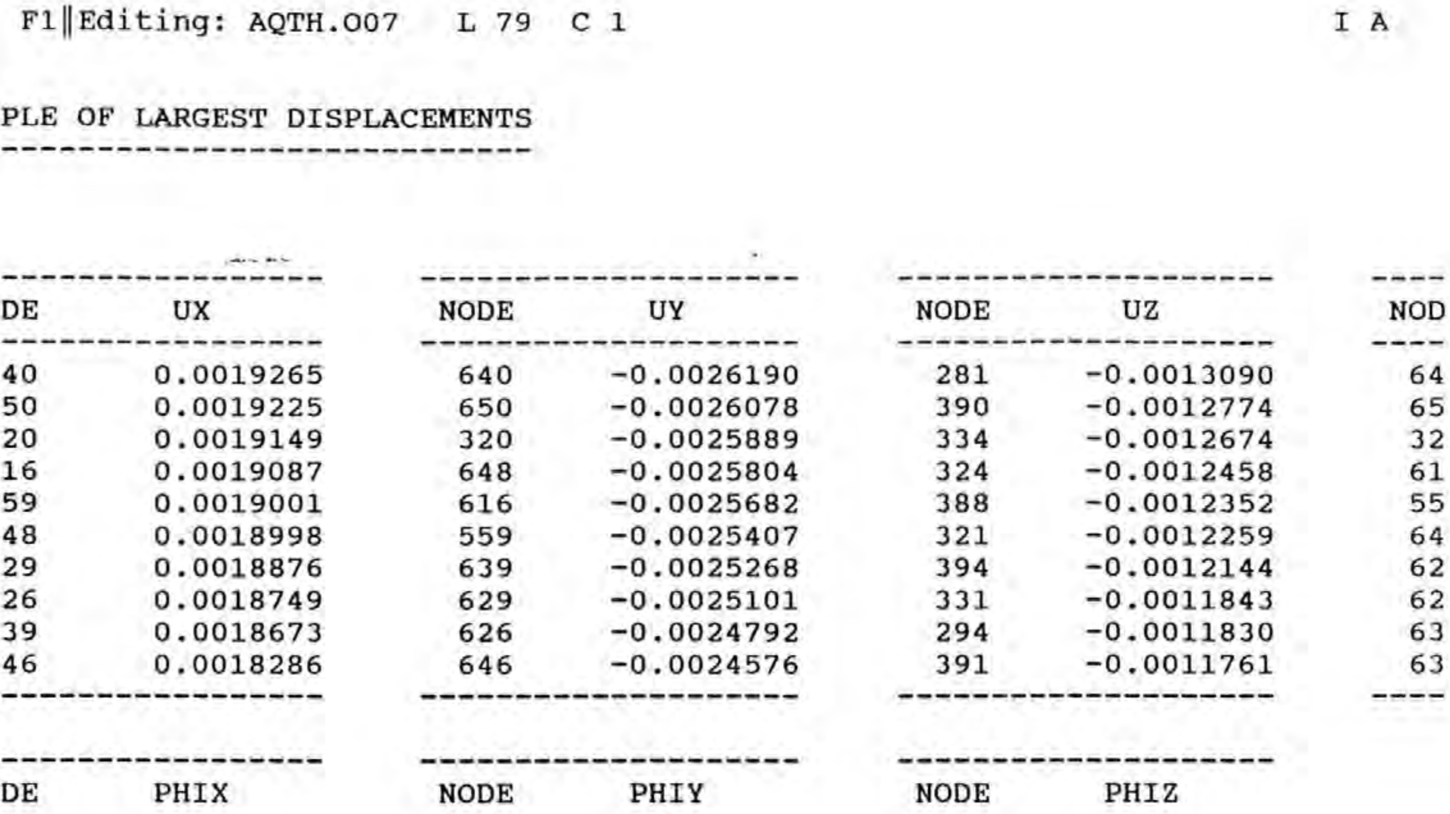
 F1‖Editing: AQTH.007   L 585  C 1                                        I A


----------------------------------------------------------------------------------
E  1            TRANSLATIONS                          ROTATIONS             RESULTAN
DE            MULTIPLIED BY 1E 3               MULTIPLIED BY 1E 3           MULTIPL
BER        UX         UY         UZ            PHIX   PHIY   PHIZ              U
----------------------------------------------------------------------------------


64      0.8937  -1.0047   0.1199          11.72  7.858 -2.415           1.3500
65      0.9442  -1.1262  -0.1121          13.42  7.853 -1.986           1.4739
66      0.8729  -1.0247  -0.0927          16.18     *    -2.923           1.3493
67      0.9284  -1.0890  -0.0343          12.96  7.710 -2.094           1.4314
68      0.9739  -1.1938  -0.2691          14.24  8.492 -1.621           1.5639
69      0.9001  -1.0855  -0.2455          17.27     *    -2.961           1.4313
70      0.9594  -1.1616  -0.1905          13.95  8.137 -1.892           1.5186
71      0.9953  -1.2363  -0.4245          14.20  9.992 -0.207           1.6430
72      0.9192  -1.1251  -0.3975          17.87     *    -2.124           1.5062
73      0.9866  -1.2210  -0.3473          14.50  8.892 -1.233           1.6077
74      0.9153  -1.1125  -0.5443          17.40     *    -1.567           1.5400
75      0.9942  -1.2308  -0.4999          13.81  10.56   0.523           1.6593
76      0.9797  -1.1921  -0.7201          12.83  10.01   0.706           1.7028
77      0.9076  -1.0917  -0.6884          16.67     *    -1.837           1.5778
78      0.9846  -1.2046  -0.6471          13.06  10.38   0.784           1.6850

 F1‖Editing: AQTH.007   L 608  C 1                                        I A
78      0.9846  -1.2046  -0.6471          13.06  10.38   0.784           1.6850
79      0.9721  -1.1732  -0.8664          12.52  9.323   0.497           1.7527
```

80	0.9017	-1.0763	-0.8326	16.18	*	-2.188	1.6324
81	0.9756	-1.1819	-0.7931	12.62	9.627	0.560	1.7256
82	0.9669	-1.1601	-1.0136	12.26	9.050	0.357	1.8188
83	0.8975	-1.0653	-0.9776	15.88	*	-2.566	1.7018
84	0.9693	-1.1661	-0.9399	12.37	9.120	0.354	1.7840
85	0.9622	-1.1482	-1.1613	12.20	8.770	0.295	1.8955
86	0.8932	-1.0544	-1.1228	15.76	*	-2.813	1.7805
87	0.9646	-1.1541	-1.0875	12.18	8.832	0.302	1.8560
88	0.9599	-1.1423	-1.2352	12.20	8.647	0.255	1.9370
89	1.0996	-1.3395	-1.1063	15.67	*	1.037	2.0560
90	1.0264	-1.2325	-1.2774	15.68	*	1.069	2.0505
91	1.0971	-1.3332	-1.1761	15.51	*	0.963	2.0891
92	1.0309	-1.2438	-1.1338	15.68	*	1.097	1.9737
93	1.2372	-1.5312	-1.0513	15.60	*	1.071	2.2317
94	1.1632	-1.4222	-1.2144	15.40	*	1.157	2.2024
95	1.2340	-1.5231	-1.1172	15.44	*	0.895	2.2563
96	1.1683	-1.4351	-1.0788	15.62	*	1.259	2.1421
97	1.1055	-1.3545	-0.9666	16.01	*	1.209	1.9978
98	1.1024	-1.3465	-1.0365	15.74	*	1.126	2.0255
99	1.0361	-1.2569	-0.9902	15.93	*	1.155	1.9062
00	1.2454	-1.5521	-0.9194	16.12	*	1.310	2.1922
01	1.2411	-1.5411	-0.9854	15.85	*	1.149	2.2105



```
 F1║Editing: AQTH.007   L 79  C 1                                     I A

PLE OF LARGEST DISPLACEMENTS
----------------------------


----------------     --------------------     --------------------     ----
DE        UX         NODE        UY           NODE        UZ           NOD
----------------     --------------------     --------------------     ----
40     0.0019265      640     -0.0026190       281     -0.0013090       64
50     0.0019225      650     -0.0026078       390     -0.0012774       65
20     0.0019149      320     -0.0025889       334     -0.0012674       32
16     0.0019087      648     -0.0025804       324     -0.0012458       61
59     0.0019001      616     -0.0025682       388     -0.0012352       55
48     0.0018998      559     -0.0025407       321     -0.0012259       64
29     0.0018876      639     -0.0025268       394     -0.0012144       62
26     0.0018749      629     -0.0025101       331     -0.0011843       62
39     0.0018673      626     -0.0024792       294     -0.0011830       63
46     0.0018286      646     -0.0024576       391     -0.0011761       63
----------------     --------------------     --------------------     ----

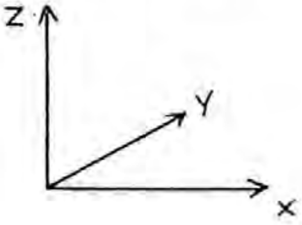
----------------     --------------------     --------------------
DE       PHIX        NODE       PHIY          NODE       PHIZ
```

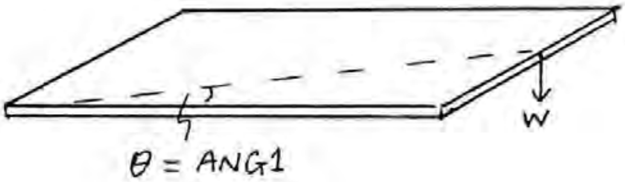
Additional Notes on Axis Rotation in PAFEC

The principal material directions (X_p, Y_p and Z_p) of an orthotropic laminate are defined in terms of 3 rotations. In the LAMINATES module, these are designated ANG1, ANG2 and ANG3, and denote rotations about the z axis, the new y axis and the new x axis *in that order*. To quote the Data Preparation Manual: "...the material principal axes should be oriented so that the Z_p direction is through the thickness. If this is not so, then PAFEC rotates further...If the rotation thus required is greater than 10°, then a warning is given.". Note that warnings don't necessarily mean that your calculation is wrong, but you should check all orientations.

The main practical difficulty is that the rotations have to be performed in the above order. As an example, consider a rectangular cantilever with a point load on the end. The laminate is 2 mm thick with lay up $[0,45,-45,90]_S$.

If the cantilever is flat in the x-y plane (z = 0), then ply orientations are defined only by ANG1:

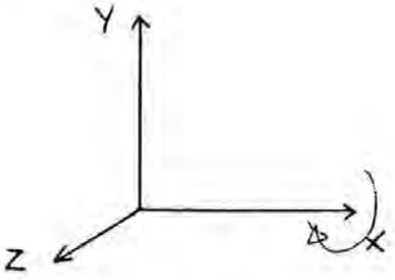


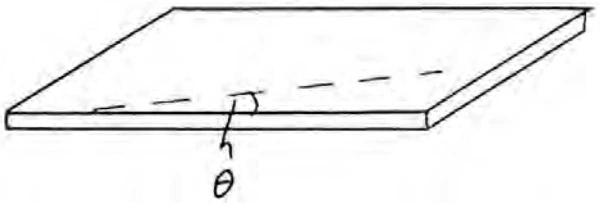


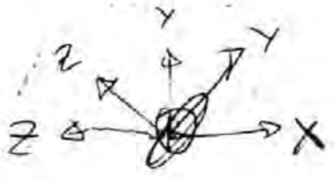
LAMINATES

NUMBER	ORTHO	LOWER	UPPER	AXIS	ANG1	ANG2	ANG3
1	1	-1E-3	-.75E-3	1	0	0	0
1	1	-.75E-3	-.5E-3	1	45	0	0
1	1	-.5E-3	-.25E-3	1	-45	0	0
1	1	-.25E-3	0	1	90	0	0
1	1	0	.25E-3	1	90	0	0
1	1	.25E-3	.5E-3	1	-45	0	0
1	1	.5E-3	.75E-3	1	45	0	0
1	1	.75E-3	1E-3	1	0	0	0

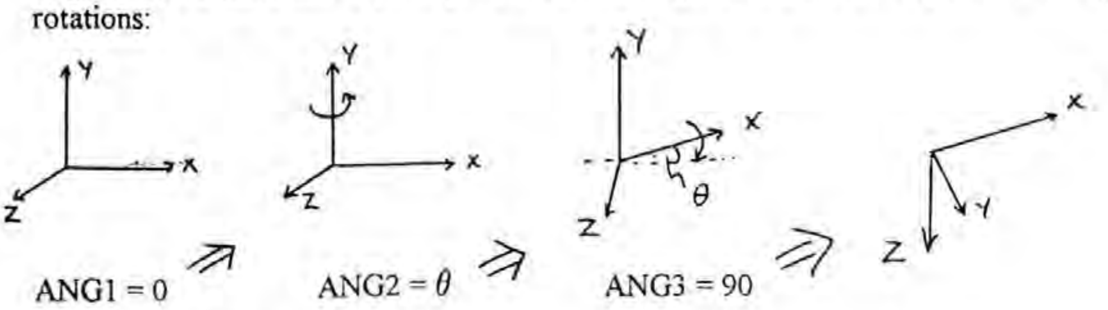
If the cantilever is orientated in some other plane, additional rotation(s) are required to bring the laminate through-thickness direction in line with the global z axis. Suppose the cantilever is flat in the x-z plane:







In general, we can define a principal direction at angle θ to the x axis by the following rotations:



The data module for the cantilever now looks like:

LAMINATES

NUMBER	ORTHO	LOWER	UPPER	AXIS	ANG1	ANG2	ANG3
1	1	-1E-3	-.75E-3	1	0	0	90
1	1	-.75E-3	-.5E-3	1	0	45	90
1	1	-.5E-3	-.25E-3	1	0	-45	90
1	1	-.25E-3	0	1	0	90	90
1	1	0	.25E-3	1	0	90	90
1	1	.25E-3	.5E-3	1	0	-45	90
1	1	.5E-3	.75E-3	1	0	45	90
1	1	.75E-3	1E-3	1	0	0	90

Note that for the 3rd rotation we could logically choose ANG3 = -90; this would still bring Zp into line with the global z axis. If you do, PAFEC generates warnings in phase 6 but calculates the correct displacements - I have no explanation for this!

In some cases, it may be simpler to define another axis set, and specify ply orientations relative to this. In the above example, we could create axis number 4 with the following module:

AXES

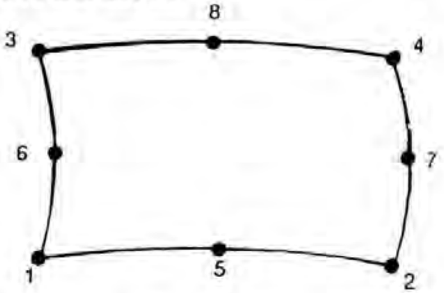
AXISNO	RELAXIS	ANG1	ANG2	ANG3
4	1	0	0	90

The LAMINATES module then becomes:

LAMINATES

NUMBER	ORTHO	LOWER	UPPER	AXIS	ANG1	ANG2	ANG3
1	1	-1E-3	-.75E-3	4	0	0	0
1	1	-.75E-3	-.5E-3	4	45	0	0
1	1	-.5E-3	-.25E-3	4	-45	0	0
1	1	-.25E-3	0	4	90	0	0
1	1	0	.25E-3	4	90	0	0
1	1	.25E-3	.5E-3	4	-45	0	0
1	1	.5E-3	.75E-3	4	45	0	0
1	1	.75E-3	1E-3	4	0	0	0

4.22
Thick shell element 46210 and 46215



Description

This is a generally curved thick shell element with eight nodes that define the middle neutral surface of the shell. This element is of the 'Ahmad' type, having three translational and three rotational degrees of freedom at each node. The isotropic elements may have either a constant or variable thickness across the elements. The orthotropic elements may only have a constant thickness across the elements.

The PROPERTY entry in the ELEMENTS or PAFBLOCKS modules refers to the PLATES.AND.SHELLS module for the isotropic elements and to the LAMINATES module for the orthotropic elements.

If thickness in the PLATES.AND.SHELLS is zero then the isotropic elements take modal thickness values from the NODES module. The midside node thickness values are interpolated from corner node values if they are omitted.

Applications

The thick shell element can be used in generally curved and folded shell problems for the intermediate range between full three dimensional and thin shell behaviour. Membrane and bending actions are included with the effects of shear deflections.

Theoretical Basis

The element is based upon a degenerate three dimensional analysis to incorporate transverse shear effects. The effects of direct stresses through the thickness of the shell are neglected. The element uses reduced integration technique with explicit integration through the thickness. This allows the element to perform well in some thin shell situations. Each node of the element has six degrees of freedom although some degrees of freedom become redundant when the element is flat. For the orthotropic elements the material principal compliance— in the XY plane and the shear compliances must be given non-zero values.

Limitations

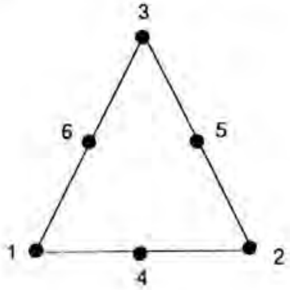
The element must not be wildly distorted. The element must not be used where a full three dimensional stress field has developed or where a shell is very thin (see chart under 45210 element). Thickness variation within the element should be kept reasonable otherwise rapid displacement variations might occur which the element may not be able to model well.

Output of stresses

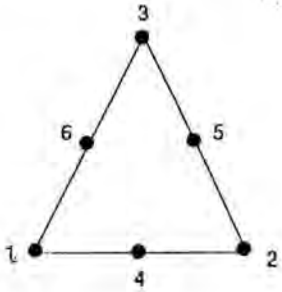
For isotropic elements the principal stresses are calculated at the nodes of the element and these are printed at the top, middle and bottom surfaces.

For orthotropic elements the stresses are given in the material principal directions.

Related elements



46110



46115

Appendix 9

B–Series propeller design charts.

MODIFIED B-SERIES PROFILES

October 1963

ORDINATES AND THICKNESSES

From maximum thickness to trailing edge

Distance of the ordinates from the maximum thickness

From maximum thickness to leading edge

r/R	100%	80%	60%	40%	20%		20%	40%	60%	80%	90%	95%	100%	r/R
					ORDINATES FOR FACE									
0,6	5,10										0,50	1,95	10,25	0,6
0,5	9,70	1,75							0,35	1,70	4,45	7,25	17,05	0,5
0,4	17,85	6,20	1,50					0,30	1,75	5,90	9,90	13,45	24,35	0,4
0,3	25,35	12,20	5,80	1,70			0,45	1,30	4,65	10,90	16,25	19,80	31,00	0,3
0,2	30,00	18,20	10,90	5,45	1,55		0,45	2,80	7,40	15,50	21,65	25,95	36,75	0,2
B 2 - 3 - 4 - 5 - 6 - 7					THICKNESSES									
0,95		44,80	72,00	88,80	97,20	100	97,20	88,40	72,00	44,80	29,50	21,60		0,95
0,9		45,15	70,00	87,00	97,00	[illegible]	97,00	87,00	70,00	45,15	30,10	22,00		0,9
0,8		40,95	67,80	85,30	96,70	[illegible]	97,00	86,30	70,00	47,00	31,65	22,45		0,8
0,7		39,40	66,90	84,90	96,65	[illegible]	97,60	89,15	73,20	49,00	32,95	23,00		0,7
0,6		40,20	67,15	85,40	96,80		98,10	90,65	75,40	51,65	34,35	23,35		0,6
0,5		41,65	68,40	86,10	96,95		97,00	89,70	77,40	55,75	37,55	25,70		0,5
0,4		41,50	68,75	86,55	97,00		97,50	90,10	77,20	55,70	38,85	27,30		0,4
0,3		38,75	65,80	85,10	96,80		97,70	90,05	75,80	53,35	37,45	26,75		0,3
0,2		35,75	61,75	81,45	94,70		97,70	89,65	74,95	51,95	35,55	24,65		0,2

Note: The percentages of the ordinates and thicknesses have reference to the maximum thickness of the corresponding sections

BLADE CONTOUR

The following values are percentages of the blade widths at 0.6 R.

B 4 - C 4 - B 5 - B 6 - B 7					B 2 - B 3					
r/R	T.E.	L.E.	Total	Maximum thickness to generator line	r/R	T.E.	L.E.	Total	Maximum thickness to generator line	r/R
1,0	20,14	-	-	- 20,14	1,0	14,87	-	-	- 14,87	1,0
0,95	42,71	11,75	54,46	- 15,48	0,95	39,86	18,10	57,96	- 10,88	0,95
0,9	47,00	25,35	72,35	- 10,83	0,9	45,01	30,76	75,77	- 7,12	0,9
0,8	48,35	41,65	90,00	- 1,37	0,8	47,77	45,08	92,85	+ 0,70	0,8
0,7	46,68	51,40	98,08	+ 8,05	0,7	46,95	52,24	99,19	+ 8,40	0,7
0,6	43,92	56,08	100,00	+ 17,18	0,6	44,08	55,92	100,00	+ 16,22	0,6
0,5	40,78	57,60	98,38	+ 22,68	0,5	40,53	56,52	97,05	+ 22,07	0,5
0,4	37,30	56,32	93,62	+ 23,65	0,4	36,62	54,91	91,53	+ 22,97	0,4
0,3	33,32	52,64	85,96	+ 22,55	0,3	32,67	51,24	83,91	+ 21,87	0,3
0,2	29,18	46,90	76,08	+ 20,27	0,2	28,68	46,05	74,73	+ 19,89	0,2

Blade width at 0.6 R

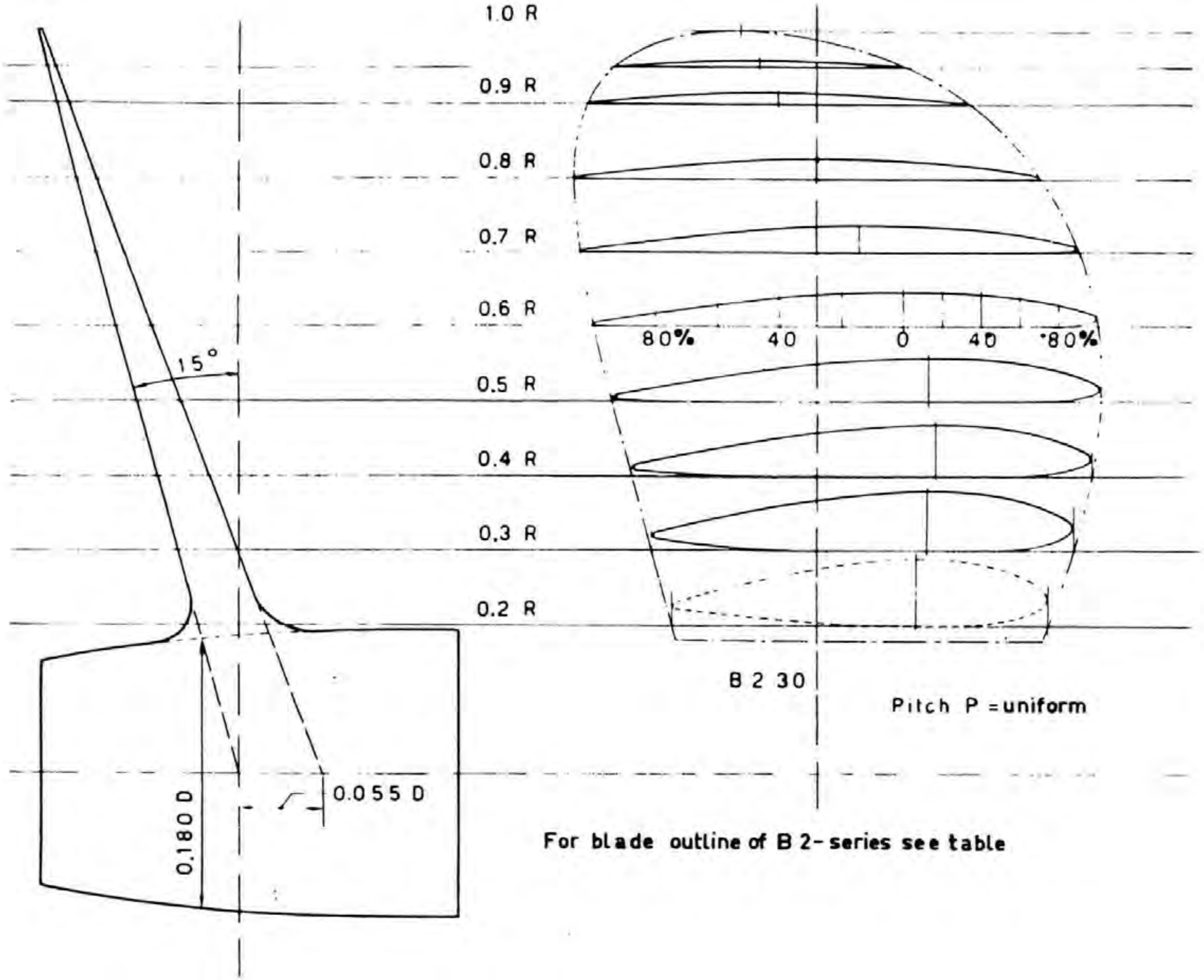
2 Blade - 1,104 x A_E/A_o x D
3 Blade - 0,7396 x A_E/A_o x D
4 Blade - 0,5467 x A_E/A_o x D
5 Blade - 0,4373 x A_E/A_o x D
6 Blade - 0,3628 x A_E/A_o x D
7 Blade - 0,3174 x A_E/A_o x D

Blade width at 0.2 R

2 Blade - 0,8250 x A_E/A_o x D
3 Blade - 0,5527 x A_E/A_o x D
4 Blade - 0.4159 x A_E/A_o x D
5 Blade - 0,3327 x A_E/A_o x D
6 Blade - 0,2760 x A_E/A_o x D
7 Blade - 0,2415 x A_E/A_o x D

FIG.5

General arrangement plan of 2 bladed B series propellers



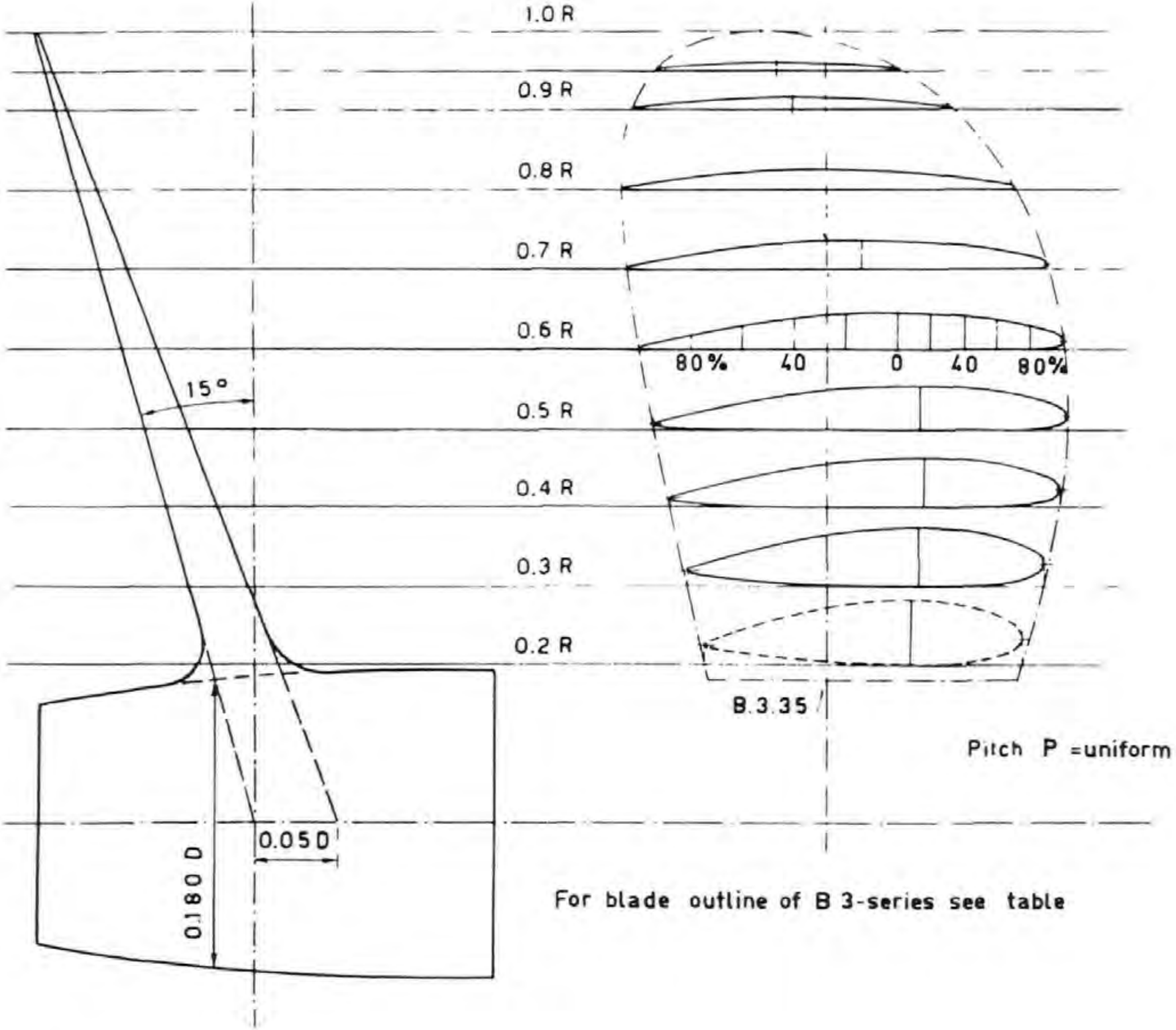
Pitch P = uniform

For blade outline of B 2-series see table

FIG.6

H2. 358 BRITISH SHIP RES ASS.

General arrangement plan of 3 bladed B series propellers



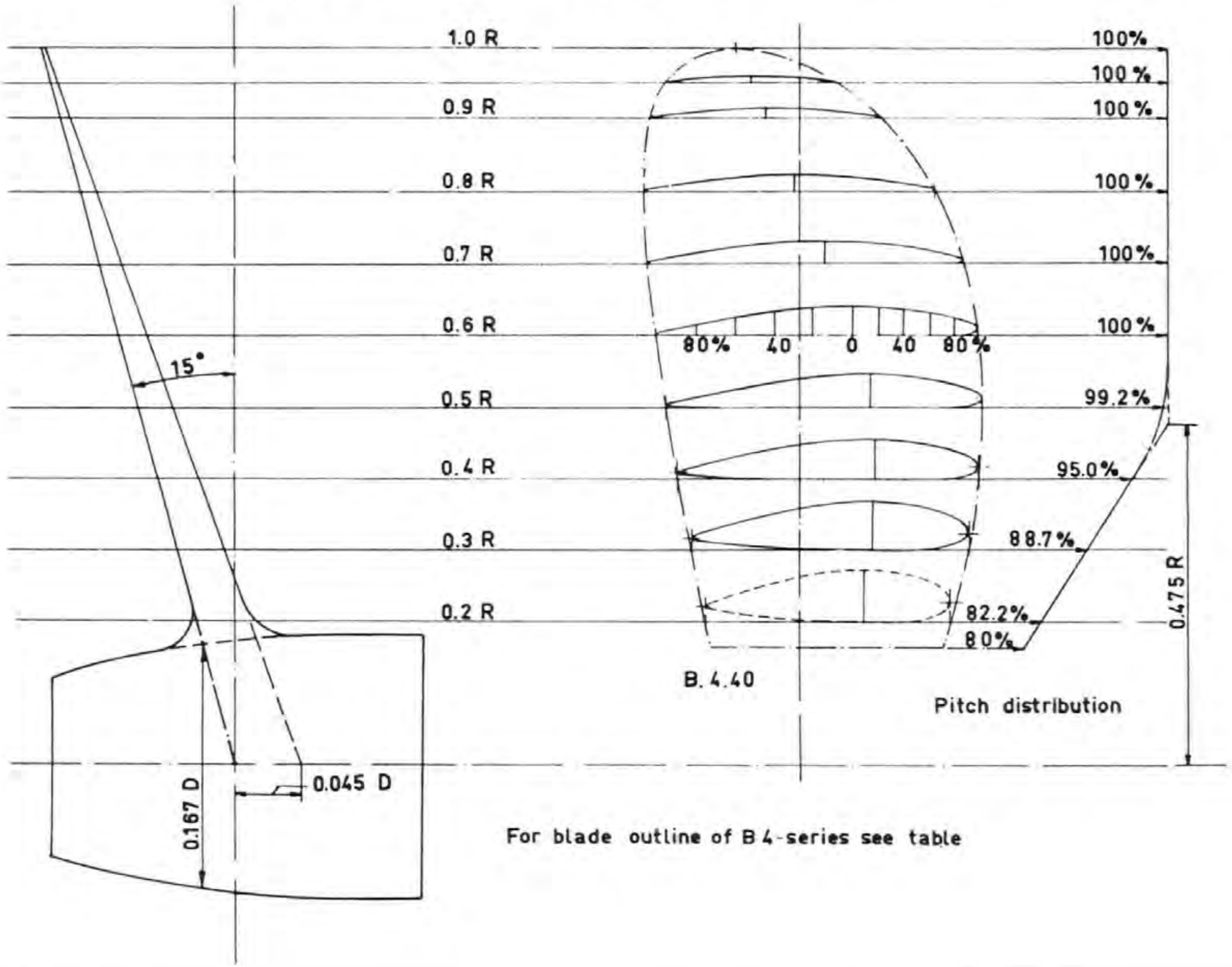
Pitch P =uniform

For blade outline of B 3-series see table

FIG.7

H2 359 BRITISH SHIP RES ASS.

General arrangement plan of 4 bladed B series propellers

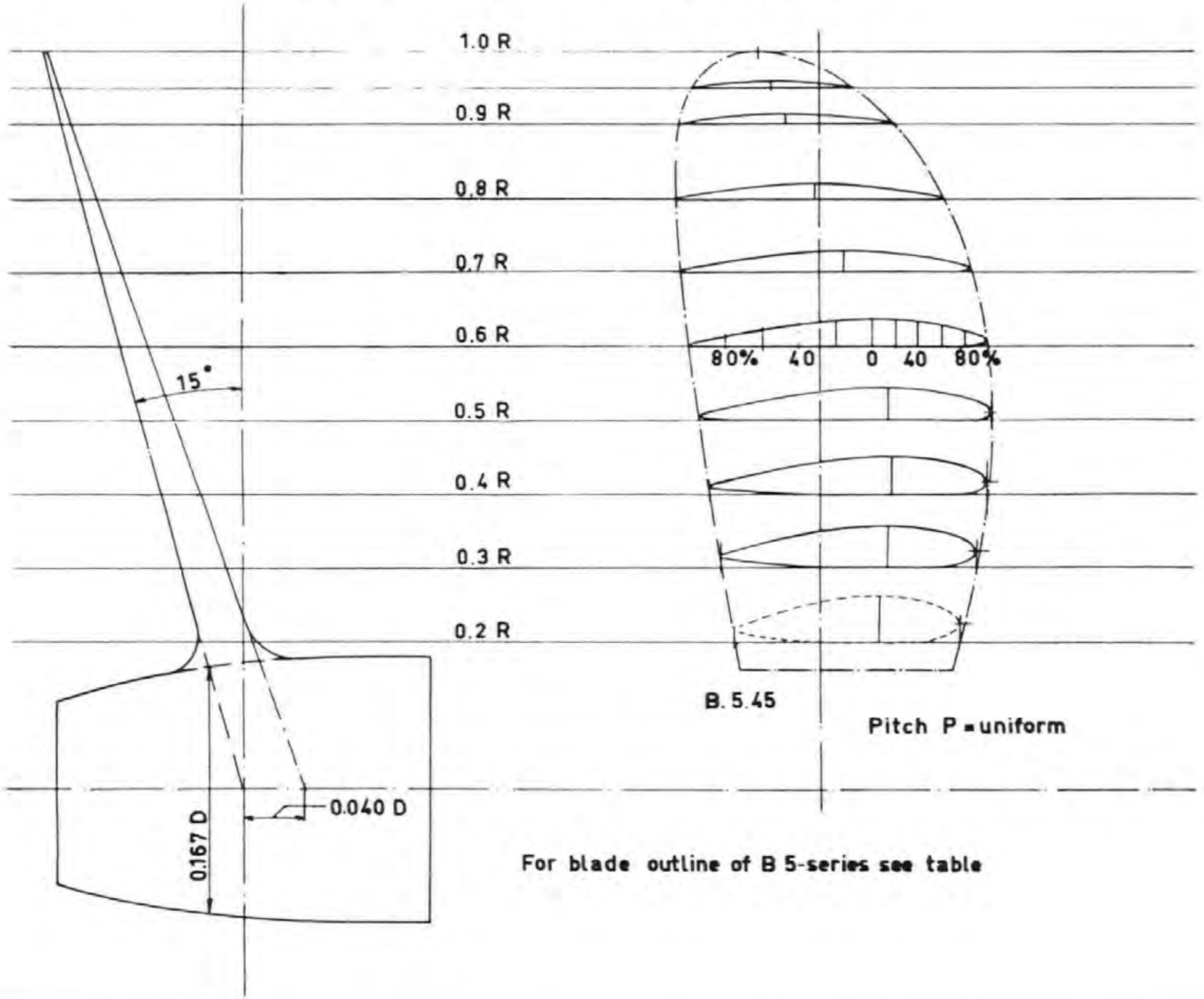


For blade outline of B 4-series see table

FIG. 8

H2 360 BRITISH SHIP RES. ASS.

General arrangement plan of 5 bladed B series propellers

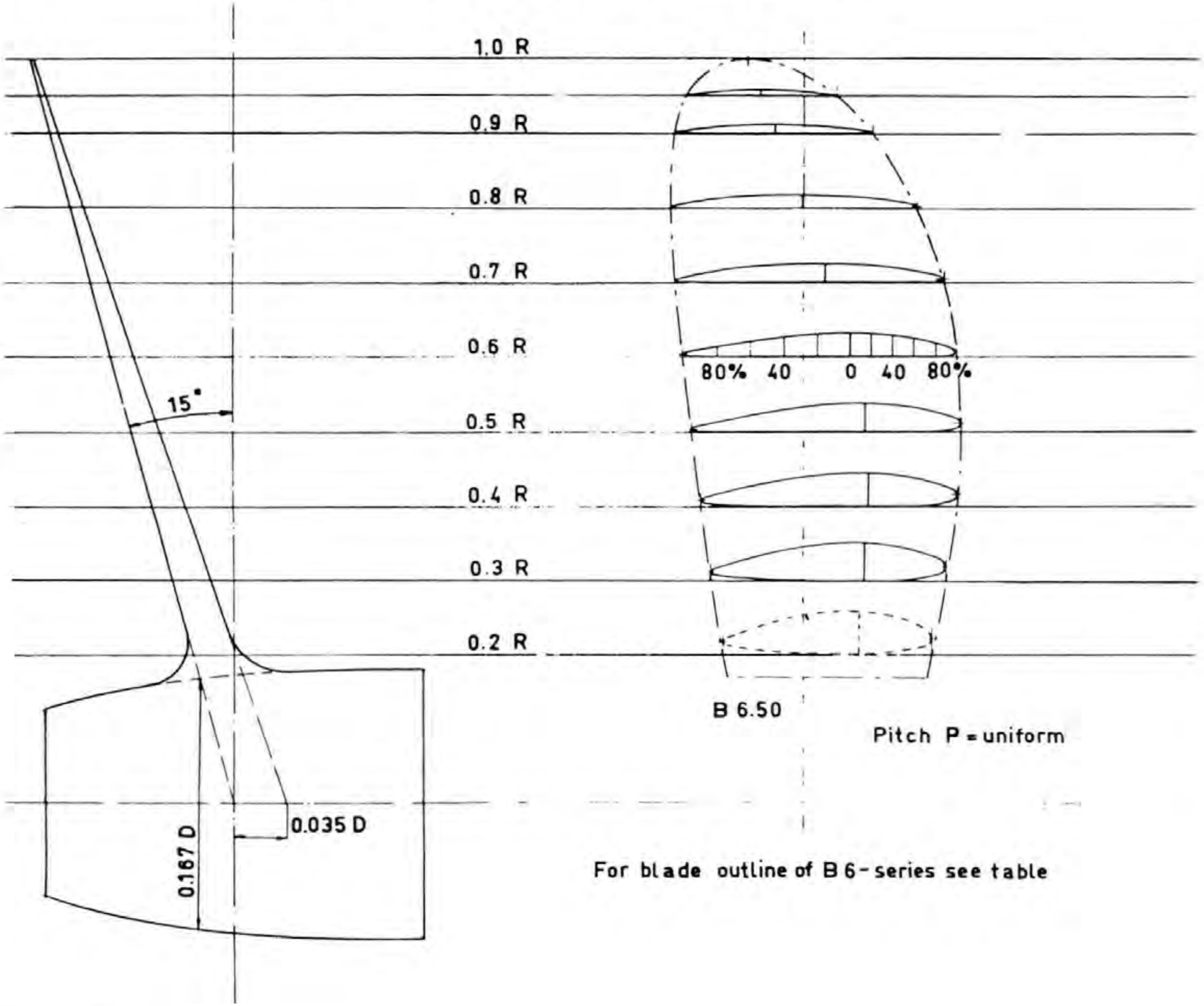


For blade outline of B 5-series see table

FIG. 9

HZ.361 BRITISH SHIP RES ASS.

General arrangement plan of 6 bladed B series propellers



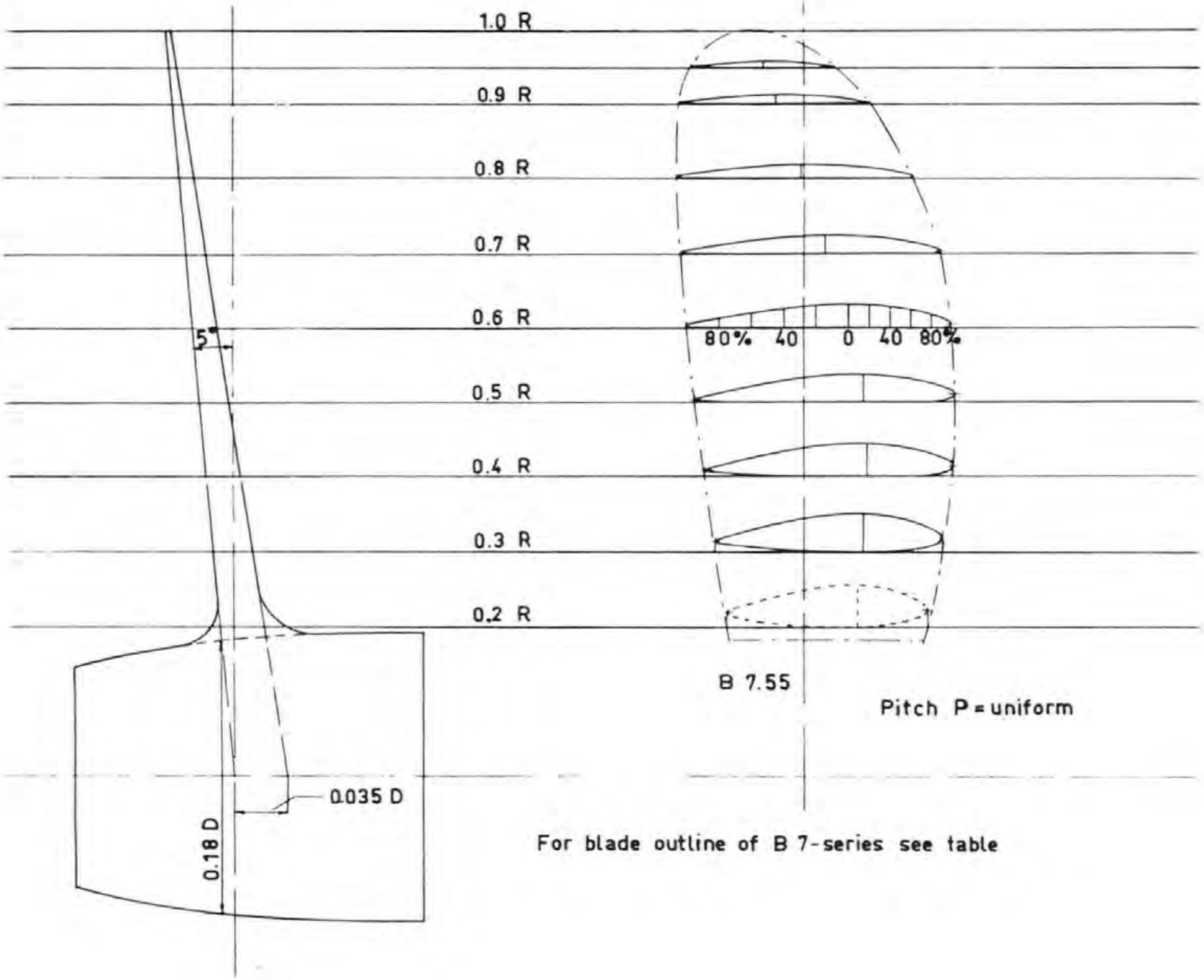
Pitch P = uniform

For blade outline of B 6-series see table

FIG. 10

HZ 362 BRITISH SHIP RES. ASS.

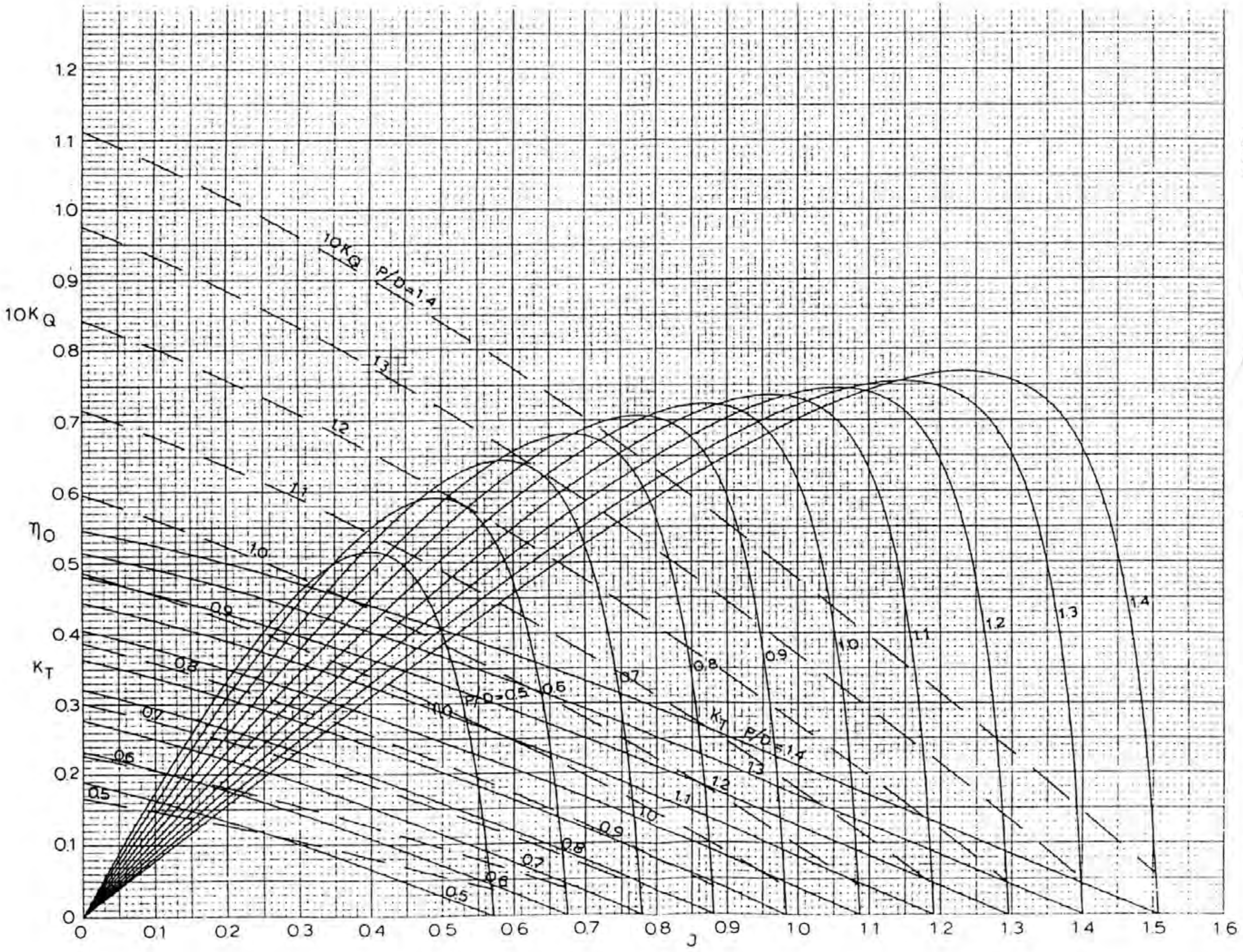
General arrangement plan of 7 bladed B series propellers



For blade outline of B 7-series see table

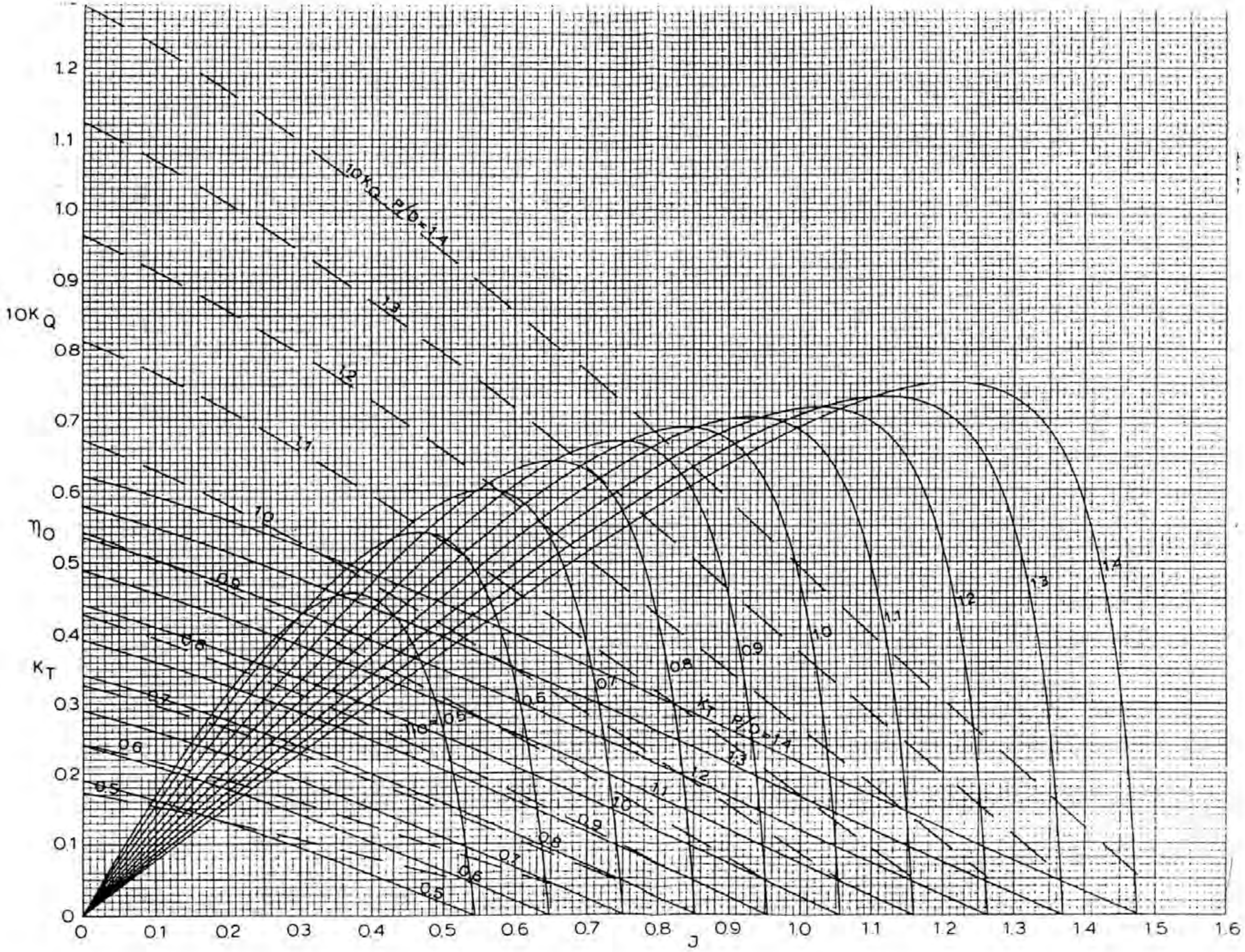
FIG. II

HR 363 BRITISH SHIP RES ASS


10K_Q
η_O
K_T
J
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
10K_Q P/D=1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
K_T P/D=1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
1.0
P/D=0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4

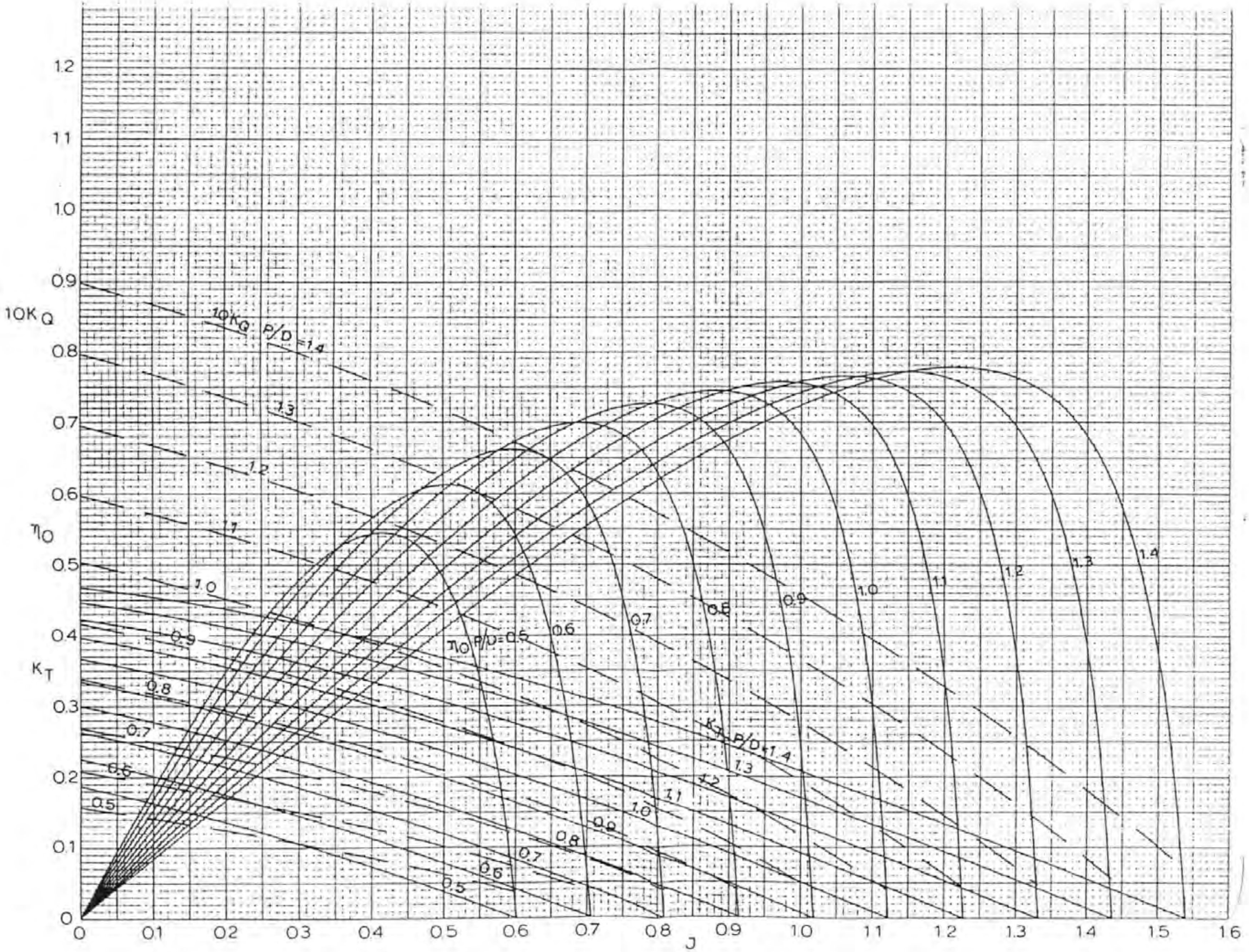
B 3-50

1973


1.2
1.1
1.0
0.9
10K Q
0.8
0.7
0.6
η O
0.5
0.4
K T
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
J
10K Q P/D=1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
K T P/D=1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
η O=0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4

B 3-65

1973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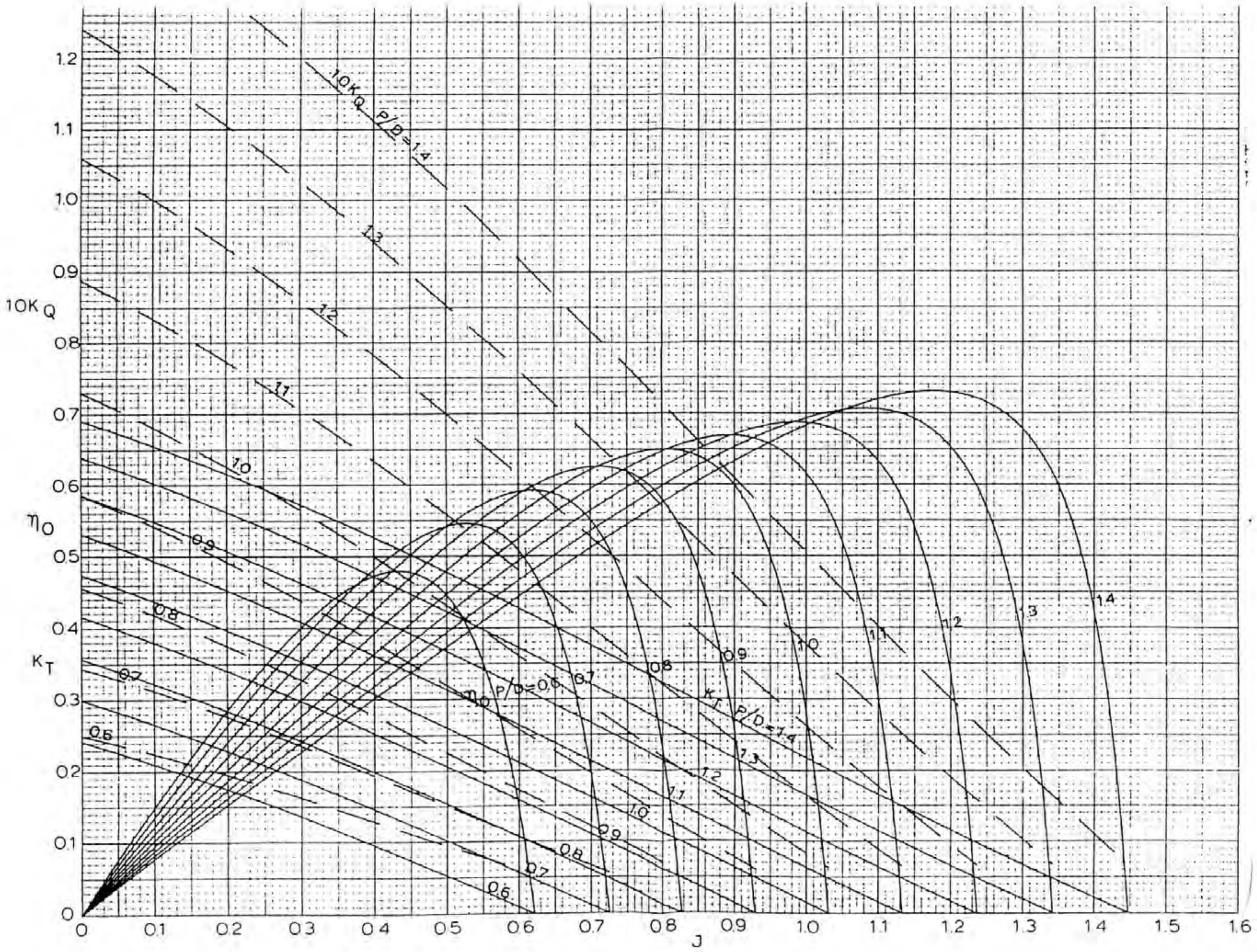
1.1
1.0
0.9
10K$_Q$
0.8
0.7
0.6
η_O
0.5
0.4
K$_T$
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
J
10K$_Q$ P/D = 1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
η_O P/D = 0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
K$_T$ P/D = 1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5

B 3-35

1973


10K$_Q$
η$_O$
K$_T$
J
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0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
10K$_Q$ P/D=1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
η$_O$ P/D=0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
K$_T$ P/D=1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6

B 3-80

1973

Appendix 10

Training courses attended.

Training Courses:

March 1993,
WEGEMT Composite materials in maritime structures,
5 day course.
Southampton University.

March 1994,
1 day seminar,
Applications of composite materials in the marine industry,
The Institute of Marine Engineers.

June 1996,
Atomic Energy Authority, Oxford,
1 day seminar; Design with composite materials.

Appendix 11

List of publications / papers / presentations.

Papers, Publications & Presentations.

SM Grove, T Searle and D Short
Education and training in composites in the marine industry
The Impact of New Technology on the Marine Industry,
Southampton Institute, Warsash, 13–15 September 1993, paper 38, pp1–7.

T Searle, J Chudley and D Short
The composite propeller
The Impact of New Technology on the Marine Industry,
Southampton Institute, Warsash, 13–15 September 1993, paper 59, pp1–10.

T Searle, J Chudley and D Short
Composites offer advantages for propellers
Reinforced Plastics, December 1993, 37(12), 24–26.

T Searle and D Short
Are composite propellers the way forward for small boats?
Materials World, February 1994, 2(2), 69–70.

T Searle
Composite propellers
CPD Seminar: Applications of Composite Materials in the Marine Industry
Institute of Marine Engineers & University of Plymouth, London, 16th March 1994.

T Searle, J Chudley, D Short and C Hodge
The use of FRP composites for ships propellers
International Conference: Structural Materials in Marine Environments,
The Royal Society, London, 11–12 May 1994.

T Searle, J Chudley, D Short, and C Hodge
The composite advantage
Propellers and Shafting, Society of Naval architects and Marine Engineers,
Virginia Beach VA, 20–21 September 1994.

J Chudley, T Searle, D Short and A Tate
Resin transfer moulding of marine products
19th International Composites Congress, British Plastics Federation,
NEC Birmingham, 22–23 November 1994.

T Searle, J Chudley, S Grove and D Short
Manufacturing of marine propellers in composite materials
High Technology Composites in Modern Applications,
Corfu, Greece, September 18–22 1995.

Appendix 12

Copies of publications.

PROCEEDINGS OF THE
INTERNATIONAL MARITIME CONFERENCE

THE IMPACT OF NEW TECHNOLOGY ON THE MARINE INDUSTRIES

September 13th, 14th and 15th 1993
at
The Warsash Campus, Southampton Institute, Warsash, UK.

Organised and sponsored by:
Southampton Institute Maritime Division

Southampton Institute
of Higher Education

EDUCATION AND TRAINING IN COMPOSITES FOR THE MARINE INDUSTRY

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ABSTRACT

The marine industry has used natural composites since man first decided to leave the land and venture on to the sea. Metals have also been used in specialised areas such as anchors and weapons, but their use increased dramatically in the early 19th century as costs fell and availability rose.

If industry is to return to using composite materials (man-made rather than natural) then a cultural change in engineering thinking is required. Without this, the use of these materials will never progress beyond the glass fibre-reinforced plastic (GRP) products of the small boatyard, and they will not take their place as viable engineering materials with their advanced capability at the disposal of the marine engineer.

The successful and economic use of composites requires a greater level of interaction and integration of design, materials selection, manufacture and quality assurance than is currently practised in general engineering. These aspirations have been expressed many times over the last 10 years or so, yet they remain unfulfilled in many industrial sectors.

For the marine industry to exploit more fully the use of composite materials, certain facilities for education and experience in the use, design and processing of composites are required. The present provision of courses and skills training in the UK is discussed. The paper also presents the results of a study into the training and technical support needs of the composite boat building industry in south-west England.

INTRODUCTION

Composites have always been important materials for marine applications, from natural composites such as wood, to modern fibre-reinforced plastics such as GRP. Our definition of 'composite' encompasses any material in which two or more constituents have been combined (macroscopically) with the intention of creating unique properties. Usually the constituents are a reinforcement (e.g. short, long or continuous fibres or particles) and a matrix (a thermoplastic or thermosetting resin, metal or ceramic).

Composites have to be understood in the general context of engineering materials - a given application does not necessarily demand composites as the most appropriate solution. Materials selection should be free of prejudice, with the engineer specifying the most effective and economic solution possible. On the other hand, it must be appreciated that composites are unique materials, and present both the designer and manufacturer with a unique set of problems and opportunities. At the core of these is the fact that one does not purchase 'off the shelf' properties - the ultimate performance of the composite component depends on the ability of the manufacturer to combine fibres and resin in a controlled, repeatable process in which both the shape and the material properties are generated simultaneously.

Commonly used composites (GRP or CFRP) give the engineer not only a lightweight moulding material, but can also open up many new design possibilities if the anisotropic potential of long or continuous fibres is exploited. Like all laminated materials, composites are liable to have relatively poor properties if subjected to through-thickness tension or peel, and this is a further factor for the designer to consider.

There is thus a continual need for education and training of personnel at all levels, and this should be seen as a permanent feature of any professional career. This will be due to:

- the rapid growth of applications, as composites become more widely used
- the development and introduction of novel materials
- changing economic, political and environmental constraints on the use of composites

We interpret 'education and training' in the widest sense - from school to higher and further education; postgraduate training and research; professional retraining; updating and awareness; fire fighting and problem solving.

Government agencies together with many of the professional institutions are currently giving education and training a very high profile. On the one hand, CPD (continuing professional development) is now seen as an important component of the engineer's career, while quality schemes (such as BS 5750) may demand minimum levels of workforce training and competence.

TRAINING FOR DESIGN

Composites in the form of GRP are already established in the marine industry for small boat hulls; the danger is that they may become confined to these applications due to familiarity and a perceived limitation of potential. There are, however, very strong cases for making other components in composite materials - these could include pipes and fittings, tanks and containers, superstructure and accommodation modules, bulkhead doors, pump casings and rotors, propellers and drive shafts.

If composites are to have a wider penetration into marine components, it will probably come about through existing staff in the design office. But this is not as simple a process as adding the properties of another metal to the data base - it requires a careful programme of learning. The designer's experience of composites may only have been as a 'fun' material in sports equipment, or in esoteric aerospace applications, and he may not therefore have considered it in his work thinking. The designer may never have worked with the material, except perhaps in the form of Isopon used for cosmetic repairs. This contrasts sharply with metals, which he has probably bent, cut, turned and welded during his training. The designer may be totally unfamiliar with the idea of manufacturing a material from fibres and a liquid; metals are always bought 'off the shelf' with their properties fixed, and the potential of anisotropy as a design tool has never been available. There is also, perhaps, the slight suspicion that light materials and structures cannot also be strong or stiff.

Thus, if the design office staff are going to consider composites along with the other traditional materials, they need to feel at home with them. Ideally, the designer must neither ignore composites, nor have the impression that they are "the best thing since sliced bread". Progress along the path of awareness needs to start at the experience level of 'make and try', and it is to be hoped that this would be part of all new employees' training. Can we wait for them eventually to reach the Designer's chair? Existing designers who wish to exploit these materials effectively need to gain this experience rapidly.

The next stage is crucial for the designer - how to analyse composite structures, making the best use of their anisotropic potential. Here a crash course is needed on the development of basic properties in composite design and laminate analysis. We have found that a carefully constructed course of about 4 or 5 days, and containing the basic elements of theory, practical design, manufacture and testing, is sufficient to allow the designer to become sufficiently confident to have a go alone.

TRAINING FOR MANUFACTURE

Training for manufacture in composites also needs consideration. If a composites manufacturing facility exists in a small company, it will probably be in the form of a hand laminating shop. In this case, component manufacture will be regarded as a semi-skilled task that is time consuming, unpleasant, wasteful of material and of variable quality. Thinking in this department needs a radical change. Firstly, all personnel involved must be made aware that they are not only producing the component, but also making the material. Hand lay up is a skilled process that requires continuous monitoring of materials and self-monitoring of the operative, if efficient material usage, designed properties and consistent quality are to be achieved.

If tighter control of properties and quality or more versatility in part shape and size is required, then other manufacturing processes must be considered. More stringent health and safety requirements may also be a factor influencing change. The installation and successful running of a new process is not trivial - understanding and experience is necessary to produce good components. Too often equipment is abandoned unused in a corner; not because it was no good, but because it was obtained with the idea that merely pressing a button or two would produce quality products first and every time.

Components of consistent quality can only be produced by a carefully thought out, well-run manufacturing system. Because the interaction between the design and manufacture of composites has to be much closer (due to the many interacting variables such fibre type, form and orientation, resin additives and cure characteristics), the structure should ideally be product driven. However, since the structure is more likely to be function oriented, just as the designer needs a clear working knowledge of manufacture, so the production staff need a clear working knowledge of design. The initial course suggested for the designer would also be appropriate for personnel involved in manufacture; it would also be particularly valuable for both sides to share a common introductory experience of composites. Both sides also need to be involved in the understanding of 'fitness for purpose'.

These are the starting points for designer and manufacturer. Specific requirements will need to be met for special designs and different processes.

EDUCATION AND TRAINING PROVISION

As well as producing graduate and postgraduate engineers, the University of Plymouth has been encouraging Technology Transfer in the form of short courses and workshops for 6 years in the general field of polymer composites manufacture. To date, nearly 900 delegates have attended a range of courses at Plymouth, although numbers have reduced markedly during the recent recession. It is hoped that benefits from this activity work both ways - industry is given a non-threatening learning environment, while academics enhance their awareness of the real world outside the campus.

All educational providers must continuously assess their provision of services in the light of their customers' requirements and their competitors' wares. In a survey carried out 3 years ago.[1], we identified 19 institutions that offered short courses for the post-experience industrial client. They ranged from the City and Guilds Certificates in GRP to postgraduate level courses in advanced automotive and aerospace materials such as metal and ceramic matrix composites. We felt at the time that there may have been duplication in some areas - in 1990, at least 6 introductory courses were being offered in advanced composites. It was also evident that the emphasis in provision (at least at the Universities and former Polytechnics) was on the graduate professional engineer, and, with one or two exceptions, few courses were intended for technical or operator staff.

We have repeated our survey in 1992/93 (the authors would be pleased to supply a copy on request). Perhaps surprisingly, in view of the general recession, most University providers have maintained their presence in the market place. The most significant change has been the increase of interest in academic qualifications for modular, part-time study. Several institutions' short courses form free-standing components of a diploma or higher degree, with each course carrying academic credit. This move has been facilitated by CATS (the Credit Accumulation and Transfer Scheme), whereby a part-time student can accumulate academic credits over a number of years, if desired from more than one institution. Having gained sufficient credits at the appropriate level, they may be 'cashed in' for the relevant qualification. Many first degrees are now modular in structure, thus opening a wide range of qualifications to the part-time student. At a lower level, NVQs (National Vocational Qualifications) are becoming more widely accepted.

Little has so far been achieved in terms of closer cooperation between the higher education providers, although we are still pursuing plans to establish a network to facilitate the distribution of information and to explore the possible benefits from joint marketing of courses. In our experience, the industrially oriented short course still sits uncomfortably in the new University's portfolio. Much greater emphasis is being placed on research and increasing full-time undergraduate student numbers. These are seen (perhaps rightly) as the core educational business, and the less tangible benefits that accrue from CPD provision tend to be ignored. We still await a commitment to Technology Transfer in our University Mission Statement.

The provision of skills training for operators and technicians is still lacking. At present, there is perhaps a surplus of skilled personnel, but this situation could change rapidly if and when the UK emerges from recession. The use of NVQs has begun to make an impression, but it has to be remembered that these provide a system for measuring competence - they do not provide a syllabus for training. It is still necessary for employees and supervisors continuously to review their training needs and to plan for the future.

TECHNICAL NEEDS OF THE BOAT BUILDING INDUSTRY

Our geographical location in Plymouth places us close to a large number of small boat building companies. This is an industrial sector with which we have frequent but irregular contact through companies' requests for laminate testing or 'instant solutions' to immediate technical problems. Pursuing our general interest in Technology Transfer, we carried out a limited survey of boat builders in south west England, with financial support from the DTI, Bristol. The survey sought information in 3 areas:

1. What materials and processes are currently in use?
2. How do companies obtain information on new materials and processes?
3. What are the training and updating needs and how might they be met?

A total of 32 questionnaires were returned out of 60 sent. In some cases, contact was made on the telephone.

The South West has one major boat builder (Marine Projects, Plymouth) employing over 800 staff. Most companies, however, are small - nearly half of the organisations surveyed have less than 10 employees. One company in five reported that their business was primarily repair.

The type of work carried out appeared to be spread evenly across a range of markets (sport, work, fishing, yacht and dinghy), with most boats falling into the 10'-30' monohull category. As expected, the most common construction is hand laid up GRP in female moulds, but there is some evidence of more advanced materials. For example, 9% of builders used honeycomb, 21% used carbon fibre and 15% post-cure their laminates.

Builders were asked how they gained knowledge about materials and techniques. Almost all the companies drew on their own experience, and between 50% and 70% relied on literature, designers' specifications or information from the materials suppliers. Less than 20% made use of courses or consultancy services.

The attitude towards innovation was only moderately encouraging. Less than half of all builders said they would find information on new products of use; 30% would seek information on materials selection. In terms of technology transfer methods, 48% favoured on the job training, 33% visits from consultants and 30% training manuals and other literature.

The dilemma seems to be that boat builders would welcome highly targeted, in-house training, but are not able and/or willing to pay commercial rates for it.

Further points emerged from follow-up interviews:

- Some boat builders have diversified due to the current state of the marine market.
- There has been an increase in the number of disputes between builder and client over fitness for purpose of the product.
- There is a reluctance to seek help from third parties - better to keep quiet about problems.
- Builders are often reluctant to carry out quality checks, property measurements or to keep fully documented records.
- There is little desire, resources or external encouragement to extend process capability beyond hand lay up, although some boat builders have adopted spray techniques.
- The industry feels that leisure products (i.e. boats) do not justify the additional expense which expert advice would incur.
- Any educational or training programme needs to be specifically tailored to the requirements of individual companies.

- There is a lack of mutual confidence and trust between designers and manufacturers.

- Investment in technical advice and support is often seen as an unacceptable expense, which only results in a less competitive product. The advantages of long term investment are not recognised.

CONCLUSIONS

There is now a range of University-based short courses available to the engineer which will provide an introduction to design and manufacture with composites. Many of these courses now carry academic credit and can contribute to a part-time higher degree. Although a few are targeted towards specific applications, most fall into the category of 'education' rather than 'training', and are intended to increase awareness on new materials and processes rather than to impart specific skills.

The small boat builder can rarely afford the luxury of a 3 or 4-day introductory course. Technology transfer in general, and education and training in particular, are only perceived to be of use if they address some identifiable need or problem within the company - medium of long term staff development is not a practical option for most small employers.

However much academics and educationalists may bemoan the lack of a learning culture in UK industry, we must accept the reality of the economic constraints facing small companies. As a technological university, we wish to be of value and service to local industry, and must therefore be responsive to its needs. The Government appears to be encouraging stronger partnerships between industry and educational establishments [2]. It has also suggested a network of 'One Stop Shops' to provide access to technical services. We believe that the higher education institutes have an important role to play, by providing regional 'Technology Shops' - rapid-response centres providing focused technical information, testing services, advice on training, etc. Small companies also need encouragement to become involved in networks for sharing information and experience among themselves - there is a natural reluctance to let the competition know what your problems are, but the potential benefits are considerable. Local educational establishments, in partnership with TECs, have a contribution to make, by acting as a catalyst for communication and offering neutral territory on which this can take place.

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Notes for

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THE COMPOSITE PROPELLER

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ABSTRACT

For some forty years the use of fibre reinforced plastic (FRP) composites has been steadily increasing in the marine industry. The synergy of high modulus, high strength fibres and polymer matrices have benefits that are discussed. The design of a propeller in a composite material allows for design features not possible with isotropic metals. The effect of being able to tailor propeller blade deformation for different vessel operating conditions is one of them, this has implications for fuel efficiency and manoeuvrability. A significant weight reduction of 75% over the equivalent bronze propeller will give a reduction in vibration and faster acceleration of the propeller to the desired speed. The design of any structure requires assessment of the loads imposed upon it. For initial design of the composite propeller, determination of blade loads was by Taylor's classical cantilever beam method. Experience of the manufacture of composite propellers to date has shown resin transfer moulding (RTM) to be a suitable process. This produces a net shaped component which only requires minimal finishing. Experimental evidence and computer analysis has shown some possible composite fibre layups to be effective at supporting significantly higher loads than those predicted by the theoretical model.

INTRODUCTION

It was estimated that during 1985, 10 000 tonnes of polyester resin was used in the U.K. marine sector alone, Marchant [1]. Some sources have predicted that globally, the use of composites will over take the use of steel by the year 2010 Flower [2].

For several decades use of fibre reinforced plastic composites in the marine industry has been increasing. The degree of sophistication is variable, depending on the application and cost constraints.

The number of novel applications for composites is increasing. The marine industry presents a varied range of applications that lend themselves to a redesign in a composite material, to gain design, performance and manufacturing advantages over conventional materials.

WHAT ARE COMPOSITES ?

Composite materials embrace a wide range of materials; for all of them the same definition holds true: *The synergy of two or more materials whose combined properties exceed the sum of the individual constituent materials properties.*

The interest of this paper is with continuous fibre polymer composites, where the fibres are the main load bearing component. Generally, these comprise of high strength, high modulus, high aspect ratio fibres, of glass, carbon, or aramid (Kevlar), within a plastic matrix, such as polyester, vinylester, epoxy or phenolic resin.

Many applications of these materials are well established, for example, high performance racing yachts or minesweepers. Some more subtle applications are just emerging. The manufacture of boat propellers in composite falls into this latter category.

WHAT ARE THE BENEFITS ?

The important question to ask is, how do composites materials enable better solutions to engineering problems ? Composite offer some of the following advantages:

- High specific strengths
- High specific stiffnesses
- Low coefficients of thermal expansion

- Resistance to environmental degradation
- Possibility of reduced cavitation erosion, Ladds [3]
- Non catastrophic failure in fatigue

- High production rates
- Healthy production environment
- Ease of producing complex shapes
- Ease of repair & maintenance

- Specific material design to the application
- The ability to tailor the elastic properties
- A polymer composite material uses about half the energy to manufacture compared to steel or aluminium Richardson [4].

THE RANGE OF POLYMER COMPOSITES

There is a spectrum of performance requirements for differing structures. Composites are tailored and manufactured to meet these. Firstly, in low volume fraction, low stress applications, glass reinforced polyester or GRP is most common, usually consisting of short fibres of E glass in a chopped strand mat form, laminated in polyester resin to give in plane isotropic material properties.

Typically the glass makes up 20-30% by volume of the material. The cost effectiveness of this material in making complex shapes such as a boat hull quickly, with semi-skilled labour, has contributed to its popularity as a production boat building material. Generally production boats such as cruising yachts built in GRP have not been considered as high performance structures. Their manufacture has been correspondingly unsophisticated, usually fast hand lay ups, in a workshop environment that has variable conditions. Although polyesters can be remarkably tolerant to this hull structures tend to be over-engineered to account for the structural inefficiencies and the manufacturing variations, they are heavier than need be and more expensive due to the extra material being used.

Secondly, for high performance, more highly stressed applications such as a competitive racing yacht, or a fire proof structure, the approach to manufacture is more rigorous. The material quality is considered in greater depth in terms of the fibre orientation, the fibre volume fraction and the void content of the laminate.

While this can lengthen the manufacturing process, savings can be made by using less material to create a more effective structure. The product may also have a longer service life and will certainly be lighter. Many companies are recognising this and are introducing more sophisticated laminates into their products. Foam cores are being used to make sandwich structures and woven glass cloths are replacing chopped strand mats. For example, in production boat building if woven E-glass & kevlar is used to replace chopped strand fibres then for the same application the structure is stronger, costs the same and is 40% lighter, Marchant [1].

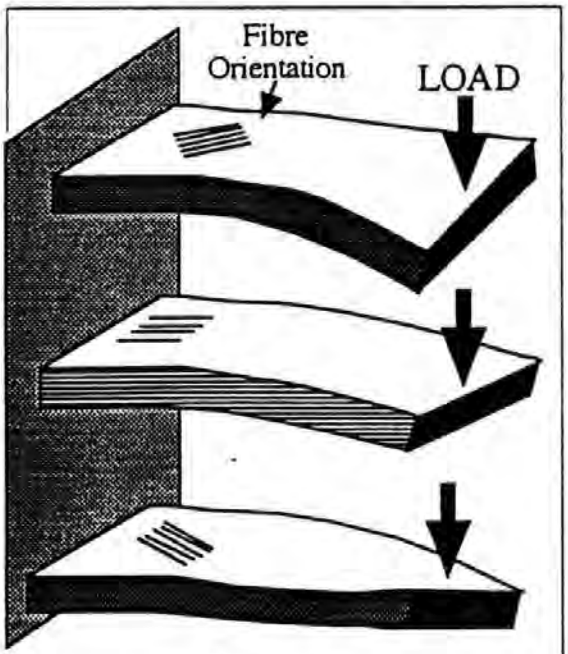


Figure 1

DESIGN POSSIBILITIES WITH COMPOSITES

Many industrial sectors have been quick to recognise the design freedom that anisotropic (directional), continuous fibre reinforced plastics have to offer. For example, the aircraft and sports industries have demonstrated improved product performance. A fighter aircraft with a sophisticated composite airframe can manoeuvre tighter and faster, and a tennis player can hit a ball harder with a lighter, stiffer carbon fibre racket.

Composites offer design variables not possible with isotropic materials. Two composite structures can be produced of the same weight, geometry and the same material, however their elastic properties can be different. Figure 1 shows how a cantilever beam twists under load depending on the fibre orientation. The stiffness of a beam like this in bending can also be tailored by changing the stacking sequence of different fibre plies that have different fibre orientations, but the tensile properties remain the same. This uniqueness of composites is useful for many structures, not least propellers. This property of hydroelastic tailoring allows the propeller blade to deform to advantage during use.

Recent research, Flower [2] has shown that as the complexity of a component increases, so composites become progressively more cost effective. Propellers have inherent complex geometry, added to which present propeller manufacture by casting in sand then finishing by hand is labour intensive.

The following list summarises the possible advantages of producing propellers in composites.

- Reduced production costs
- Component longevity
- Reduction in cavitation damage, Ladds [3]
- Damage tolerance & ease of repair
- No corrosion
- Possible reduction in fouling
- Easier maintenance
- Higher manufacturing yield
- New shaft attachment possibilities
- No need for painting, (as in the case of aluminium propellers)
- Introduction of designed deformation of propeller blades under load to achieve greater hydrodynamic efficiency
- Significantly reduced weight, perhaps as high as 75%. This should mean a reduction in vibration, a smaller prop shaft and faster acceleration to the required speed. Associated with this is reduced bearing wear.

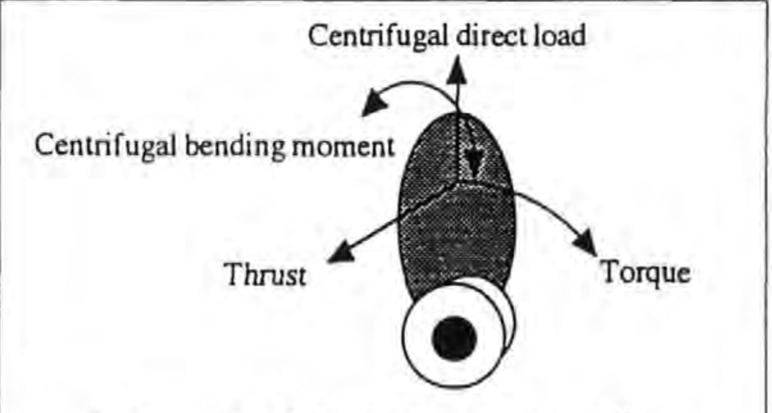


Figure 2 Major loads on a propeller

PROPELLER LOADING

Before the structure of the propeller can be designed, a sound analysis of the loads it is subjected to is required. The foundations of this were laid in 1910 by Taylor [7]when he published work on a method to reduce to rule the stresses upon propeller blades. In his method he treated the propeller blade as a simple cantilever beam acted upon by thrust, torque, centrifugal bending and centrifugal direct loads (Figure 2).

This approach is necessarily an approximation to what actually happens to a propeller in use, Carlton [5] has recently developed this into a readily applicable method. From the sum of these loads the stress at the root of the propeller can be approximated:

$$\sigma_{\text{total}} = \sigma_{\text{thrust}} + \sigma_{\text{torque}} + \sigma_{\text{centrifugal bending moment}} + \sigma_{\text{centrifugal direct load}} + \sigma_{\perp}$$

The stress $\sigma_{\perp}$, includes loads due to weather and impact with debris and must generally be dealt with by a suitable factor of safety and information from experimental impact testing. The stress due to centrifugal loads usually contribute between 5 and 20% of the overall stress. Figure 3 (Carlton) shows how thrust and torque loads are distributed along the blade length. Since the blade is loaded primarily in bending, the greatest stresses will be at the outer fibres of the root section.

For a small 3 bladed propeller of 12 inch diameter, 18 inch pitch with no blade rake, on a vessel travelling at 7 knots from a 20 horse power engine, the approximate theoretical loads can be shown to be:

Load Component	*Bending moment*	*Stress at root*
Thrust	**28Nm**	**26MPa**
Torque	**13Nm**	**12Mpa**
Centrifugal bending moment	**0**	**0**
Centrifugal direct stress	**0**	**1MPa**
Total	**41Nm**	**39Mpa**

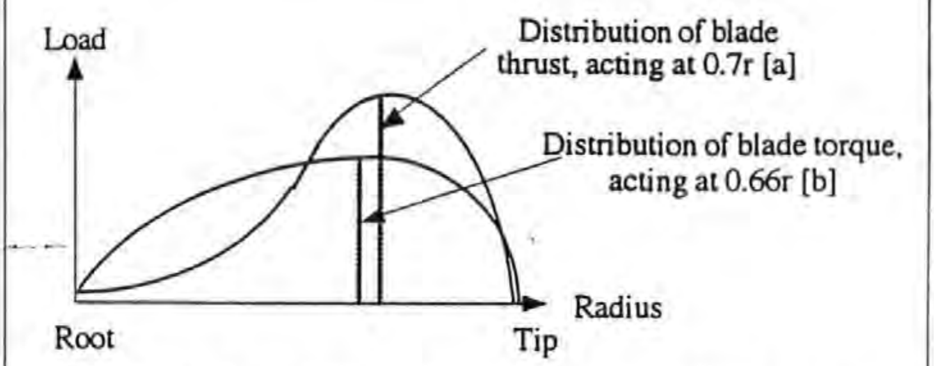


Figure 3 Distribution of loads along the length of a propeller blade

MATERIAL DESIGN

With an estimation of the loads on the propeller the composite structure can be tailored to support these loads. The structural requirements of the propeller can be summarised:

1. To produce a structure to support the theoretical loads with a margin for unknown loads (factor of safety).
2. To produce a structure which can be effectively manufactured.
3. It must be cost effective.
4. The material should be tailored to have the desired elastic properties.

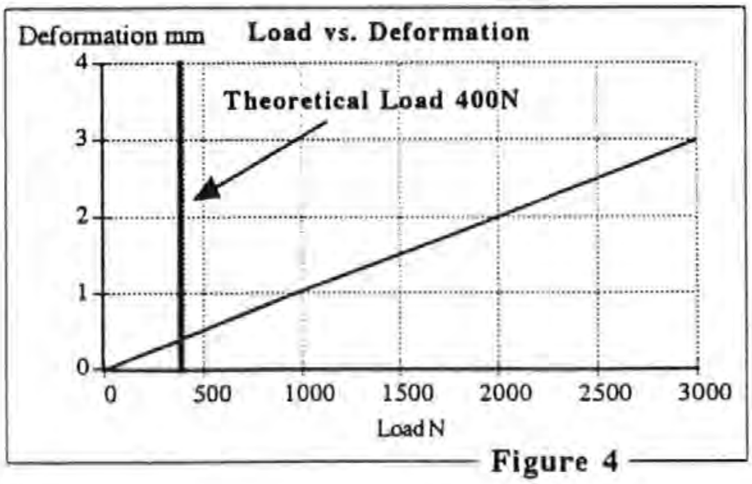


Figure 4

To obtain initial material properties, laminate analysis software is used. A number of commercially available packages are available to perform this analysis. "Genlam" from "Think Composites" models a unit square plate of uniform thickness. This can be scaled to approximate the dimensions of a propeller blade. Properties of the chosen laminate, the loads developed in each ply of material and the deformation under load can be shown. For example, the material used for some of the propellers manufactured so far consists of 24 plies of unidirectional glass and 4 plies of quadraxial glass in epoxy resin, giving a material thickness of 12mm. These plies drop away from the root area of the blade. Figure 4 illustrates the deformation of this laminate under a bending moment, (shown on the graph as a direct load). The next stage to the analysis is to use the properties generated with laminate analysis software in conjunction with a finite element model. The precise elastic behaviour can be predicted this way.

MANUFACTURE

The overall success of a component such as this propeller depends on the successful manufacture of the component to give the designed properties and characteristics. For composites, this has not always been the case in the past. Thus much of this work focuses on manufacture. The interaction of design and manufacture is essential if the full potential of the material is to be realised.

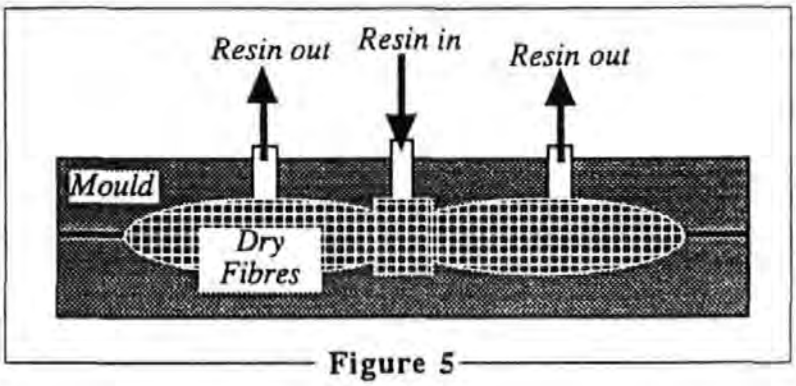


Figure 5

The chosen manufacturing route is Resin Transfer Moulding (RTM), illustrated in figure 5. Essentially the process uses a closed mould into which dry reinforcing fibres are placed. On closing the mould resin is injected at low pressure, 1 or 2 bar, or the resin is drawn in under vacuum only, or a combination of both. This process has a number of advantages that make it a good first choice.[6] These include:

- Low void content
- Good control of properties, repeatable results
- Flexibility of mould design
- Reduction in labour & material waste
- Clean process, handling of dry fibres
- Good for volume production
- Good for large components
- Quick process
- Tooling cost is low.

The manufacture of the component is limited only by the ability to produce a mould. RTM offers improved properties to hand lay up. Compression moulding with pre-pregs can offer better material quality than RTM but for greater tooling cost and slower turn around time. RTM can be used to produce more complex component than compression moulding. RTM offers the cost effective method of producing complex parts, [6].

Experimentation has shown RTM to be a successful method for producing propellers. Work is still required to optimise the process. However so far it has been shown that vacuum on its own works well for transferring resin into the mould. Positioning of the inlet and outlet ports is crucial and not obvious by intuition. Experimentation has begun show the tips of the blades to be the best location of the outlet ports. Volume fraction of the fibre is a limiting factor to the successful injection of resin. Local volume fractions of greater than 65% fail to wet out with resin.

TESTING

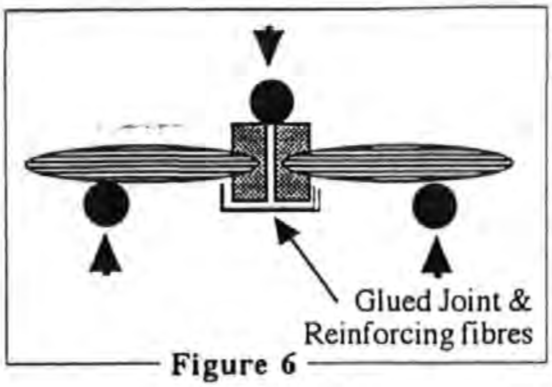


Figure 6

A program of testing is currently seeking to establish the fitness for purpose of the propellers resulting from this research. Laboratory experiments have been performed to measure strength and stiffness properties. Firstly a 12 inch diameter 3 bladed composite propeller was tested in a 3 point bend rig. Two of the three blades were removed and bonded together back to back with some reinforcing fibres on the underside (tensile) part of the joint to enable the test to be performed, (figure 6). Care was taken that the properties of the blade and not the glue was tested. Secondly a series of wedge shaped composite test specimens were manufactured by RTM. These have the same section moduli along their length as the blades of the propeller under test. The benefit in producing test pieces in this manner was that the structural properties were retained whilst manufacture and testing was much easier. The same 3 point bend tests were performed as for figure 6. Figure 7 shows the test. The results from both these experiments and a representative laminate analysis curve correlate well. Deformations are small for the theoretical load.

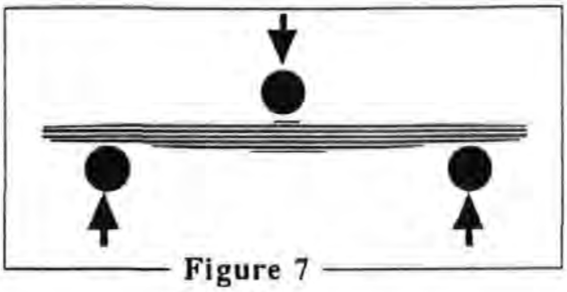
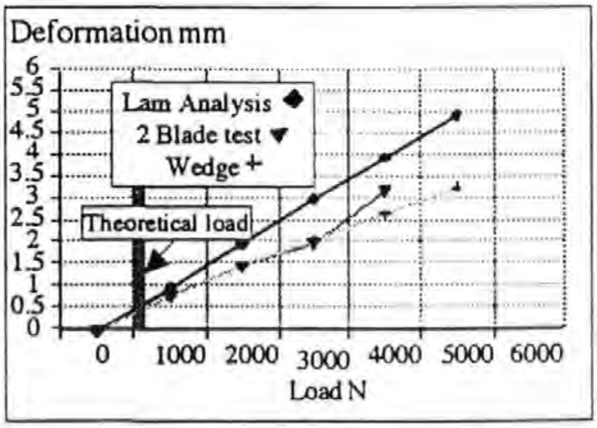


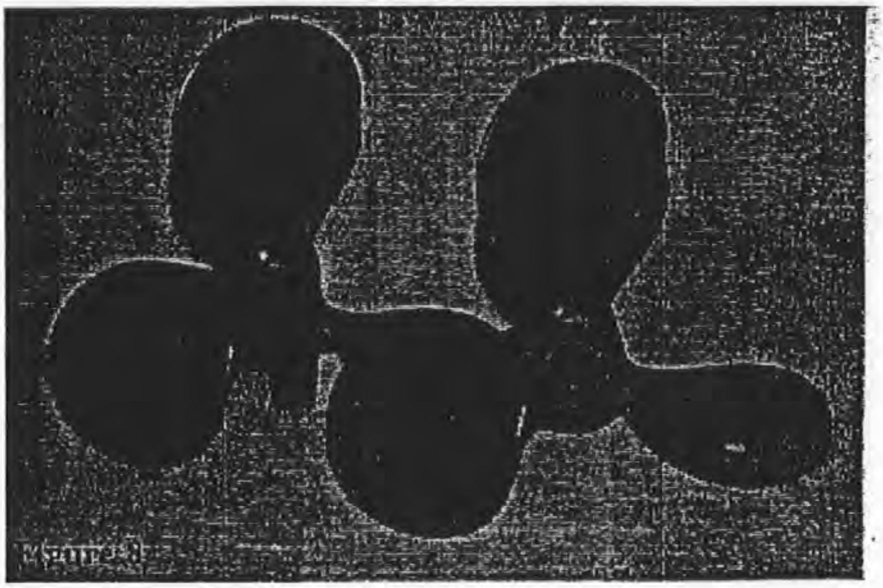
Figure 7



Future work is to include tank testing to establish the efficiency and long term endurance of the propeller. Strain gauges will be used in these tests to check the theoretical loads. These can be conveniently located in the composite during manufacture Testing on a small work boat is also planned.

CONCLUSIONS

This paper has endeavoured to give an informative outline of a program of research at the Advanced Composites Manufacturing Centre and The Institute of Marine Studies at The University of Plymouth. The work is pre-competitive, but it has started to show the design, operating, manufacturing and cost advantages of redesigning the propeller in composite materials. Figure 8 shows a composite propeller (right) with the bronze one that was used to produce the RTM mould.



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Notes for
THE COMPOSITE PROPELLOR

REINFORCED *Plastics*

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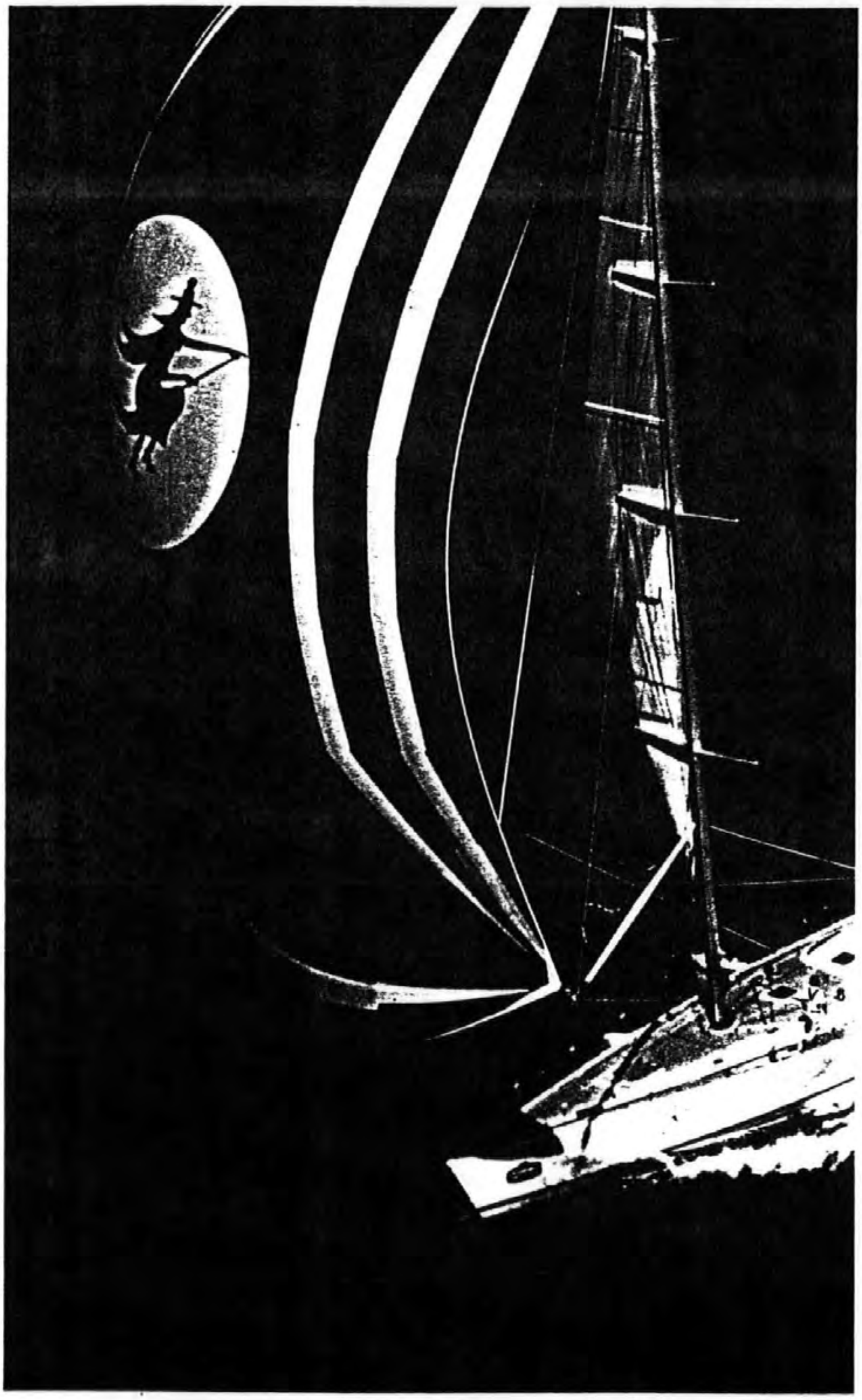


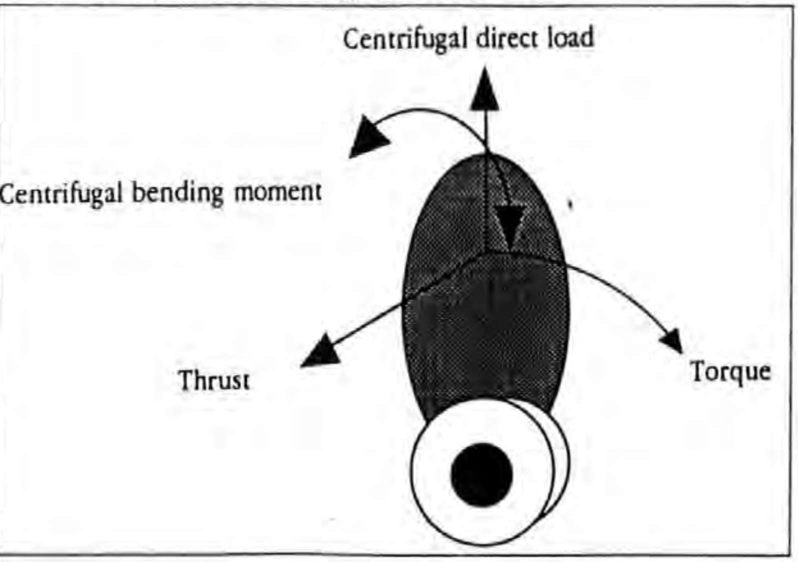
- **Composites for marine fun and safety**
- **Material trends in composite boatbuilding**
- **Composites for propellers**
- **Using semi rigid PVC foam**
- **Composites in public transport**

Composites offer advantages or propellers

he benefits of continuous fibre reinforced plastics r the manufacture of marine propellers remain rgely unexplored. There are some composite blades r defence applications and injection moulded opellers for outboard motors, but these are the ception. Tim Searle says that work currently being ndertaken by the University of Plymouth, UK, may sult in the manufacture of traditional manganese onze and nickel aluminium bronze propellers anging significantly as the benefits of composites e exploited to a greater degree.

IGURE 1: Two art female tool.

IGURE 2: Major loads on a typical propeller.



As the geometry of a component becomes more complicated, then generally it becomes progressively more cost effective to manufacture from composites rather than metals. As propellers are inherently complex in shape this holds true. Generally metal propellers are sand cast, then machined and finished by hand, resulting in a lengthy and labour intensive manufacturing process. The alternative composite process uses a two part female tool (Figure 1). The composite mouldings that are produced are geometrically accurate, repeatable and require virtually no subsequent finishing other than trimming a thin flash from the mould split line. Whilst this does require the manufacture of a tool at a greater expense than a sand mould for casting a metal propeller, a number of glass reinforced plastic (GRP) moulds have been made for this project relatively cheaply. Although at this stage, for one off propeller designs this has marginal economic feasibility, as the numbers increase to five or six propellers from one mould, manufacture rapidly becomes very cost effective. Development work to integrate the design and manufacture of tooling to a seamless computer aided design/computer aided manufacturing (CAD/CAM) process should allow a tool to be produced at a greatly reduced cost in the near future.

In addition to these manufacturing advantages, there are further benefits that are not possible with isotropic metals. For example the composite can be hydro-elastically designed to control the elastic behaviour of the propeller blades. Thus during operation the pitch of the blade changes as a result of the bending moment on it. This property has significant implications for the overall efficiency and performance of the propeller. Currently, tank tests are being performed to quantify this on a range of differently tailored composite propellers. Other advantages from using composites include the following:

- reduced corrosion;
- higher manufacturing yield;
- new shaft attachment possibilities;

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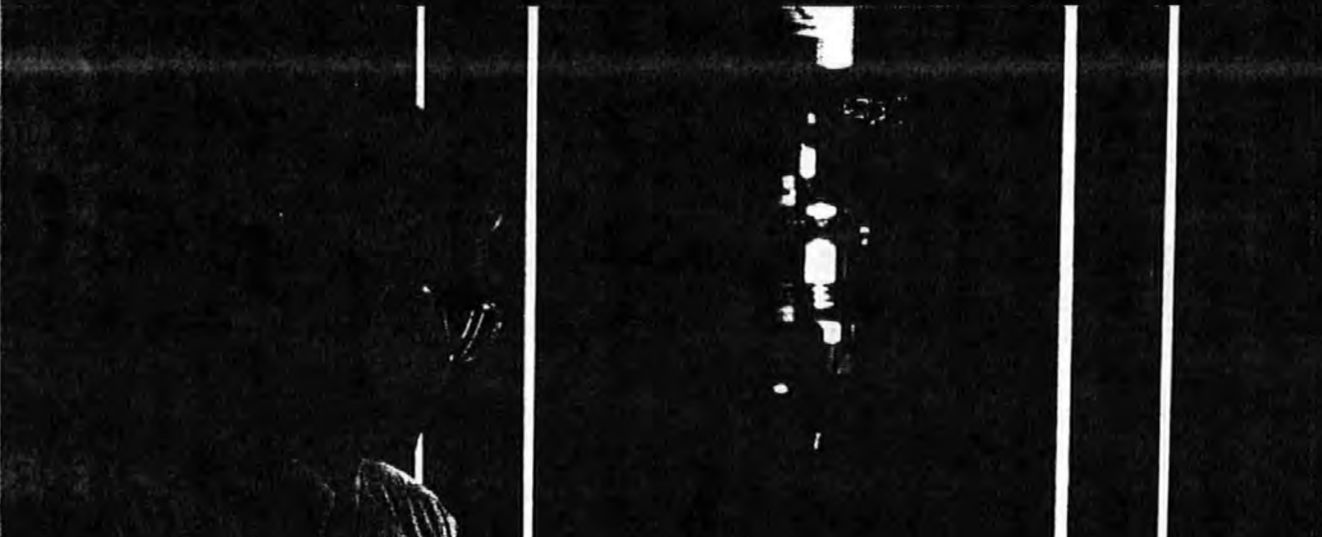

◆ COMPOSITE MATERIALS ◆ INFRARED THERMOGRAPHY ◆
◆ SOFTWARE REVIEW ◆ MECHANICAL TESTING EQUIPMENT ◆

ARE COMPOSITE PROPELLERS the way forward for small boats?

by Tim Searle and David Shot*

Precompetitive research on using composites for propellers of small boats has begun to show design, operating, manufacturing and cost advantages

For some decades now, the use of fibre reinforced plastic composites in marine related products has been steadily growing. Propellers represent a relatively new area for composites, although a number of composite propellers for different applications have emerged during the past few years. On the whole, these are for defence applications although some injection moulded propellers with detachable blades are now on the market for outboard motors. In general, however, it seems that the propeller market has so far been untouched by the benefits of continuous fibre reinforced plastics. Perhaps this is because of a prejudice against composites in certain areas of the propeller manufacturing industry. This is due partly to technical misunderstandings and partly to an inherent resistance to change. However, during the next few years the manufacture of propellers, traditionally made from manganese bronze and nickel aluminium bronze, may change significantly as composites are exploited to a greater degree.

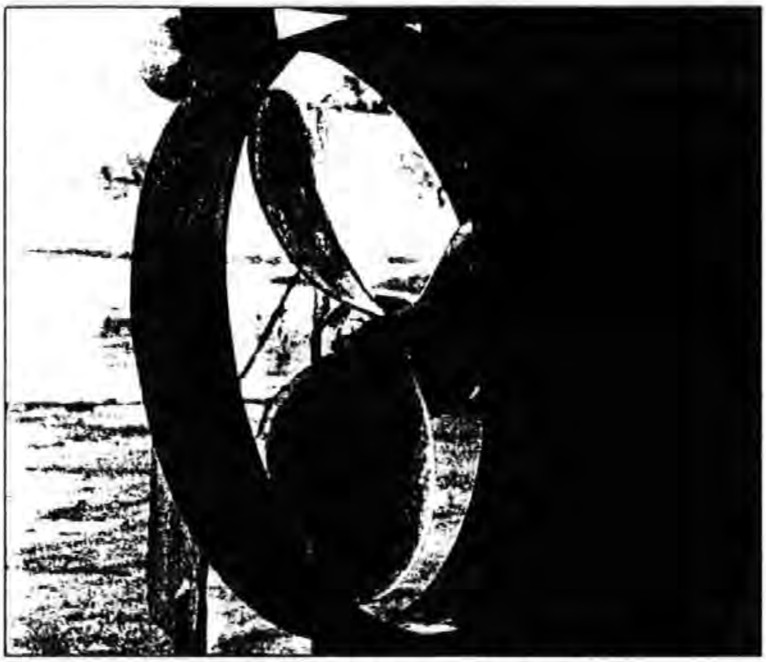

Figure 1 A composite propeller installed on a 23 foot work boat

Present research at the University of Plymouth concentrates on propellers for small fishing boats, work boats and leisure craft with inboard mounted engines, although some work has been started to develop composite replacement blades for damaged metal outboard propellers.

Manganese bronze and nickel aluminium bronze are the usual materials for almost all but outboard propellers. Changing to a composite would bring numerous benefits, such as:

- reduced corrosion
- a higher manufacturing yield
- new shaft attachment possibilities
- a significant weight reduction (up to 75%)
- reduced vibration and a modified acoustic signature
- a reduction in damage caused by cavitation
- easier repair
- damage tolerance
- longevity
- a healthier manufacturing environment.

The major benefits, however, arise in manufacturing and the hydro-elastic design potential that a continuous fibre composite can offer. The anisotropy of continuous fibre composites, not available in isotropic metals, allows the elasticity of the material to be tailored. Thus, under a bending load the laminate can twist as well as bend. This property can be exploited so that the pitch angle of the blade can change, in use, as a result of the hydrodynamic loads on it. This property has significant implications for the overall efficiency range and performance of the propeller.

This does depend on successful manufacturing techniques to give the designed properties and characteristics. For composites, this has not always been the case. The interaction of design and manufacture is essential if the full potential of the material is to be realised, and the manufacturing route chosen is therefore resin transfer moulding (RTM). This process has a number of advantages over other composites manufacturing processes:

- low void content
- good control of properties
- repeatable component geometry
- flexibility of mould design
- reduction in labour and material waste
- clean process, as the fibres are handled dry
- good for volume production
- good for large components
- fast processing times compared to metals
- tooling cost need not be high.

As the geometry of a component

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becomes more complicated, then generally it becomes progressively more cost effective to manufacture in composites rather than metals. As propellers are inherently complex in shape this holds true.

The composite process uses a two-part closed tool. Whilst this type of tool is more expensive than the predominant sand casting manufacturing process for metal propellers, which can only be used once, the composite mouldings that are produced are geometrically accurate, repeatable and require virtually no subsequent finishing other than trimming a thin flash from the mould split line. Casting metals in sand requires lengthy and labour intensive final machining and finishing. A number of GRP moulds have been made for this project relatively inexpensively. At this stage, for one-off propeller designs this has marginal economic feasibility, but as the numbers increase in the order of five or six propellers from one mould, manufacture rapidly becomes very cost effective. It should be possible in the near future to integrate the design and manufacture of tooling to a seamless CAD/CAM process so that tooling can be produced at very much reduced cost.

Essentially RTM can be used to produce complex, high quality parts very cost effectively when compared to the alternatives such as compression moulding pre-pregs. A range of propellers have been successfully made by RTM of glass and epoxy laminates with volume fractions of the order of 50%. Work is currently being carried out optimise some of the processing parameters to maintain a high yield from the process.

The mechanical loads to which the propeller is subjected and the ease of manufacture have been the major design drivers so far. A redesign of the geometry for improved hydrodynamic performance is pending awaiting the results of open water tank tests and computer simulations.

The major loads acting on the propeller can be calculated from known parameters relating to the boat and its engine, such as the boat's speed, engine power and rpm, and the geometric details of the propeller. The size of these theoretical loads, for propellers without high skew, is small by comparison to the load carrying ability of either traditional propeller materials or, for example, a 45% by volume orthotropic E glass/epoxy laminate.

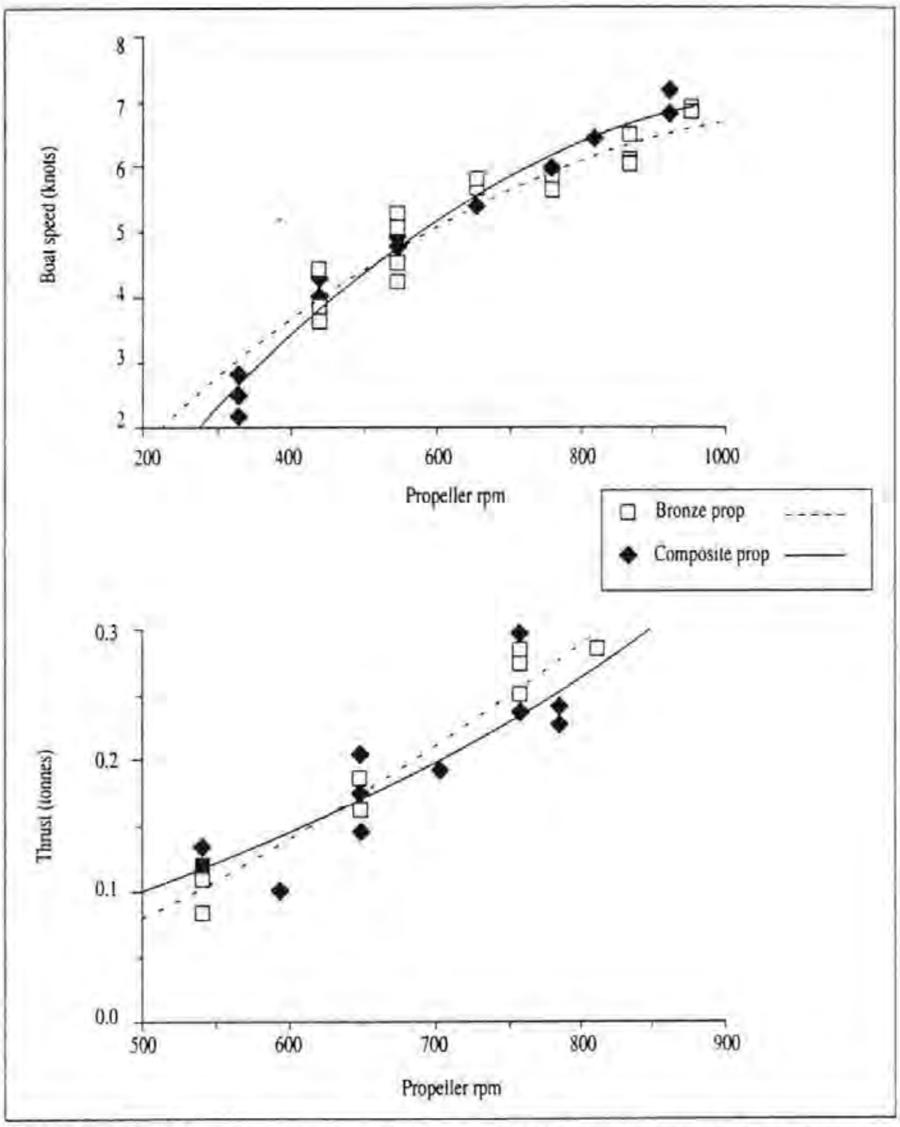

Figure 2 Results from performance trials on a composite propeller installed on a 23 foot work boat: speed vs rpm (top) and bollard pull test (bottom)

The design of the propeller blade laminate should also take into account criteria that are difficult to quantify, such as collisions with objects in the water. Work has been done to study the effects of large impacts on a variety of composite structures. The major factor that influences their performance is the quality of manufacture. Correctly manufactured composites can absorb significant amounts of energy from impacts.

A programme of testing at the University of Plymouth is currently seeking to establish the fitness for purpose of the propellers resulting from this research. Laboratory experiments have been performed to measure strength and stiffness properties of the laminates currently being used and it has been shown that for the theoretical loads deformations are small.

Sea trials have been carried out on a 20 inch three-bladed composite propeller installed on a 23 foot work boat with a 40 hp diesel engine, figure 1. Experiments to measure top speed and thrust from the bollard pull condition, (ie the thrust generated from the engine and propeller with the back of the boat tied to a bollard) have shown the hydrodynamic performance of the new composite propeller to be the same as that of the bronze one, figure 2. The composite propeller has only been designed as a retrofit at this stage, so none of the benefits of hydro-elastic tailoring have been exploited. As this article is being written, tank tests are being performed to quantify this on a range of differently tailored composite propellers and K_T/K_Q charts are being produced that characterise the efficiency envelopes of these propellers.

The longevity of the propeller is still to be evaluated, although after several weeks' use there were no indications that the material was unsuitable. ◆

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Paper 5

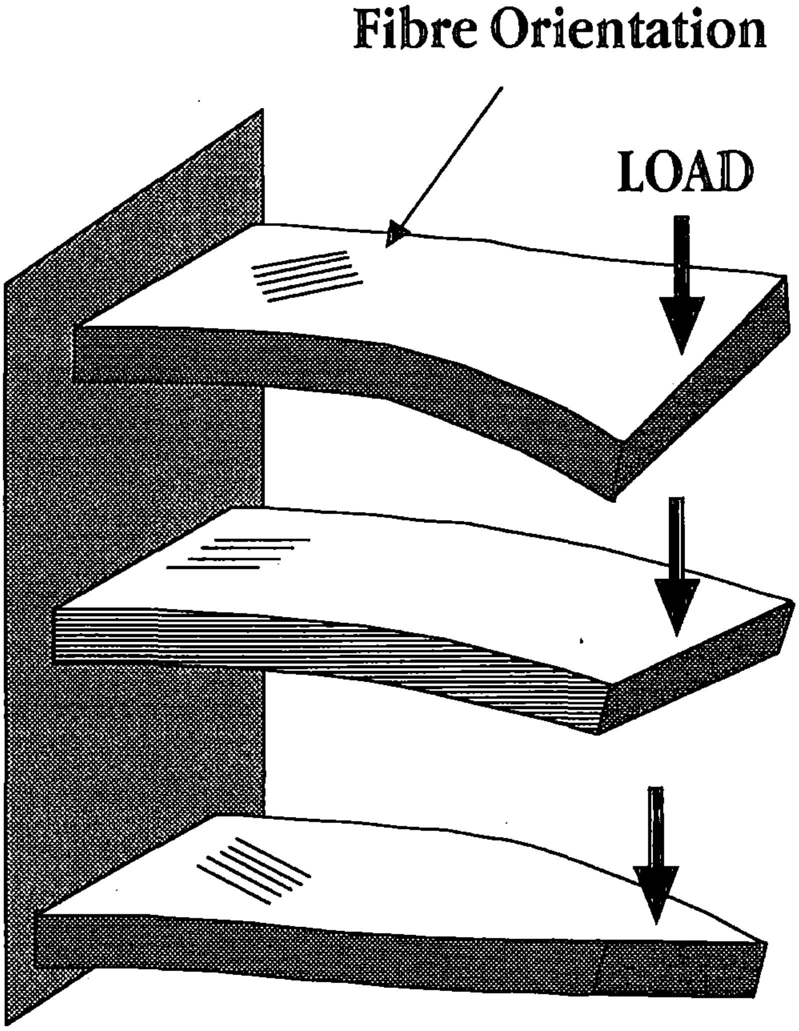
Composite Propellers

Tim Searle
Advanced Composites
Manufacturing Centre
University of Plymouth

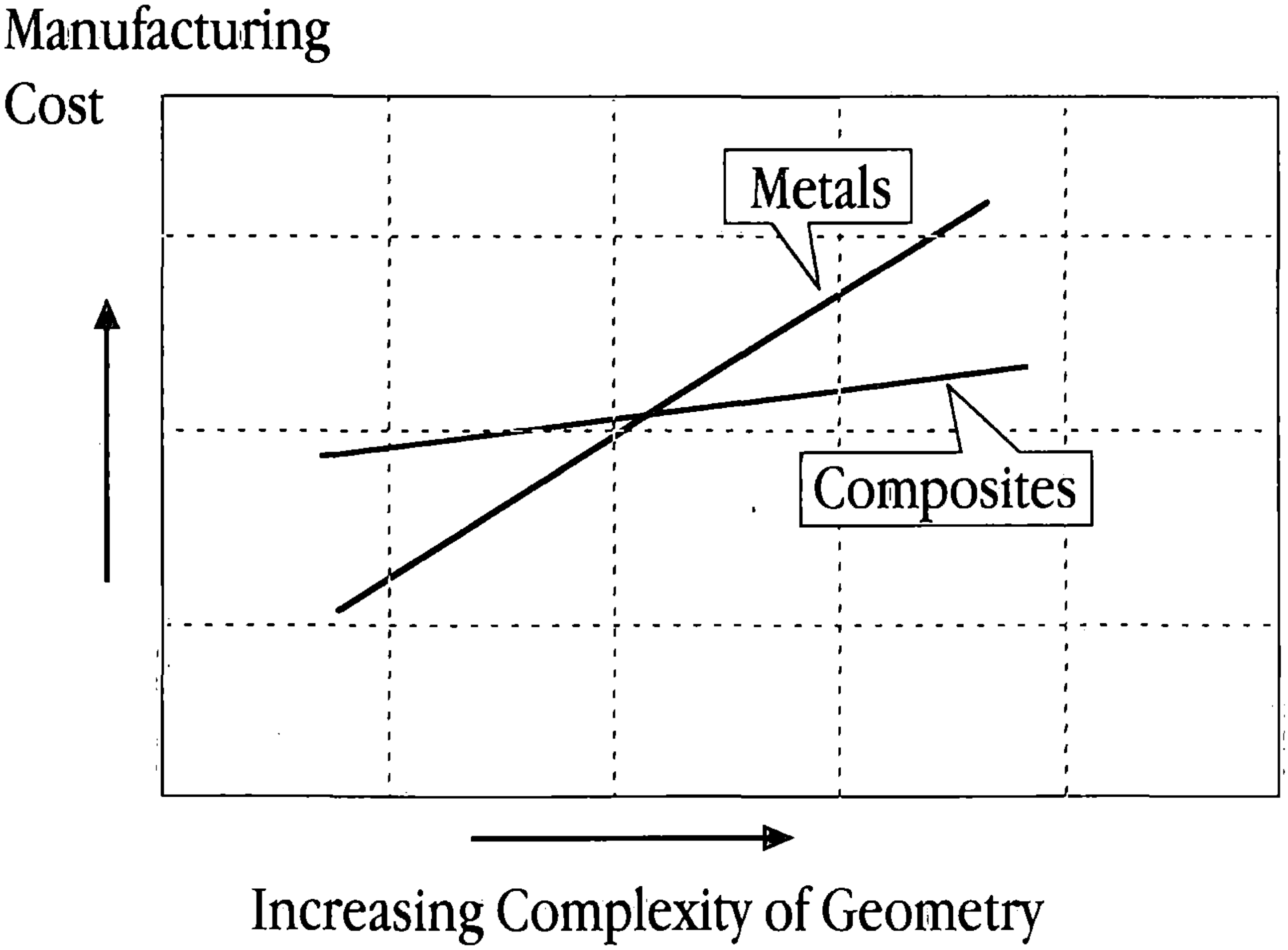
Why composites ?

- Reduced corrosion
- Higher manufacturing yield
- A significant weight reduction (up to 75%)
- Reduced vibration
- Reduction in damage caused by cavitation
- Damage tolerance
- Healthier manufacturing environment
- Improved design freedom over traditional materials
- Low cost manufacturing

Hydroelastic Tailoring...



Processing Cost...



Design Criteria...

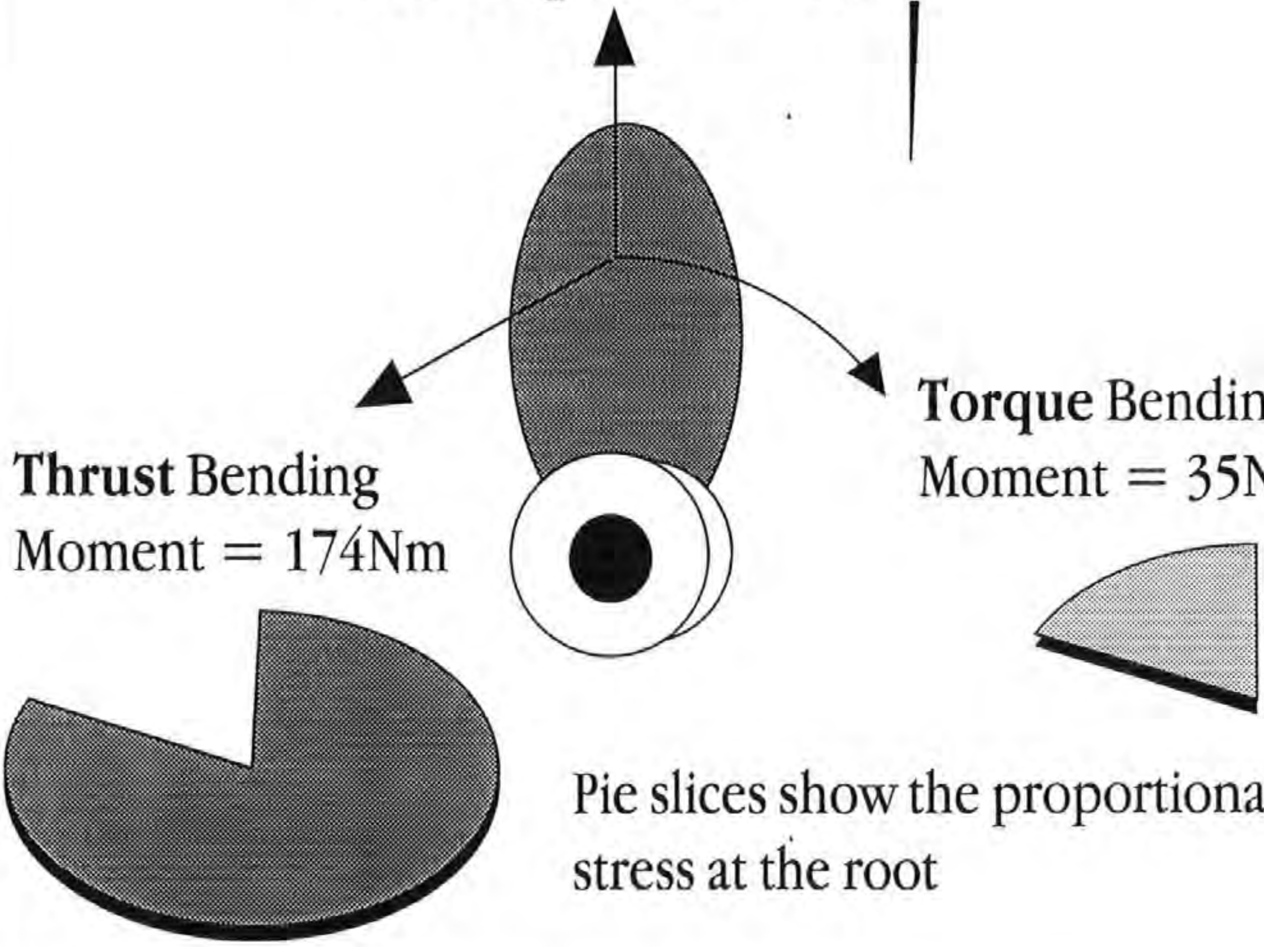
Loads
Cost effective manufacture
Retrofit
Improved hydrodynamic efficiency by hydroelastic tailoring

E-glass
Epoxy
Resin Transfer Moulding
Manganese bronze boss insert

Propeller Loading...

For the propellers used in trials

- 20 inch diameter
- 12 inch pitch
- 3 blades
- 0.5 DAR
- 7 Knots
- 945 RPM
- 38 hp



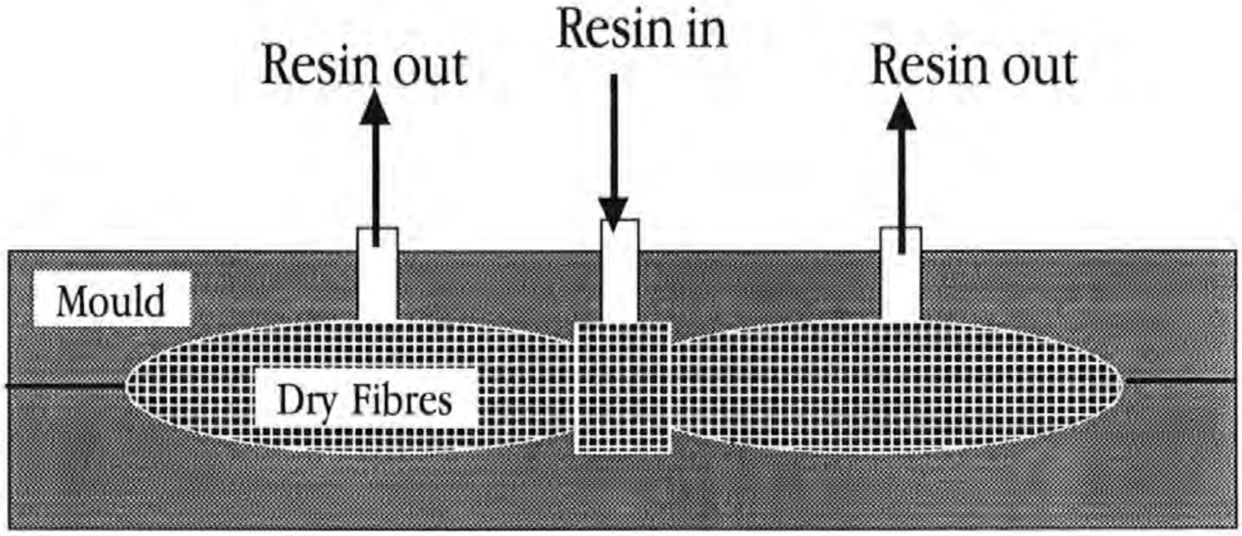
Centrifugal Load = 430N

Thrust Bending Moment = 174Nm

Torque Bending Moment = 35Nm

Pie slices show the proportional stress at the root

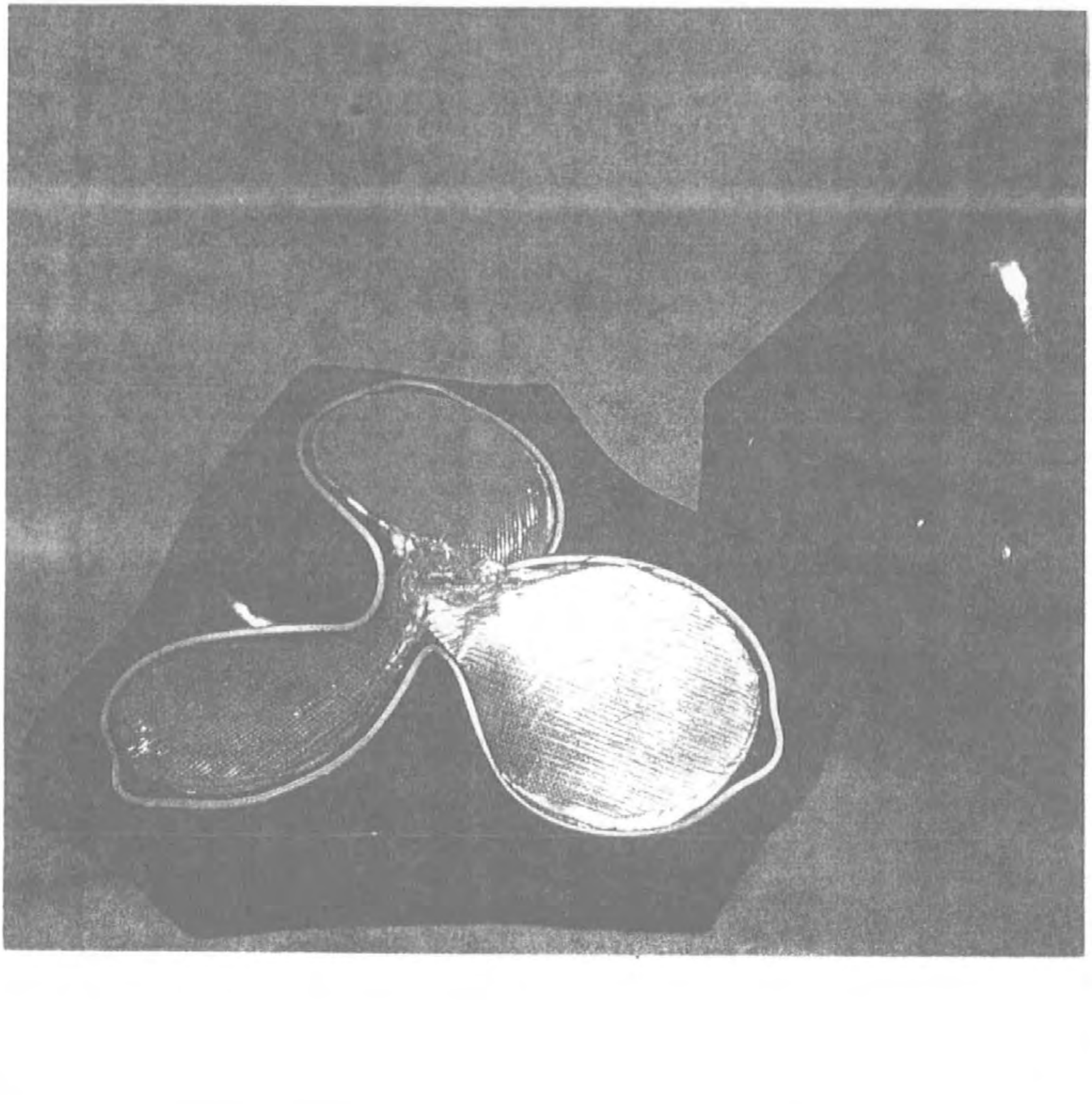
Resin Transfer Moulding...



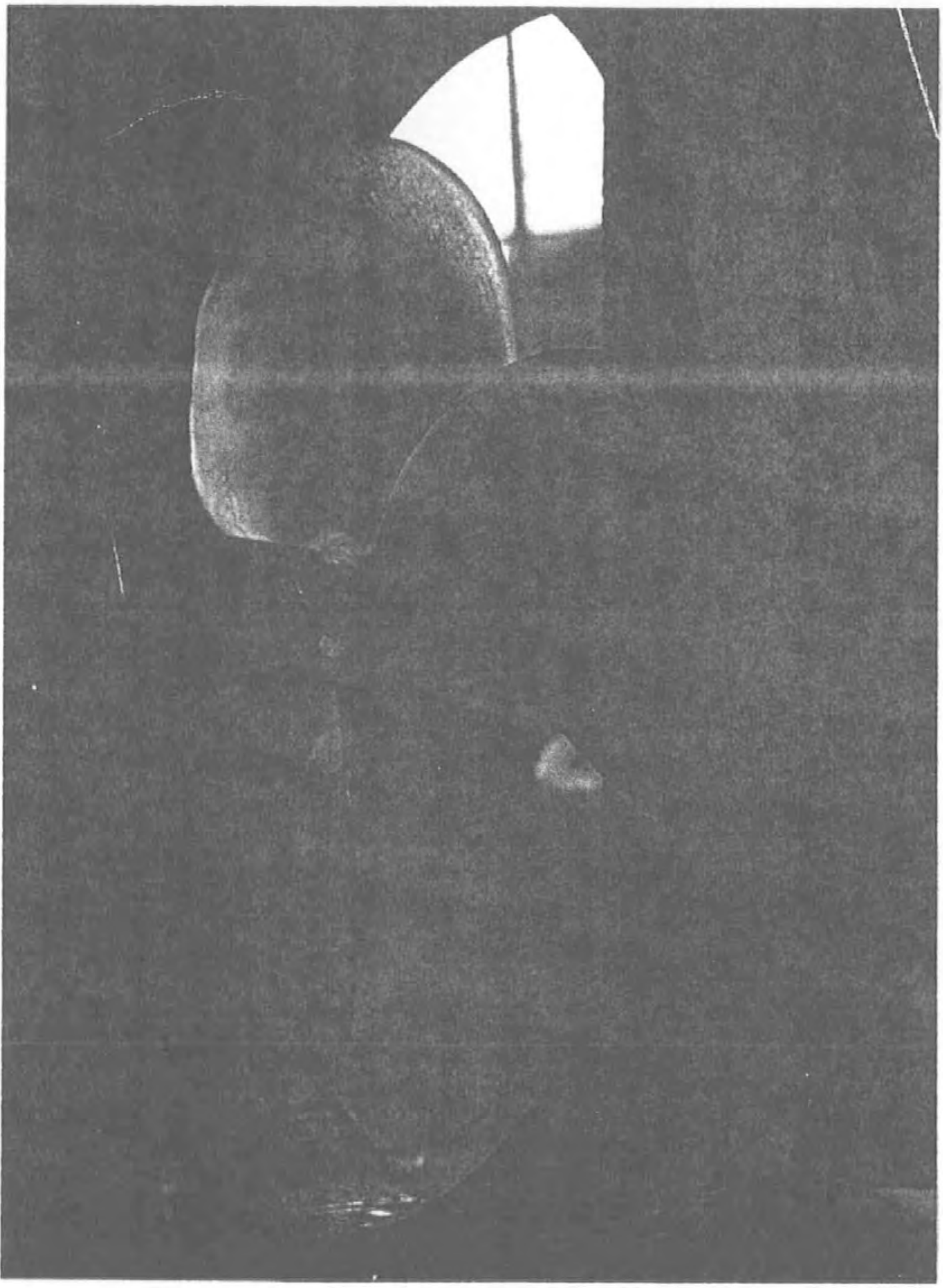
Advantages of RTM...

- Low void content
- Good control of properties, repeatable results
- Flexibility of mould design
- Reduction in labour & material waste
- Clean process, as fibres are handled dry
- Good for volume production
- Good for large components
- Quick process
- Tooling cost is low.

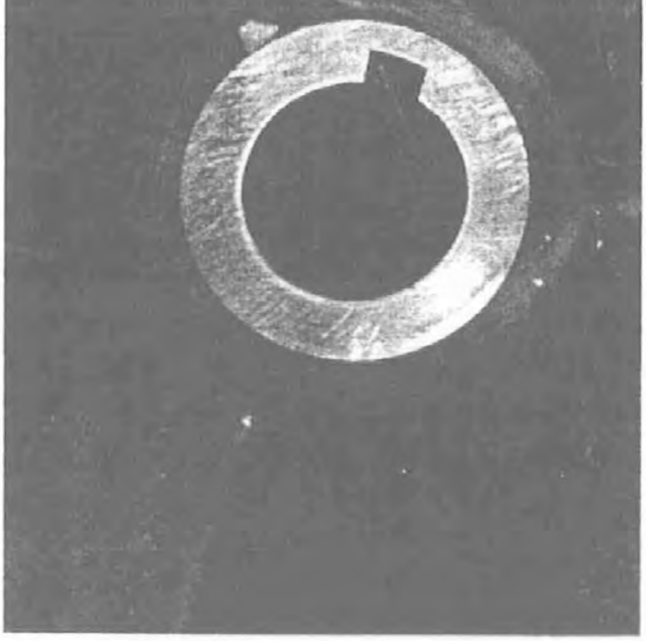
The Mould...



Propeller Installed...



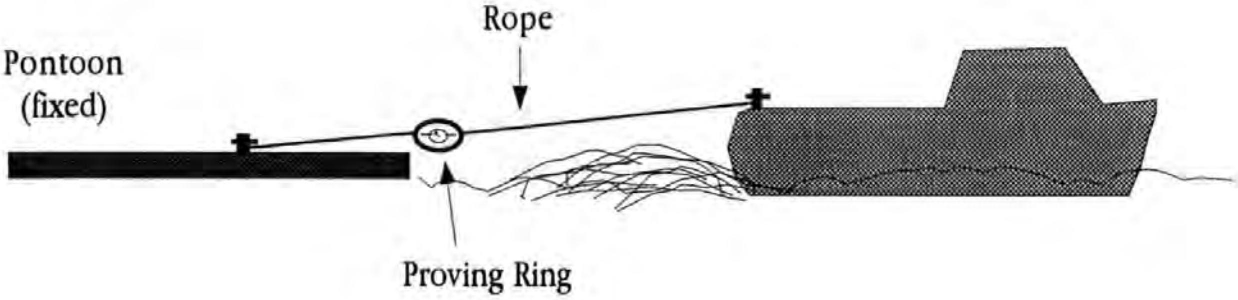
The Boss...

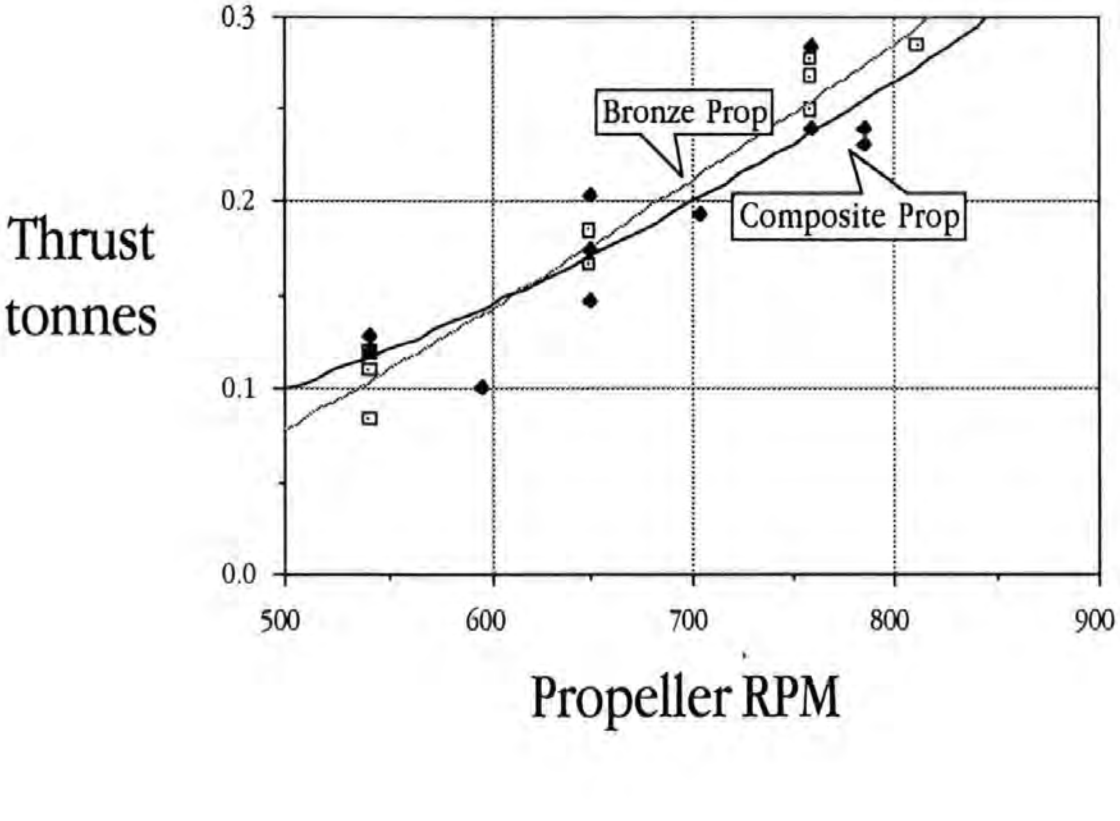


Testing...

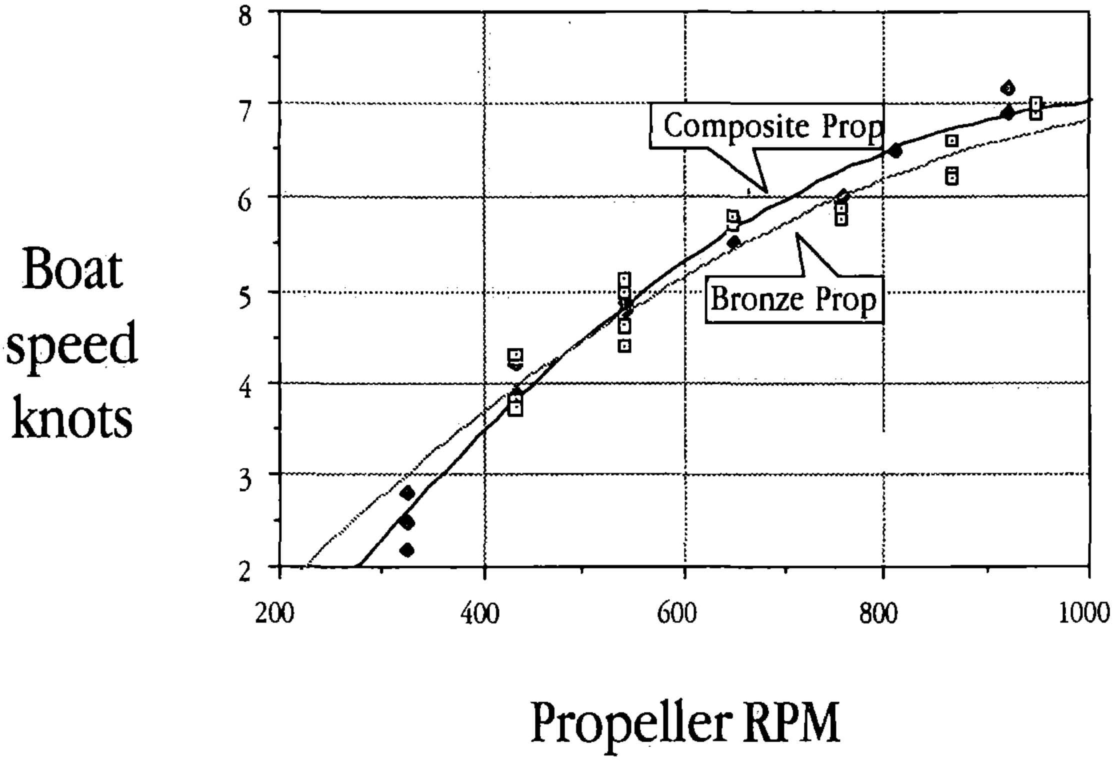
- Laboratory Testing
- Bollard Pull
- Speed trials
- Ongoing longevity testing
- Open water towing tank test

Bollard Pull...



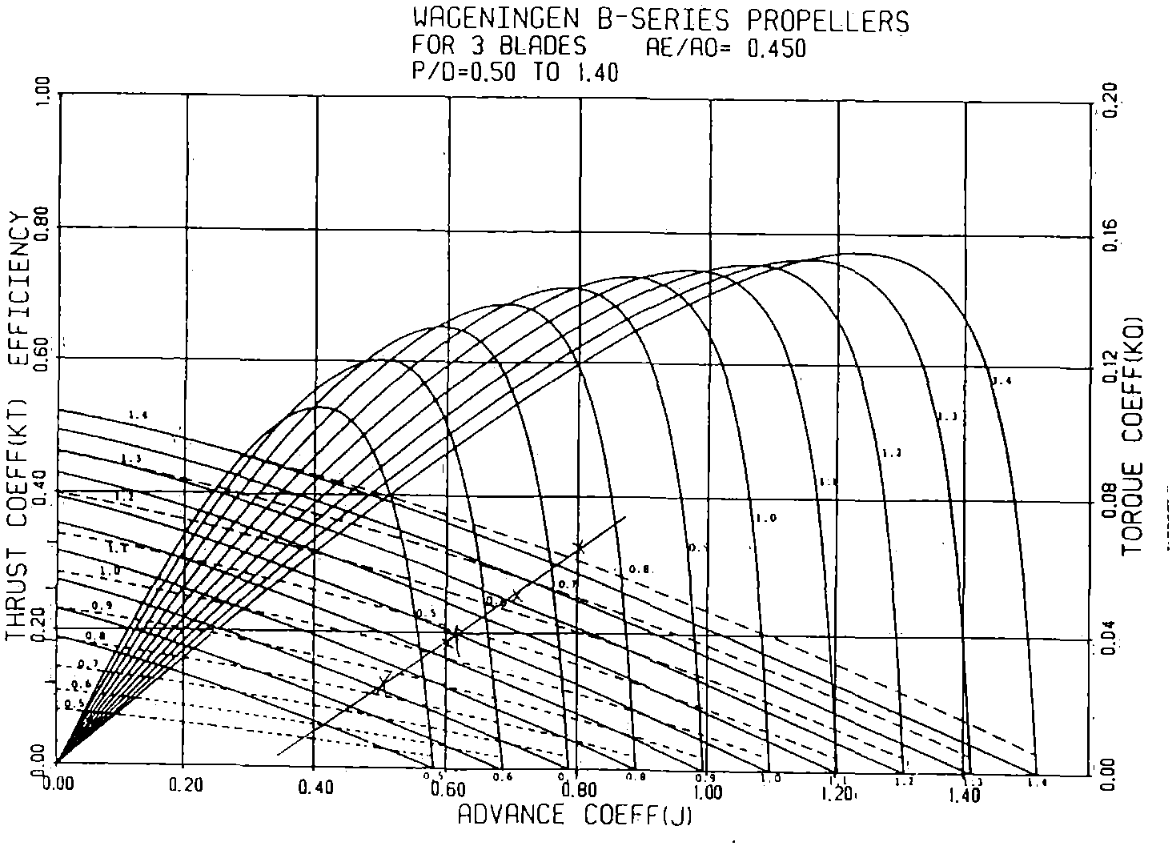


Speed...


8
7
6
5
4
3
2
200
400
600
800
1000
Composite Prop
Bronze Prop
Boat speed knots
Propeller RPM

Open Water Test...

Efficiency: K_T K_Q & η_o



Conclusions...

- An effective manufacturing route has been demonstrated
- A composite propeller has been shown to have comparable performance to the metal one
- The potential exists to manufacture propellers of improved design very cost effectively

Structural Materials in Marine Environments

11–12 May 1994

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and The Institute of Marine Engineers

The Use of FRP Composites for Ships Propellers

T. Searle, J. Chudley, D. Short & C.Hodge

The Advanced Composites Manufacturing
Centre & Marine Dynamics Research Group
University of Plymouth

Abstract

Certain market sectors such as the aircraft and sports industries have shown by the improved performance of their products, the advantages of using composites. This, in part, is because of the advantages of tailoring the anisotropic (directional) properties of the material, as well as, the increased stiffness, reduction in weight, corrosion and manufacturing cost. The design of a propeller in a composite material allows for design features not possible with isotropic metals. The effect of being able to tailor propeller blade deformation by appropriate fibre alignment and distribution means the efficiency of the propeller can be improved. Experience in the manufacture of composite propellers to date has shown resin transfer moulding (RTM) to be a suitable process. Tank tests and vessel trials have also been undertaken to evaluate the performance characteristics of a range of composite propellers. Results are presented in this paper.

1. The Benefits from Composites

Composite materials embrace a wide range of materials; for all of them the same definition holds true: *The synergy of two or more materials whose combined properties exceed the sum of the individual constituent materials properties.* The interest of this paper is with continuous fibre polymer composites, where the fibres are the main load bearing component. Generally, these comprise of high strength, high modulus, high aspect ratio fibres, of glass, carbon, or aramid (Kevlar), within a plastic matrix, such as polyester, vinylester, epoxy or phenolic resin. Many applications of these materials are well established, for example, high performance racing yachts or minesweepers. Some more subtle applications are just emerging. The manufacture of boat propellers in composite falls into this latter category.

The important question to ask is, how do composites materials enable better solutions to engineering problems ? Composite offer the following advantages:

- High specific strengths
- High specific stiffnesses
- Low coefficients of thermal expansion

- Resistance to environmental degradation
- Possibility of reduced cavitation erosion [1]
- Non catastrophic failure in fatigue

- High production rates
- Healthy production environment
- Ease of producing complex shapes
- Ease of repair & maintenance

- Specific material design to the application
- The ability to tailor the elastic properties
- A polymer composite material uses about half the energy to manufacture compared to steel or aluminium [2].

2. The Manufacture of Composite Propellers

As well as the benefits of material properties, the manufacturing advantages are significant to. When the geometry of a component increases in complexity, so it becomes more cost effective to use particular materials. Generally an increase in component complexity, favours the use of composites over metals in terms of manufacturing cost [3]. Propellers have inherently complex geometry, so this on its own gives good reason to explore composites for propeller manufacture.

Generally metal propellers are cast in sand, then machined and finished by hand, resulting in a lengthy and labour intensive manufacturing process. For high performance propellers, where a extremely high degree of geometric accuracy is required, then NC machining is employed. The alternative composite process uses a two part RTM tool, figure 1.

The composite mouldings that are produced are geometrically accurate, repeatable and require virtually no subsequent finishing other than trimming a thin flash from the mould split line. Whilst this does require the manufacture of a tool at a greater expense than a sand mould for casting a metal propeller, a number of GRP moulds have been made for this project relatively inexpensively. Although at this stage, for one off propeller designs this has marginal economic feasibility but as the numbers increase in the order of five or six propellers from one mould, manufacture rapidly becomes cost effective [4]. Development work to integrate the design and manufacture of tooling to a seamless CAD/CAM process should allow in the near future tooling to be produced of very much reduced cost. The NC machining required for propellers where the tolerances are strict should be better applied to the production of the mould for one blade. From this the appropriate number of composite blades would be produced which are then joined at the hub.

In order to define and mould accurately the surface of the propeller, a closed mould is required. This limits the process to either compression or Resin transfer moulding.
RTM has been used to date for the following reasons:

- Low void content
- Good control of properties
- Repeatable results
- Flexibility of mould design
- Reduction in labour & material waste
- Clean process, handling of dry fibres
- Good for volume production
- Good for large components
- Quick process
- Tooling cost need not be high

RTM figure 2 has been used to great effect in the production of aircraft propeller blades [5] and many components where high structural performance is required. RTM has been demonstrated successfully in the production of a range of small boat propellers during research at The University of Plymouth.

In order to achieve high quality mouldings with RTM, it is essential that the processing parameters are correct. This becomes more critical as the fibre volume fraction of the component increases. High volumes of fibre reinforcement have low permeability and reduce the ability of the resin to permeate through the fibre pack. Experience has shown that high volume fraction fibre packs of low permeability can reduce the consistency of the laminate quality. Crucial parameters include the following:

- Low resin viscosity
- Accurate tooling
- Careful loading of fibres
- Fibre weave style that is conducive to resin flow

Resin viscosity is a dominant parameter. This should be low enough to allow the resin to permeate the fibre pack and enable filling of the mould before the resin starts to gel and. 2 poise has been shown to be an appropriate viscosity for high volume fraction laminates, this can be achieved with most epoxies by heating to between 40ºC and 50ºC. Using viscosities of this order enables mould fill to be significantly quicker than would be achieved using the same resin at room temperature. This is shown more fully in figure 3 where a standard RTM mould has been used with different resin viscosities.

Accurate tooling that seals to a vacuum and maintains consistent dimensions of the mould cavity is required. The fibre plies and ply drop offs are defined by the mould dimensions. If either the mould does not close to the same position each time it is used, or the plies are out of position, large changes in the fibre volume fractions can occur. A small error in loading fibres into the mould can lead to a large change in local fibre volume fraction. A sizable increase in local volume fraction may mean dry patch are left. Areas of inconsistent low volume fraction should be avoided as this creates an easy path taking resin past and away from areas of fibre not already permeated by resin. A fibre weave style can greatly assist the process, fabrics that maintain small channels under the pressure of the mould closure, between the fibre tows also increases the reliability of the manufacture.

Loading the fibres into the mould, is assisted by pre–forming with a thermo plastic binder allowing accurate placement. These are aligned to absorb the major loads the propeller is subjected to. Therefore the predominant alignment is from the root to the tip, although several tows are placed around the blade edges to absorb local impacts.Typically the volume fraction is about 50%. So far, a manganese bronze boss has been moulded in situ within each propeller. This is to enable a reliable retrofit of the composite propeller to the boat.

3.Hydroelastic Tailoring.

A new set of variables exists with the introduction of continuous fibre composites, not available in metals.The designer has greater freedom to tailor many of the properties within the material. No longer is geometry, (properties being equal), the only structural variable. But with specific alignment and distribution of load bearing fibres,within a given geometric envelope, weight, elasticity, flexural stiffness, failure mode and cost can all be more tightly controlled.

By aligning fibres at different angles, it can be seen from figure 4 that a twist can be introduced in a simple cantilever beam. This principle has been used extensively in the aerospace industry to control the deformation of fixed wing and helicopter blades [6].

This hydro elastic tailoring has immediate application to marine propellers. The option now exists to build a propeller where the pitch can vary in response to the hydrodynamic load upon it. Effectively, a controllable pitch propeller with no moving parts. Whilst this will not give the range of pitch that clearly a fully CP propeller has, it will allow some efficiency benefits where cost and space restrict the propeller to a fixed pitch. The efficiency envelope on the Kt Kq chart should widen as the pitch changes to accommodate different operating conditions. The advantage should also exist to have a greater degree of control to the onset of cavitation with propellers that have to operate within this regime.

4. Tank Testing.

Although work to design a working hydroelastic propeller is still in its infancy, a number of designs have been successfully tank tested to asses the potential of the concept.

Five propellers, having different elastic properties, were used in an open water towing tank test. Each propeller was tested at a range of different advance coefficients (J) to determine the thrust coefficients (Kt) and torque coefficients (Kq) and hence the open water efficiency. Each propeller was of the design set out in table 1. Five propellers were tested, each with different material properties, summarised in table 2.

- The bronze propeller is included as a control by which to measure the composite propellers.
- Propellers 2 & 4 are not tailored to any particular bending characteristic, however they were not as stiff as the bronze propeller.
- Propeller 5 was made with a foam core so that it was considerably more elastic than propeller 3,

although both 3 & 5 were designed so that as load is developed on the blade, twist coupled to the bending causes the pitch to back off.

The aim of the open water test was to determine, in an introductory sense, the effect of different blade elasticities on the shape of the efficiency envelope. In allowing the pitch to reduce as the load comes on the blade, greater RPM for a given torque should be possible and therefore greater efficiency, as the pitch remains course for lower loads.

Figures 5–8 show the results of the open water test, each compared to the bronze, put onto separate charts for clarity. The open water efficiencies have been calculated from the thrust and torque coefficients in the usual manner.

With the exception of the foam sandwich propeller, the composite propellers are all more efficient than the bronze at lower J values and less efficient at the optimum J value. The reverse is true for the foam sandwich propeller which has a smaller width to the efficiency curve.
These results should be taken within the context of their preliminary nature and the scatter on the graphs. However, whilst not conclusive in absolute terms, the indications are, firstly that the composite propellers are as efficient as their manganese bronze counterparts. Secondly, that it is possible to change the shape of the efficiency envelope by altering the elasticity of the material the propeller is manufactured from and this could be made high or low aspect ratio, depending on the application of the vessel.

5. Sea Trials.

A boat was used to trial a 20 inch by 12 inch by 0.5 DAR composite propeller .The vessel was a 23' GRP work boat powered by a 31hp continuous or 38hp intermittent diesel engine. The maximum engine RPM at top boat speed is approximately 1700 with a gearbox reduction of 1.85 to 1. The main purpose of the boat is safety cover for student recreation. It can carry up to 12 people plus diving equipment. The installed propeller is shown in figure 9.

The aims of using this boat to trial a composite propeller were as follows:

- To check the boss attachment
- To check the structural integrity of the propeller
- To measure the thrust from the bollard pull condition for the composite and bronze propellers
- To measure the speed vs RPM of the boat using the composite and bronze propellers

A composite propeller was installed and left on the boat for 3 weeks, during which time the propeller remained immersed in the water and was used regularly. At the end of three weeks, experiments were performed to measure the bollard pull and the speed/RPM characteristics of both the composite and bronze propeller figures 10 &11.

After these tests were performed the propeller was removed for inspection:

- The boss joint showed no signs of degradation.
- During the period of immersion no marine growth occurred.
- One of the leading blade edges had been slightly scuffed, this was probably due to an impact with an underwater object.
- The results indicate, taking into account the scatter on the graphs, that the composite propeller performs the same as the bronze in terms of thrust and propelling the boat at top speed.

The longevity with respect to water absorption, impact damage and marine growth is to be confirmed during subsequent experimentation.

6.Conclusions

Work reported in this paper is pre–market, however, preliminary studies have indicated that potentially, significant benefits exist by manufacturing marine propellers this way. The competitive manufacturing process, reduction in weight, the ability to tailor the elastic behaviour and reduced corrosion should give composite propellers a firm market sector in the near future.

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Table 1 The propeller design used in the tank testing

Diameter	12 Inches
Pitch	14 Inches
DAR	0.5
No. Blades	3

Table 2 Fibre layups for propellers used in the tank testing

Propeller	Material	Fibre Volume Fraction	Fibre Alignment
One	Manganese Bronze	•	•
Two	E-Glass &Epoxy	48 %	Quasi Isotropic
Three	E-Glass &Epoxy	35 %	Tailored so that the pitch backs off under load
Four	E-Glass &Polyester	17 %	Quasi Isotropic
Five	E-Glass &Epoxy Foam core	40 %	Tailored so that the pitch backs off under load

Fig. 1 The mould for the production of propellers by RTM.

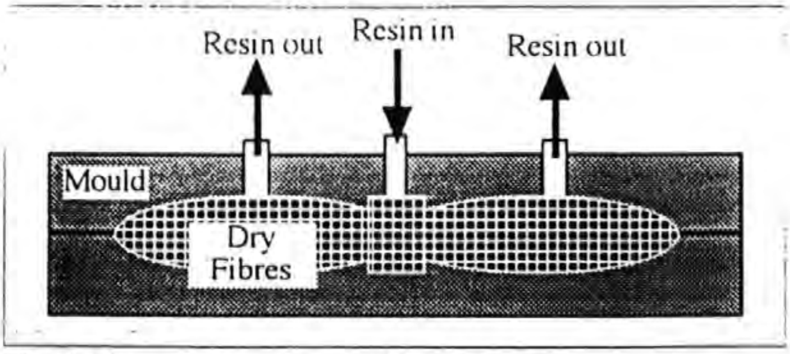

Fig. 2 The resin transfer moulding process.

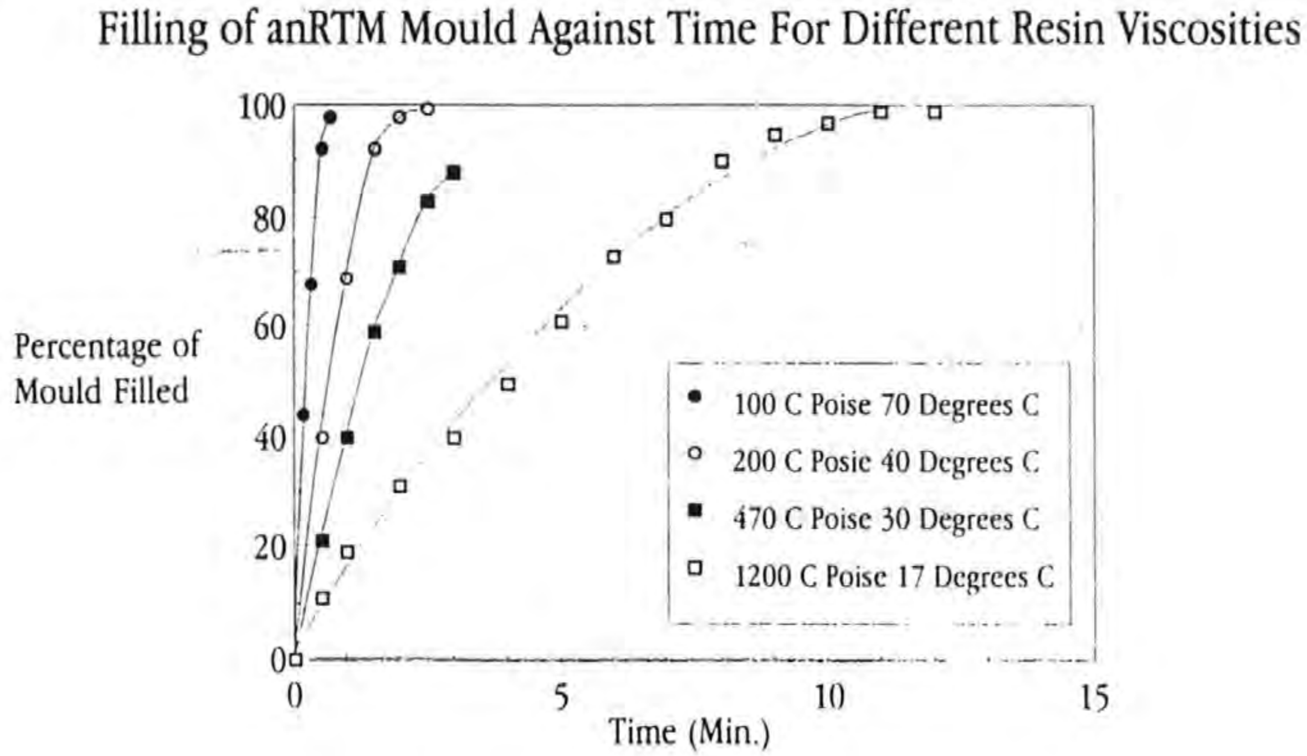
Filling of anRTM Mould Against Time For Different Resin Viscosities

Fig. 3 Fill times for standard RTM mould using different resin viscocities

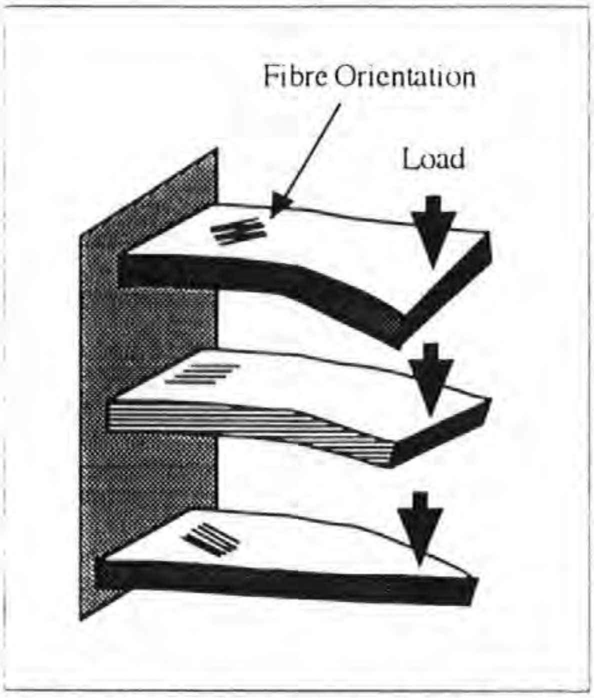

Fig.4 Differing elastic properties for a cantilever beam.

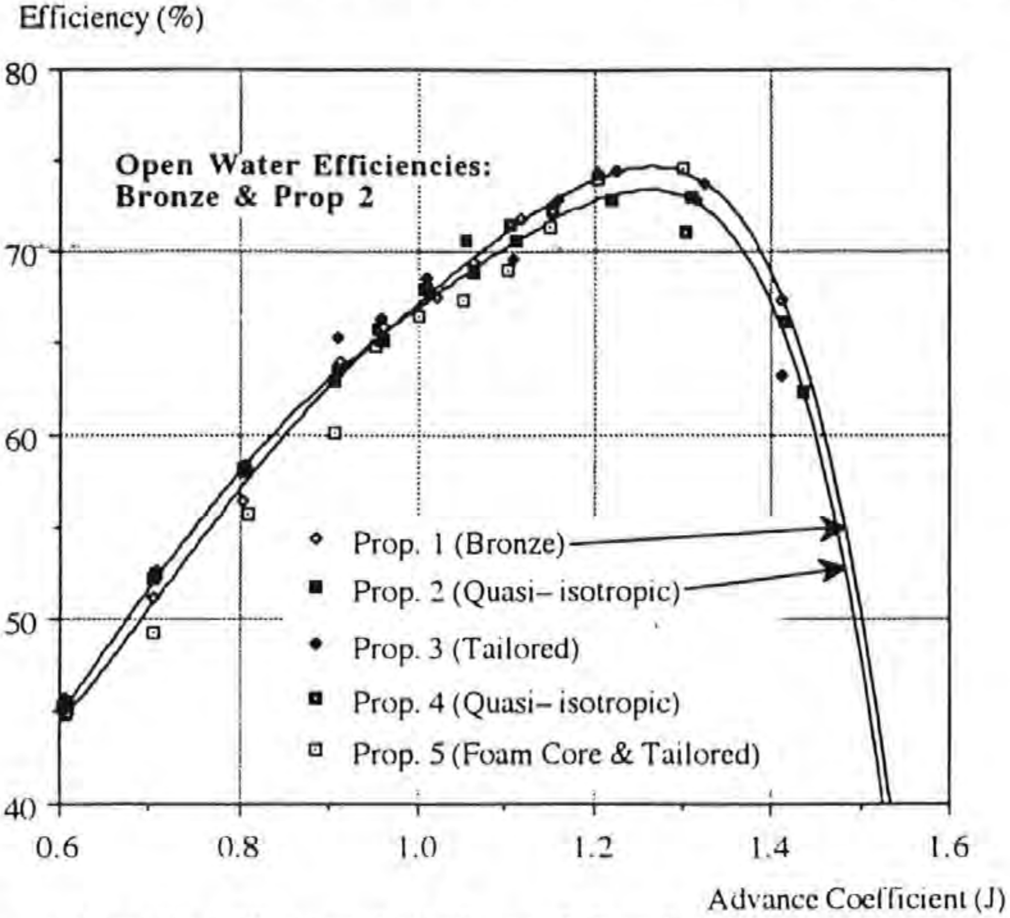

Fig.5 Open Water Efficiency for the Bronze & Propeller 2.

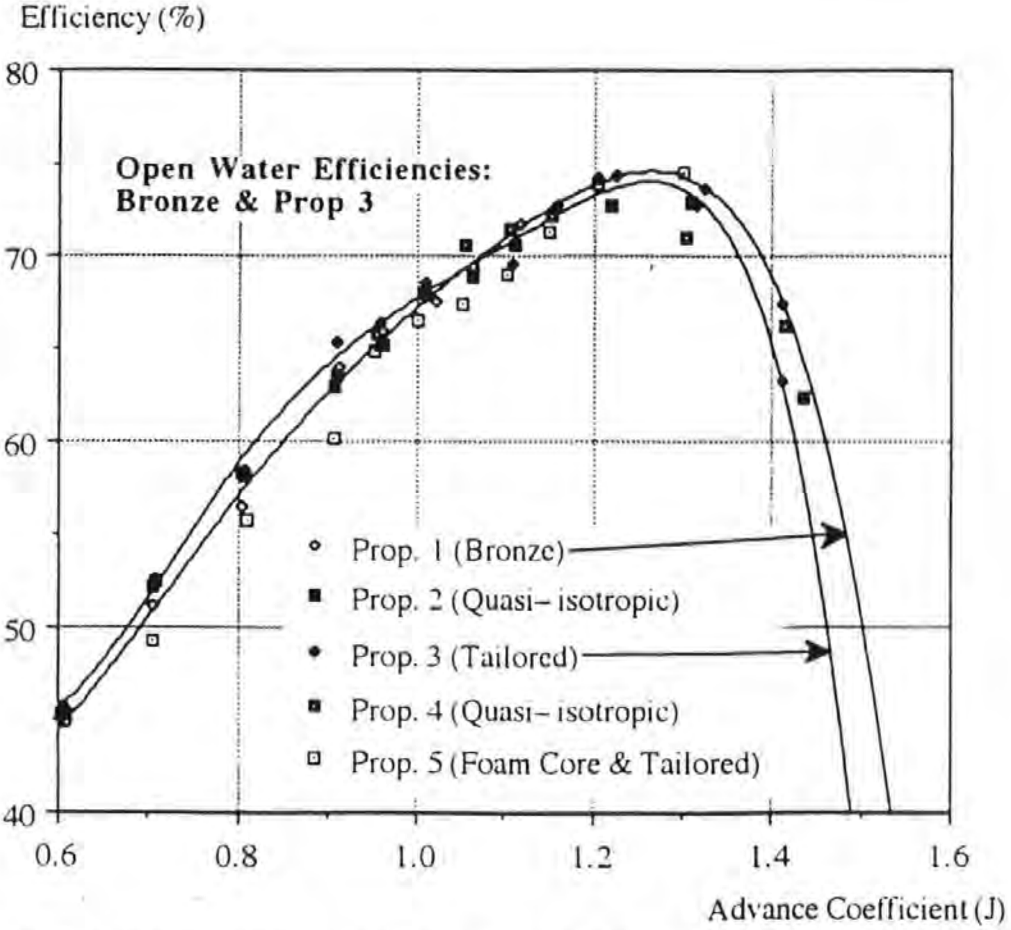

Fig.6 Open Water Efficiency for the Bronze & Propeller 3.

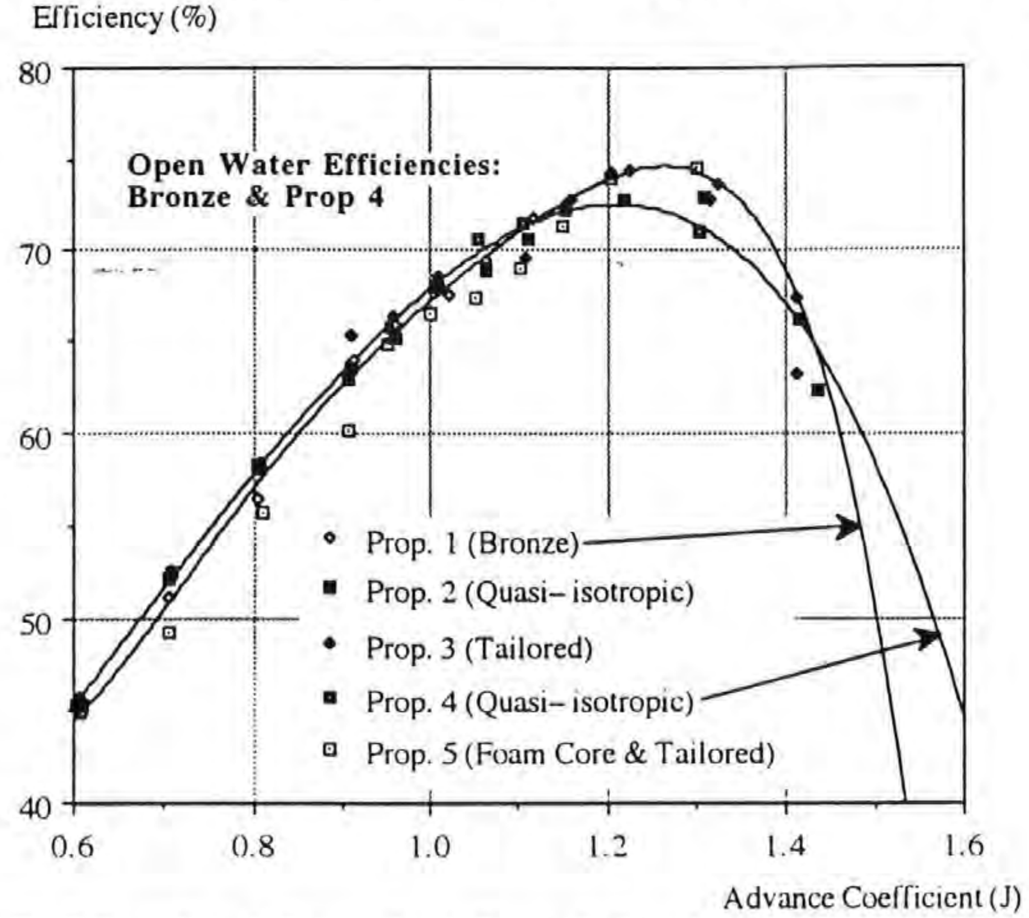

Fig.7 Open Water Efficiency for the Bronze & Propeller 4.

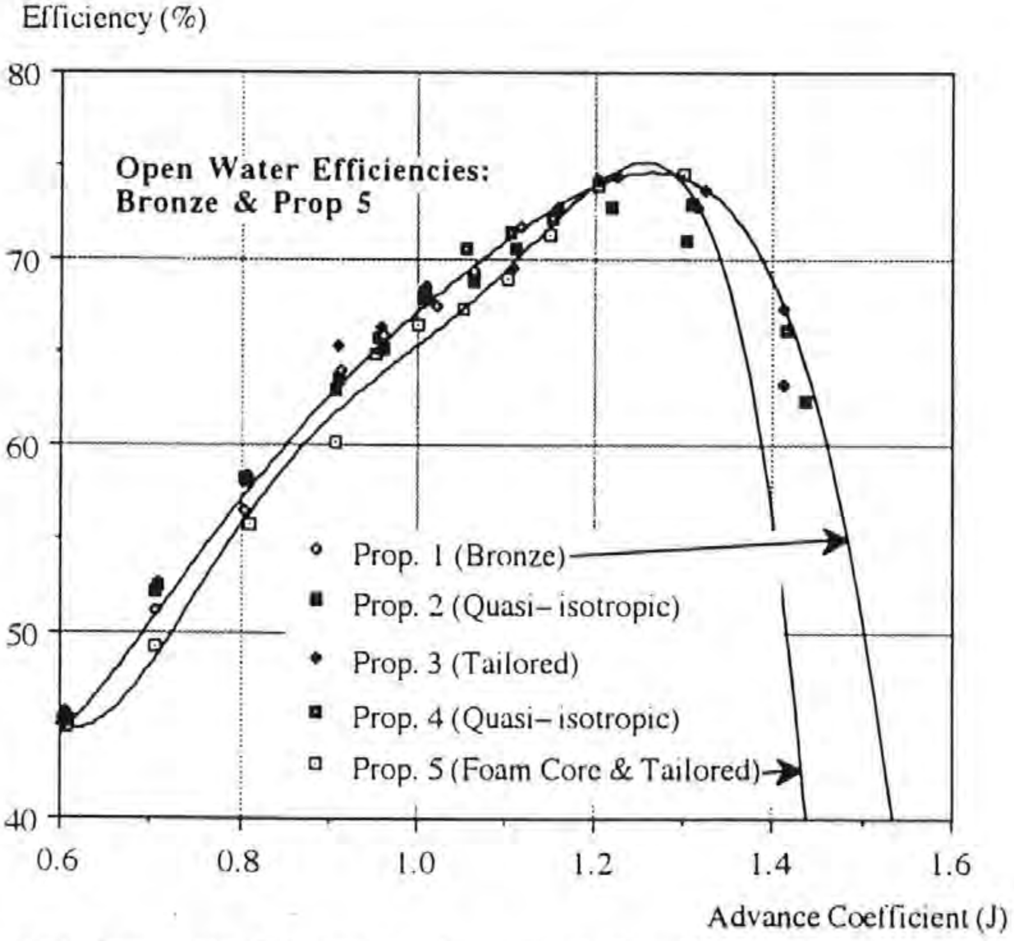

Fig.8 Open Water Efficiency for the Bronze & Propeller 5.

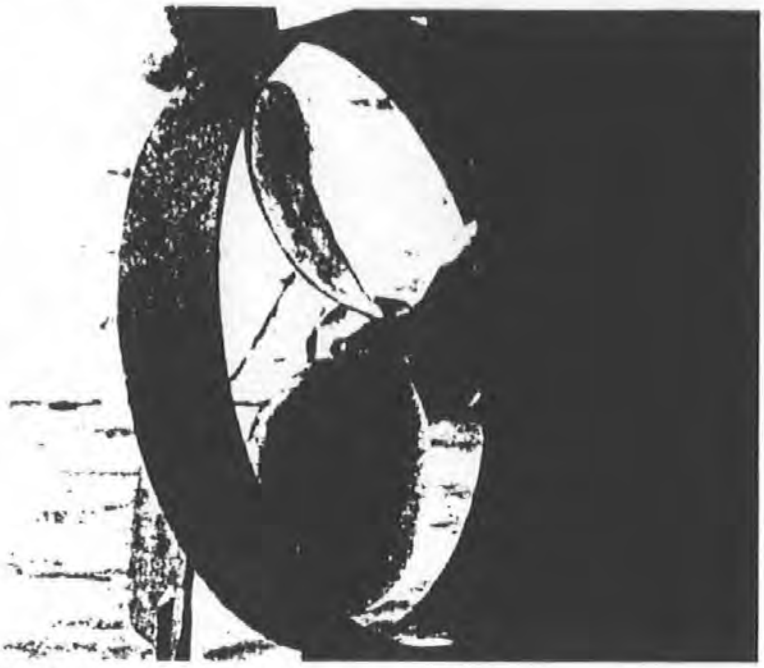

Fig.9 The composite propeller installed

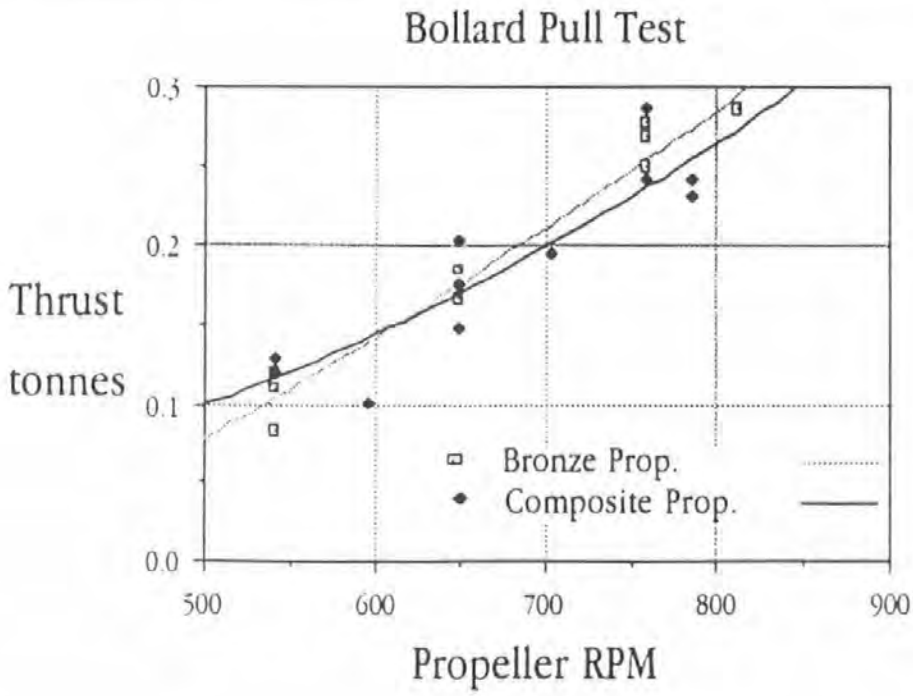

Fig.10 The bollard pull results

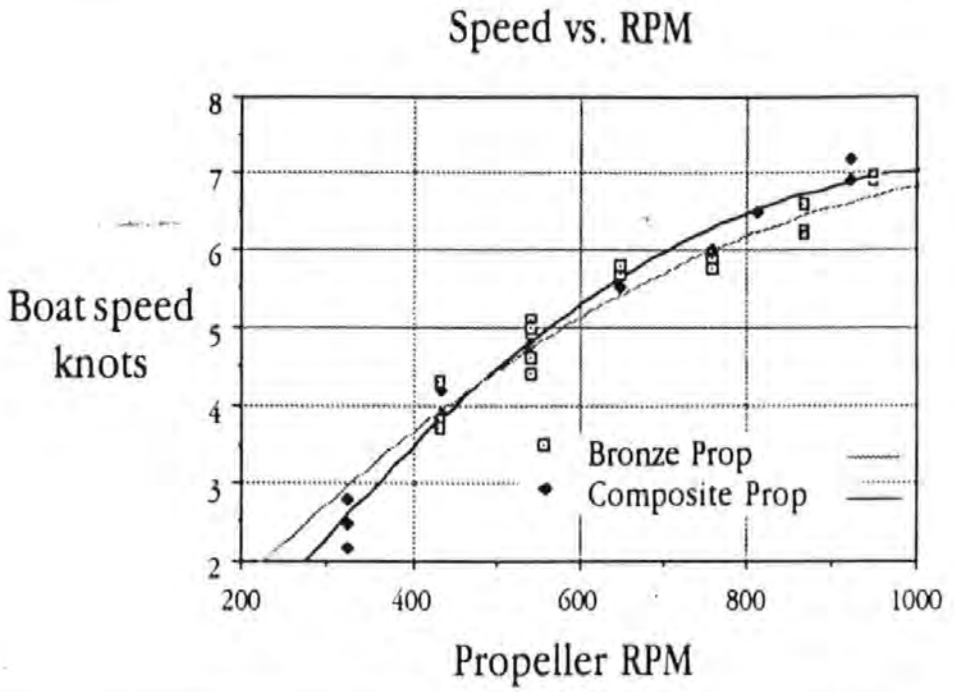

Fig. 11 Speed trial results

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The Composite Advantage

No. 22

Tim Searle, Visitor, **John Chudley**, Visitor, **David Short**, Visitor,
Chris Hodge, Member

ABSTRACT

For some decades the use of fibre reinforced plastic (FRP) composites have been steadily increasing in the marine industry. The synergy of high modulus, high strength fibres and polymer matrices have significant benefits that are discussed briefly in the first part of this paper.

The design of a propeller in a composite material allows for design features not possible with isotropic metals. The effect of being able to tailor propeller blade deformation by appropriate fibre alignment and distribution means the efficiency of the propeller can be improved, as well as a reduction in weight, corrosion and cost of manufacture.

Experience in the manufacture of composite propellers to date has shown resin transfer moulding (RTM) to be a suitable process. The ability to inject the resin into a closed mould where the reinforcing fibres are already in place means the technique is clean, quick and repeatable. When the mould is opened the propeller requires only minimal finishing.

Tank tests and vessel trials have been undertaken to evaluate the performance characteristics of a range of composite propellers. Results are presented in this paper.

NOMENCLATURE

V_a	Speed of advance
σ_{total}	Total stress
σ_T	Stress due to thrust
σ_Q	Stress due to torque
σ_{CBM}	Stress due to centrifugal bending moment
σ_{CF}	Stress due to centrifugal direct stress
$\sigma_\perp$	Stress due to unknown out of plane bending moments
A	Stress section area
Z	Section modulus
θ	Stress section pitch angle
a	Thrust moment arm
b	Torque moment arm
P_s	Engine power
η_m	Shaft efficiency
η_p	Propeller efficiency
B_L	Number of blades
n	Propeller RPM
r_0	Nondimensional radius of stress section
L	Centrifugal bending moment arm
F_c	Centrifugal force

THE MATERIAL ADVANTAGE.

It was estimated that during 1985, 10 000 tonnes of polyester resin was used in the United Kingdom (UK) marine sector alone (1). Some sources have predicted that globally, the use of composites will over take the use of steel by the year 2010 (2). For several decades use of FRP composites in the marine industry has been increasing. The degree of sophistication is variable, depending on the application and cost constraints, also the number of novel applications for composites is increasing. The marine industry presents a varied range of applications that lend themselves to a redesign in a composite material, to gain design, performance and manufacturing advantages over conventional materials.

Composite materials embrace a wide range of materials; for all of them the same definition holds true:

> *The synergy of two or more materials whose combined properties exceed the sum of the individual constituent materials properties.*

The interest of this paper is with continuous fibre polymer composites, where the fibres are the main load bearing component. Generally, these comprise of high strength, high modulus, high aspect ratio fibres, of glass, carbon, or aramid (Kevlar), within a plastic matrix, such as polyester, vinylester, epoxy or phenolic resin. Many applications of these materials are well established, for example, high performance racing yachts or minesweepers. Some more subtle applications are just emerging. The manufacture of boat propellers in composite falls into this latter category.

The important question to ask is, how do composites materials enable better solutions to engineering problems? Compositesoffer the following advantages:

- High specific strengths.
- High specific stiffnesses.
- Low coefficients of thermal expansion.
- Resistance to environmental degradation.
- Possibility of reduced cavitation erosion(3).
- Non catastrophic failure in fatigue.
- High production rates.
- Healthy production environment.
- Ease of producing complex shapes.
- Ease of repair & maintenance.
- Specific material design to the application.
- The ability to tailor the elastic properties.
- A polymer composite material uses about half the energy to manufacture compared to steel or aluminium (4).

Experience has shown that large structures can be successfully constructed from continuous fibre composites. The exploitation of these materials for applications such as wind turbine blades, bridges and varying sizes of boat hulls have demonstrated this. There should be no restriction on the size possible for a propeller.

The longevity of the composite propellers is still to be assessed, however much evidence exists that points favourably to certain advantages with composites. Electrolytic corrosion is often a problem with metal propellers, particularly in a sea water environment where many different metals have to co-exist in the stern area of a ship or boat. An all composite propeller doesn't have this complication.

The life of many propellers is determined by the damaging effect of cavitation upon its surface. Experimental work has shown composites to perform well in cavitating environments and can erode significantly less than metals (3).

A frequent prejudice with composites is their apparent inability to withstand impacts. There is little evidence to support this view. Correctly manufactured composites with low void content and high fibre content have, for many applications such as ballistic panelling and aircraft propeller blades, been shown to be very tough (5). In fact composites offer a more favourable failure mechanism than metals. An impact to a composite will not result in a permanent plastic deformation or a propagating crack, instead a loss of stiffness results and the geometry can remain virtually unchanged. This is more favourable than the plastic deformation associated with metals. Where the possibility for minor chips exists, metal propellers are susceptible anyway, particularly high performance propellers that have delicate edges. Should damage occur to a composite propeller, be it minor scratches and chips or serious de-lamination, then repair is straight forward by bonding in place new fibres and using epoxy based fillers to restore the hydrodynamic shape.

A further prejudice with composites is water absorption. Composites do absorb water, however by the correct choice of materials and sufficient manufacturing quality this problem can be minimised (6).

THE MANUFACTURING ADVANTAGE

As well as the benefits of material properties, the manufacturing advantages are significant to. When the geometry of a component increases in complexity, so it becomes more cost effective to use particular materials. Generally an increase in component complexity, favours the use of composites over metals in terms of manufacturing cost (2). Propellers have inherently complex geometry, so this on its own gives good reason to explore composites for the manufacturing process.

Generally metal propellers are cast in sand, then machined and finished by hand, resulting in a lengthy and labour intensive manufacturing process. For high performance propellers, where a extremely high degree of geometric accuracy is required, then NC machining is employed. The alternative composite process uses a two part female tool, Fig. 1.

Fig.1 A Mould For the Production of Propellers by RTM

The composite mouldings that are produced are geometrically accurate, repeatable and require virtually no subsequent finishing other than trimming a thin flash from the mould split line. Whilst this does require the manufacture of a tool at a greater expense than a sand mould for casting a metal propeller, a number of GRP moulds have been made for this project relatively inexpensively. Although at this stage one off composite propellers have marginal economic feasibility, as the numbers increase in the order of five or six, manufacture rapidly becomes cost effective (7).

Development work to integrate the design and manufacture of tooling to a seamless CAD/CAM process should allow in the near future tooling to be produced at a very much reduced cost. The NC machining required for propellers where the tolerances are strict should be better applied to the production of the mould for one blade. From this the appropriate number of composite blades would be produced which are then joined at the hub.

In order to define and mould accurately the surface of the propeller, a closed mould is required. This limits the process to either compression or RTM.

RTM has been used to date for the following reasons:

- Low void content.
- Good control of properties.
- Repeatable results.
- Flexibility of mould design.
- Reduction in labour & material waste.
- Clean process, handling of dry fibres.
- Good for volume production.
- Good for large components.
- Quick process.
- Tooling cost need not be high.

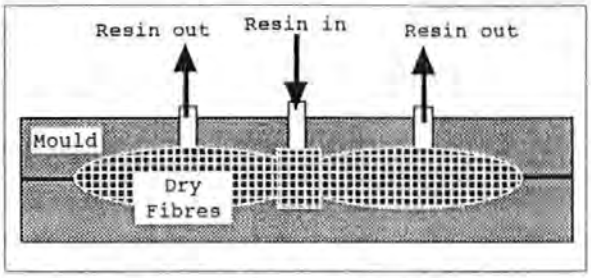

Fig. 2 The RTM Process.

RTM, Fig. 2, has been used to great effect in the production of aircraft propeller blades (8) and many components where high structural performance is required. RTM has been demonstrated successfully in the production of a range of small boat propellers during research at The University of Plymouth.

MANUFACTURE OF A PROTOTYPE COMPOSITE PROPELLER.

In order to achieve high quality mouldings with RTM, it is essential that the processing parameters are correct. This becomes more critical as the fibre volume fraction of the component increases. High volumes of fibre reinforcement have low permeabilities and reduce the ability of the resin to permeate through the fibre pack. Crucial parameters include the following:

- Low resin viscosity.
- Fibre weave style that is conducive to resin flow.
- Accurate tooling.
- Careful loading of fibres.

Resin viscosity is a dominant parameter. This should be low enough to allow quick filling of the mould and thus give greater change of filling completely within a given time. Two poise has been shown to be an appropriate viscosity for high volume fraction laminates, this can be achieved with most epoxies by heating to between 40°C and 50°C. Using viscosities of this order enables mould fill to be significantly quicker than would be achieved using the same resin at room temperature.

Of additional crucial importance, is the fibre architecture. The reliability and uniformity of the mould fill as well as the speed the mould fills depend heavily on to what extent the fibre weave style allows three dimensional flow, Fig. 3. This can be achieved in practice by having spacing between the fibre tows.

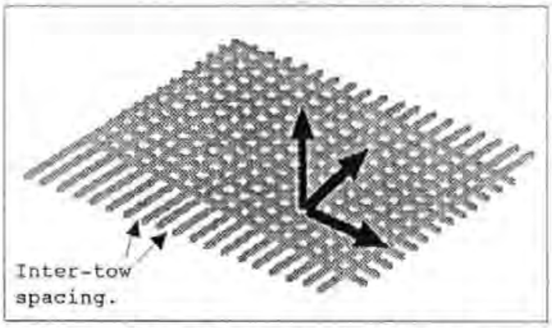

Fig. 3 Three Dimensional Resin Flow.

A comparison between two different fibre weave architectures used in a small experimental mould is shown in Fig. 4. The curves illustrate the fill times. It can be seen that the curve marked (□) shows a significantly longer fill time, also, although not shown here, a much more erratic resin flow front is exhibited by this weave architecture. This material is characterised by poor through thickness permeability.

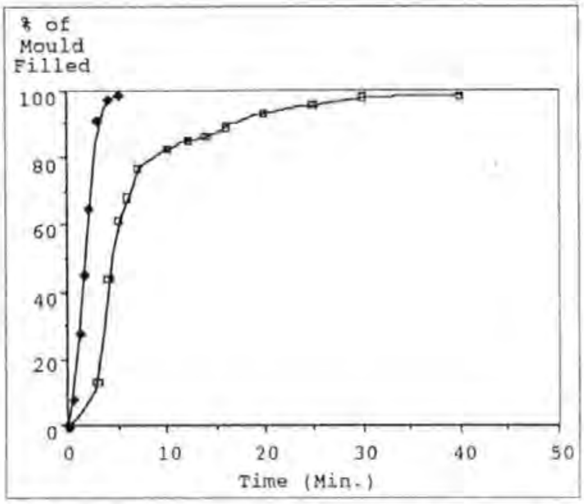

Fig. 4 Fill Times For Two Different Fibre Architectures

Accurate tooling that seals to a vacuum and maintains consistent dimensions of the mould cavity is required. The fibre plies and ply drop offs are defined by the mould dimensions. If either the mould does not close to the same position each time it is used, or the plies are out of position, large changes in the fibre volume fractions can occur. A small error in loading fibres into the mould can lead to a large change in local fibre volume fraction. A sizable increase in local volume fraction may mean dry patches are left. Areas of inconsistent low volume fraction should be avoided as this creates an easy path taking resin past and away from areas of fibre not already permeated by resin. A fibre weave style can greatly assist the process, fabrics that maintain small channels under the pressure of the mould closure, between the fibre tows also increases the reliability of the manufacture.

Loading the fibres into the mould for the propellers manufactured at the University, is assisted by pre-forming with a thermo plastic binder allowing accurate placement. For development purposes glass fibres have been considered the most appropriate, being low cost. These are aligned to absorb the major loads the propeller is subjected to. Therefore the predominant alignment is from the root to the tip, although several tows are placed around the blade edges to absorb local impacts. Typically the volume fraction is about 50%. So far, a manganese bronze tapered bush has been moulded in situ within each propeller. This is to enable a reliable retrofit of the composite propeller to an existing shaft arrangement, Fig. 5.

Fig. 5 Bronze Bush Insert

BLADE LOADING

The initial composite structures for these propellers have been designed to theoretical loads given by treating the propeller blade as a cantilever. Early work on this method was carried out by Taylor at the beginning of the century (9) . For most propeller shapes, those whose blade width is not greater than the blade length (10) and whose geometry is not highly skewed, initial stress analysis by this method has been shown to give good results. To determine the precise stress levels in the blade structure brought about by the geometry, material distribution and externally applied loads, however, it is necessary to produce a finite element model.

For the maximum loading condition, at full speed or bollard pull at greatest RPM, thrust, torque and centrifugal loads are calculated. Since thrust acts perpendicular to the propeller disc and torque acts in plane with the propeller disc, the forces must be resolved for the angle of minimum inertia of the blade. The major loads:

- Bending moment due to thrust.
- Bending moment due to torque.
- Direct load from centrifugal forces.
- Bending moment from centrifugal forces on raked blades.

These apply to propellers that are not highly skewed, when this is the case, a 10% correlation has been shown with measured results (11). The equations to perform these calculations have been written into a computer program. It is not the purpose of this paper to expound this subject further, however the fundamental equations are shown in equations (1-5) (11). These do not give a complete stress picture, but they do give initial figures for design.

$$\text{Stress due to thrust} = \frac{P_{s.}\,\eta_{m.}\,\eta_{p.}\,(a\text{-}r_0)r.\cos\theta}{V_a\,B_{L.}\,Z} \qquad \text{Equation(1)}$$

$$\text{Stress due to torque} = \frac{P_s\,\eta_{m.}\,(b\text{-}r_0)\sin\theta}{2\pi.\,n.\,b.\,B_{L.}\,Z} \qquad \text{Equation(2)}$$

$$\text{Stress due to Centrifugal load (direct)} = \frac{F_c}{A} \qquad \text{Equation(3)}$$

$$\text{Stress due to Centrifugal Bending Moment} = \frac{F_c \times L}{Z} \qquad \text{Equation(4)}$$

$$\text{Stress Total} = \sigma_T + \sigma_Q + \sigma_{CMB} + \sigma_{CF} + \sigma_{\perp} \qquad \text{Equation(5)}$$

THE HYDRODYNAMIC ADVANTAGE.

A new set of variables exists with the introduction of continuous fibre composites, not available in metals. Composites have directional properties (anisotropy). This allows the designer greater freedom to tailor many of the properties within the material. No longer is geometry, (properties being equal), the only structural variable. But with specific alignment and distribution of load bearing fibres, within a given geometric envelope, weight, elasticity, flexural stiffness, failure mode and cost can all be more tightly controlled.

By aligning fibres at different angles, it can be seen from, Fig. 6 that a twist can be introduced in a simple cantilever beam. This principle has been used extensively in the aerospace industry to control the deformation of fixed wing and helicopter blades (12).

This hydro elastic tailoring has immediate application to marine propellers. The option now exists to build a propeller where the pitch can vary in response to the hydrodynamic load upon it. This will create efficiency benefits where cost and space restrict the propeller to a fixed pitch. The efficiency envelope on the Kt Kq chart should widen as the pitch changes to accommodate different operating conditions. The advantage should also exist to have a greater degree of control to the onset of cavitation with propellers that have to operate within this regime.

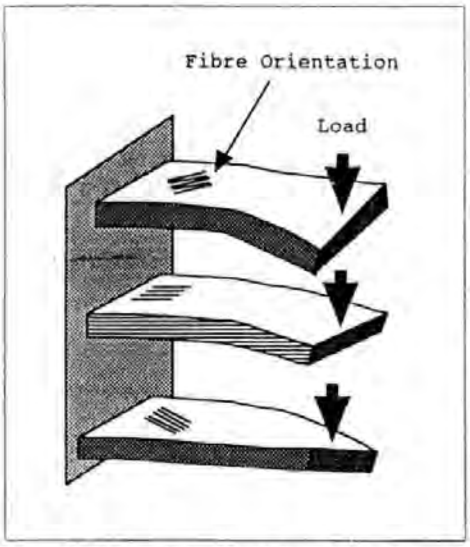

Fig. 6 Differing Elastic Properties for a Cantilever Beam.

TANK TESTING

Although work to design a working hydroelastic propeller is still in its infancy, a number of designs have been successfully tank tested to asses the potential of the concept.

Five propellers, having different elastic properties, were used in an open water towing tank test. Each propeller was tested at a range of different advance coefficients (J) to determine the thrust coefficients (Kt) and torque coefficients (Kq) and hence the open water efficiency. Each propeller was of the design shown in table 1.

Diameter	12 Inches
Pitch	14 Inches
DAR	0.5
No. Blades	3

Table 1.

5 propellers were tested, each with different material properties, summarised in table 2.

Propeller	Material	Fibre Volume Fraction	Fibre Alignment
One	Manganese Bronze		
Two	E-Glass &Epoxy	48 %	Quasi Isotropic
Three	E-Glass &Epoxy	35 %	Tailored so that the pitch backs off under load
Four	E-Glass & Polyester	17 %	Quasi Isotropic
Five	E-Glass & Epoxy Foam core	40 %	Tailored so that the pitch backs off under load

Table 2

- The bronze propeller is included as a "yard stick" by which to measure the composite propellers.

- Propellers 2 & 4 are not tailored to any particular bending characteristic, however they were not as stiff as the bronze propeller.

- Propeller 5 was made with a foam core so that it was considerably more elastic than propeller 3, although both 3 & 5 were designed so that as load is developed on the blade, twist coupled to the bending causes the pitch to back off.

The aim of the open water test was to determine, in an introductory sense, the effect of different blade elasticities on the shape of the efficiency envelope. In allowing the pitch to reduce as the load comes on the blade, greater RPM for a given torque should be possible and therefore greater efficiency, as the pitch remains course for lower loads.

Fig. 7 to Fig. 10 show the results of the open water test, each compared to the bronze, put onto separate charts for clarity. The open water efficiencies have been calculated from the thrust and torque coefficients in the usual manner.

With the exception of the foam sandwich propeller, the composite propellers are all more efficient than the bronze at lower J values and less efficient at the optimum J value. The reverse is true for the foam sandwich propeller which has a smaller width to the efficiency curve.

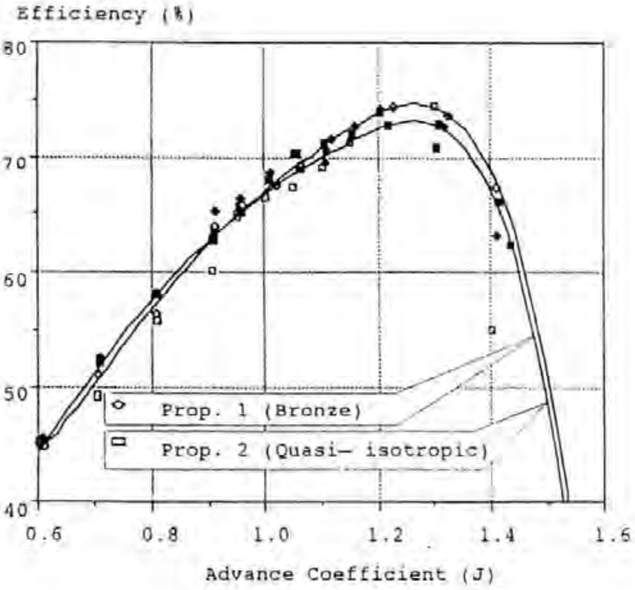

Fig.7 Open Water Efficiencies:Bronze & Prop 2

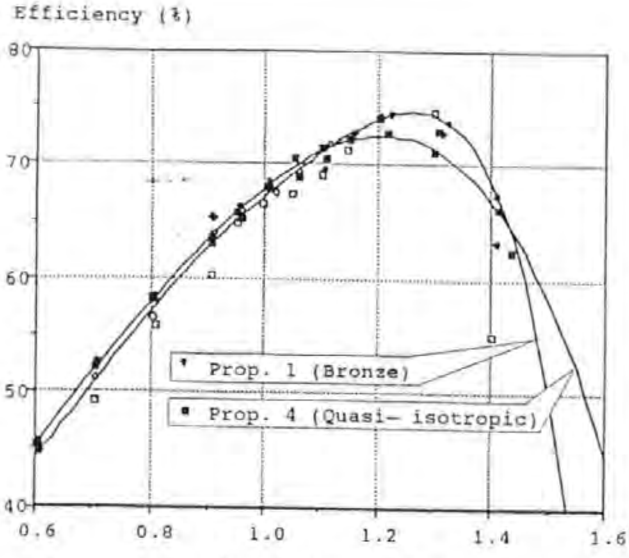

Fig.8 Open Water Efficiencies:Bronze & Prop 3

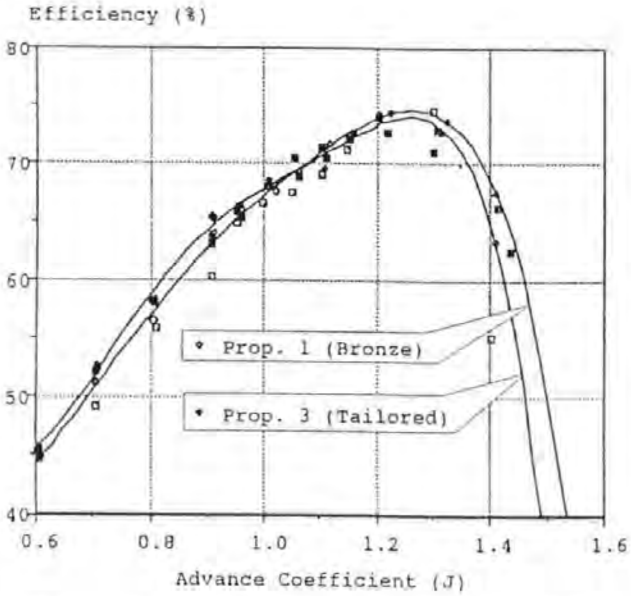

Fig.9 Open Water Efficiencies:Bronze & Prop 4

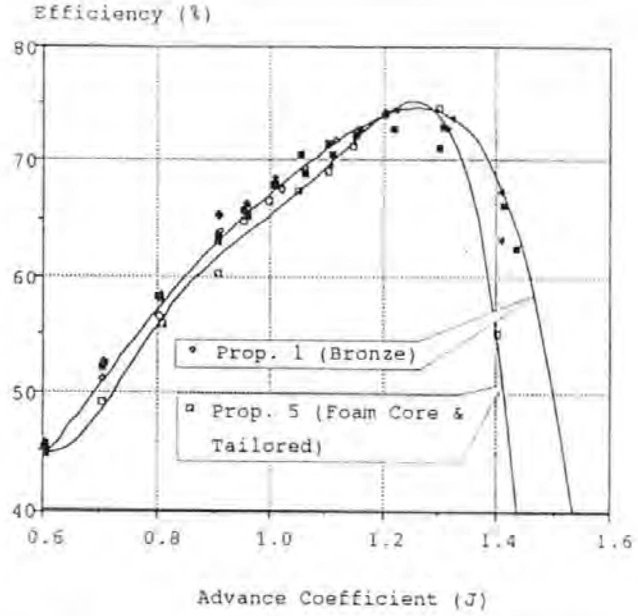

Fig.10 Open Water Efficiencies:Bronze & Prop 5

These results should be taken within the context of their preliminary nature and the scatter on the graphs. However, whilst not conclusive in absolute terms, the indications are, firstly that the composite propellers are as efficient as their manganese bronze counterparts. Secondly, that it is possible to change the shape of the efficiency envelope by altering the elasticity of the material the propeller is manufactured from and this could be made high or low aspect ratio, depending on the application of the vessel.

SEA TRIALS

A boat was used to trial a 0.5m X 0.3m X 3.50 (20" X 12" X 3.50) composite propeller Fig. 11. The vessel was a 7m (23') GRP work boat powered by a 23kw (31hp) continuous or 28kw (38hp) intermittent diesel engine. The maximum engine RPM at top boat speed is 1700 with a gearbox reduction of 1.85 to 1. The main purpose of the boat is safety cover for student recreation. It can carry up to 12 people plus diving equipment.

The aims of using this boat to trial a composite propeller were as follows:

- To check the boss attachment.
- To check the structural integrity of the propeller.
- To measure the thrust from the bollard pull condition for the composite and bronze propellers.
- To measure the speed vs RPM of the boat using the composite and bronze propellers.

A composite propeller was installed early in 1994, Fig. 11 during which time the propeller has remained immersed in the water and has been used regularly. Experiments have been performed to measure the bollard pull and the speed/RPM characteristics of both the composite and bronze propeller, Fig.12 and Fig. 13.

Fig. 11 The Composite Propeller Installed on the Vessel

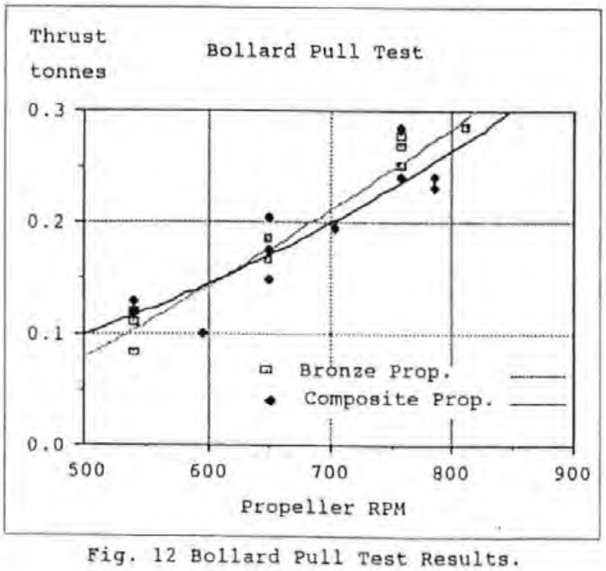

Fig. 12 Bollard Pull Test Results.

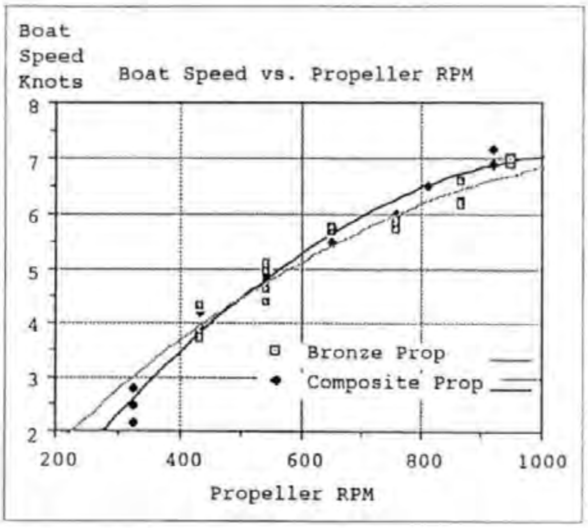

Fig. 13 Speed Test Results

After these tests were performed the propeller was removed for inspection:

- The boss joint showed no signs of degradation.
- During the period of immersion no marine growth occurred.
- One of the leading blade edges had been slightly scuffed, this was probably due to an impact with an underwater object.
- The results indicate, taking into account the scatter on the graphs, that the composite propeller performs the same as the bronze in terms of thrust and propelling the boat at top speed. The longevity with respect to water absorption, impact damage and marine growth is to be confirmed.

CONCLUSIONS & FUTURE WORK

Work reported in this paper is pre-market, however, preliminary studies have indicated that potentially, significant benefits exist by manufacturing marine propellers this way. Future work is beginning to focus in on three diverse areas. Firstly, the economic production of hydroelastic propellers for the domestic market, providing low cost alternative propellers that will give fuel savings for fishing boats, work boats and pleasure craft. Secondly, replacement out board propellers are currently being manufactured. A third area is investigating the design of sophisticated, high performance, high cost, multi part propellers.

The competitive manufacturing process, reduction in weight, the ability to tailor the elastic behaviour and reduced corrosion should give composite propellers a firm sector of the market in the near future.

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Resin transfer moulding of marine products

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1. Summary.

Work has been carried out on three projects all utilising the advantages of composite materials and the cost effective benefits of resin transfer moulding (RTM). A range of composite propellers as an alternative to manganese bronze and nickel aluminium bronze (NAB) propellers, have been manufactured and tested. Secondly outboard motor propellers can suffer abuse because they are often required to operate in shallow waters. Replacing or refurbishing a metal outboard propeller is expensive. The composite alternative offers an extremely cost effective replacement that gives similar performance. Thirdly, NAB propeller support brackets are heavy and costly components to produce, this paper explains how a demonstrator of part of a propeller support bracket has been made which shows significant weight savings as well as considerable potential cost savings.

2. Introduction.

For some years now the members of the Advanced Composites Manufacturing Centre (ACMC) at the University of Plymouth have considered that hydrodynamic surfaces are ideally suited for manufacture in composite materials. Faithful shape reproduction, surface finish, weight reduction and other considerations are put forward later in this paper.

It is considered by ACMC that advantages could be gained by in producing marine propellers, pumps of all types, stabilising vanes, hydrofoils and rudders in composite materials. The work plan has been to carry out projects that would demonstrate to industry that such concepts are feasible.

It has always been an ACMC policy to consider "near" industry projects. The first to be considered in this paper is a small boat propeller. The second addressed the urgent need for a more cost effective way of restoring to use University outboard motor propellers, that had sustained blade damage as a result of student enthusiasm, led to the propeller replacement project. The possibilities of producing a propeller support brackets in composites presented another challenge and is a step forward towards all composite stern gear. This paper presents these tentative steps undertaken by ACMC and the Marine Technology Division of the University of Plymouth.

Experience in the composite industry has shown RTM to be a cost effective route to the manufacture of high performance composite components. Work at ACMC has validated RTM as a successful method for the production of the range of small boat propellers and the propeller support bracket. The ability to use low cost tooling to produce complex geometrical shapes in a safe and healthy environment has been demonstrated to good effect.

Certain benefits inherent with composites have been recognised, these have particular significance to propellers and other marine components.

- Failure mechanisms are not always catastrophic.
- Good corrosion resistance.
- Reduced cavitation erosion damage [ref 1].
- Reduced weight compared with metal components.
- Hydroelastic tailoring.
- Reduced production costs.
- Ease of repair.
- Structural integrity is comparable and often better that metals [ref 2].

3. The composite propeller.

In order to exploit these advantages, several composite propellers have been designed and manufactured. The size of propeller on which much of the initial work has been done is 20 inch diameter, 12 inch pitch, with 3 blades. The design is governed by a number of criteria.

3.1 Propeller blade loading.

The initial composite structures for these propellers have been designed to theoretical loads given by treating the propeller blade as a cantilever. Early work on this method was carried out by Taylor at the beginning of the century [ref 3]. For most propeller shapes, those whose blade width is not greater than the blade length [ref 4] and whose geometry is not highly skewed, initial stress analysis by this method has been shown to give good results, torque loads for this type of propellers have also been shown to be small [ref 5].

For the maximum loading condition, at full speed or bollard pull at greatest RPM, thrust, torque and centrifugal loads can be calculated. Since thrust acts perpendicular to the propeller disc and torque acts in plane with the propeller disc, the forces must be resolved for the angle of minimum inertia of the blade. The major loads can be summarised.

- Bending moment due to thrust.
- Bending moment due to torque.
- Direct load from centrifugal forces.
- Bending moment from centrifugal forces on raked blades.

At present work is being undertaken to validate this model. Instrumentation is being constructed to measure load levels in the propeller on the vessel on which the composite propeller is being used.

3.2 Manufacture.

The selection of an appropriate manufacturing process is a further criteria. The requirement is for a process where components of complex geometry and of good structural integrity can be produced cost effectively. RTM was selected.

In order to achieve high quality mouldings with RTM, it is essential that the processing parameters are correct. This becomes more critical as the fibre volume fraction of the component increases. High volumes of fibre reinforcement have low permeabilities and reduce the ability of the resin to permeate through the fibre pack. Crucial parameters include the following.

- Correct resin viscosity.
- Fibre weave style that is conducive to resin flow.
- Accurate tooling.
- Careful loading of fibres.

Resin viscosity is a dominant parameter. This should be low enough to allow quick filling of the mould and thus give greater chance of filling completely within a given time. Two poise has been shown to be an appropriate viscosity for high volume fraction laminates, this can be achieved with epoxies by raising the temperature.

Also of crucial importance, is the fibre architecture. The reliability and uniformity of the mould fill, as well as the speed the mould fills, depend heavily on what extent the fibre weave style allows three dimensional flow, figure 1.

Figure 1. Three dimensional resin flow.

This can be achieved in practice by having small channels between the fibre tows often built into the fibre weave.

A comparison between two different fibre weave architectures at the same volume fraction used in a small experimental mould is shown in figure 2. The curves illustrate the fill times. It can be seen that the curve marked □, shows a significantly longer fill time, also, although not shown here, a much more erratic resin flow front is exhibited by this weave architecture. This material is characterised by poor through thickness permeability.

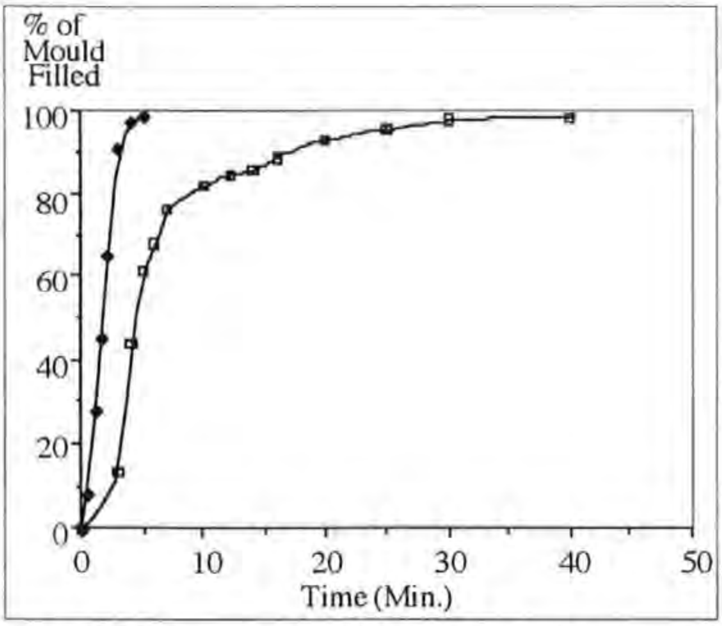

Figure 2. Fill times for two different fibre architectures in a small test mould

Well made, accurate tooling that seals, maintains a vacuum and consistent dimensions of the mould cavity is essential. If either the mould does not close to the same position each time it is used, or the plies are not accurately positioned in the mould, large changes in the fibre volume fractions can occur. A small error in loading fibres into the mould can lead to a large change in local fibre volume fraction. A sizable increase in local volume fraction can lead to dry patches. Areas of inconsistent low volume fraction should be avoided as this creates an easy path taking resin past and away from areas of fibre not already permeated by resin, giving lack of wetting of the fibres, voids and shrinkage defects in the resin rich areas.

Loading the fibres into the mould for the propellers manufactured at the University, is assisted by pre–forming with a thermo plastic binder allowing accurate placement. For development purposes glass fibres have been considered the most appropriate reinforcement on the grounds of cost. These are aligned to absorb the major loads the propeller is subjected to. Therefore the predominant alignment is from the root to the tip, although several tows are placed around the blade edges to absorb local impacts.

3.3 Retro fitting.

For initial trials work a retrofit of the composite propeller was required to allow straight forward instalment to the test vessel. A manganese bronze tapered bush has been moulded in situ within each propeller. This has enabled reliable attachment of the composite propeller to the existing shaft arrangement, figure 3. Future work is to look at alternative attachment methods.

4. Evaluation and running experience.

Having carried out the manufacture, an ongoing programme of testing has been initiated. Bollard pull, top speed and open water tank tests have confirmed the hydrodynamic performance of the composite propeller to be the same as the equivalent metal one, with potential for an improvement. However the test that is considered to be of the most critical importance at this stage is the longevity.

Figure 3. Bronze bush insert

Figure 4. 20 inch diameter composite propeller installed on a 23 foot motor vessel

The following list summarises the practical experience to date:

- Installed on the vessel for 6 months
- During this time the propeller has remained immersed in sea water and has only come out of the water for inspection and routine boat maintenance.
- Total running time accumulated is 150 hours
- A rope and a thick electrical cable have become entangled around the propeller causing no significant damage.
- Fouling on the blade is no more than would be expected for a comparable composite boat hull, this is to be addressed shortly with an anti–fouling additive to the propeller surface.
- A 75% weight saving has been shown over the metal propeller. Figure 4 shows the propeller installed.

5. The outboard propeller.

Mention has already been made of the need to find an effective solution for replacing damaged out board motor propellers. Traditional alternatives to metal outboard propellers have usually been made from injection moulded short fibre filled thermo plastics. A number of these are on the market, some offering the possibility of replacing individual blades should damage occur.

A different approach has been demonstrated by the ACMC project. RTM has been used to produce continuous fibre,high volume fraction, blade sets. Existing metal hubs have been used with the old blades machined off. The new composite blades are designed to fit over the old, modified, metal hub, figure 5.

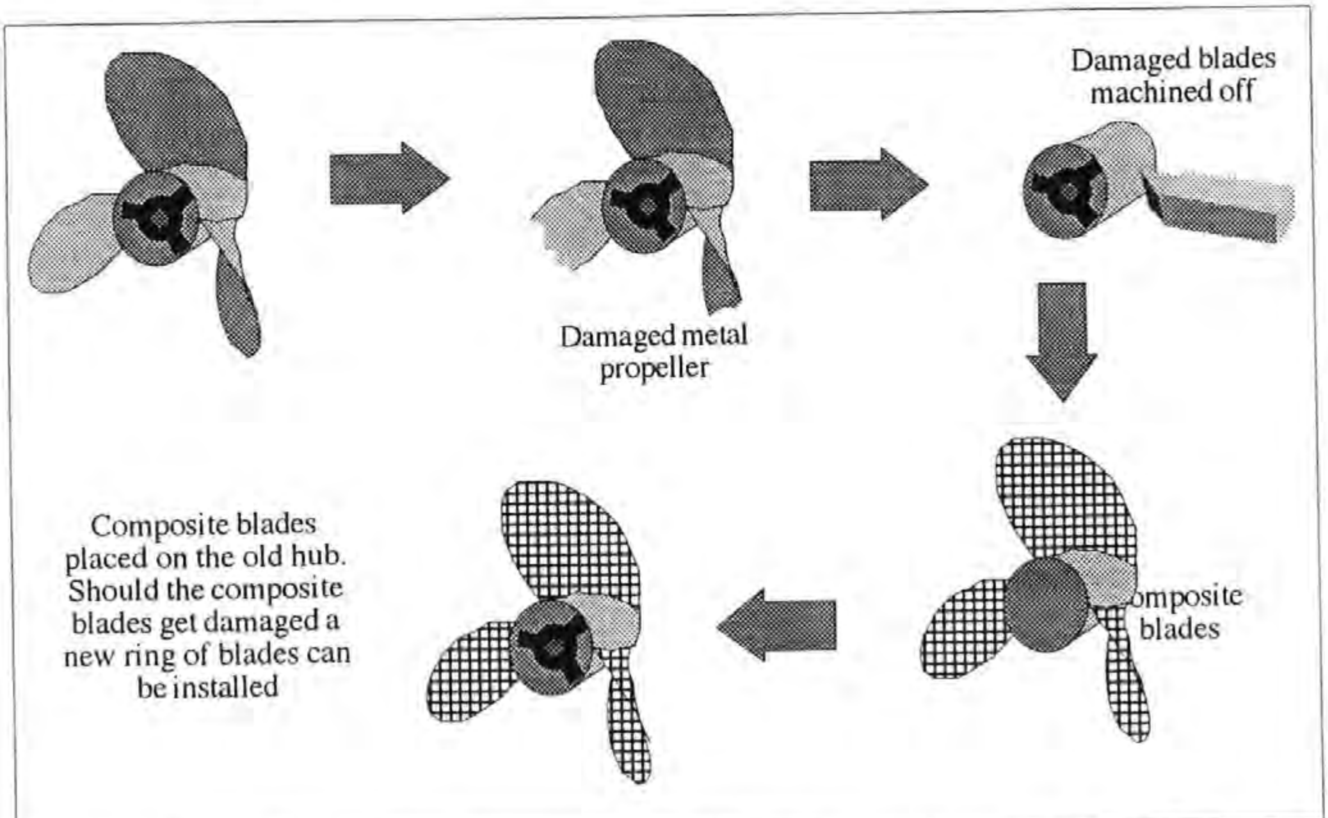

Figure 5. The alternative composite blades slide over the existing, modified metal hub.

Figure 6. The composite outboard propeller

Any minor damage to the composite blades can be repaired by the layman with a simple kit of epoxy fillers. Major damage which is common with careless and enthusiastic use can be rectified by replacing the low cost blades but keeping the metal hub. Typically an 11 inch diameter aluminium propeller costs in the region of £100 to buy and £60 for reconditioning.

Careful control of the fibre loading and resin injection has enabled reliable and repeatable blades sets to be produced. Low cost RTM tooling has enabled an economical alternative to aluminium or stainless steel more commonly found in the production of outboard propellers.

Successful tests have been performed with the composite replacement outboard propeller on a 13 foot Delquay Dory powered by a 40 horse power engine. Initial subjective opinions on the performance of the propeller by personnel who use the boats regularly were very favourable. Figure 6 shows the finished article.

5. Propeller support brackets.

Support brackets for propeller shaft bearings are currently produced from NAB or manganese bronze. Brackets made from these materials do achieve their intended design purpose, however, problems have been recognised in the areas of weight, cost of production, corrosion protection and attachment to the hull.

In order to investigate an alternative composite bracket a RTM tool was constructed so that part of an "A" bracket for a fast high performance planning boat could be produced. The part component chosen was one leg of the "A" bracket that attaches to the hull. This was considered to be representative of the difficult part to manufacture and the most highly loaded part of the structure.

4 brackets were produced from the following materials:

- Continuous random mat/epoxy
- E glass/epoxy
- E glass & carbon/epoxy
- E glass & foam/epoxy

Volume fractions likely to be required for the structural strength were achieved with each layup. Figure 7 shows the glass/carbon bracket. Having successfully manufactured 4 brackets, observations were made, based on the following experimental analysis.

Figure 7. The glass propeller support bracket demonstrator (without the bearing)

5.1 Weight saving.

Significant weight savings were achieved, as can be seen in table 1.

Steel Bracket	17.8 kg	(calculated equivalent weight)
NAB	19.7 kg	(calculated equivalent weight)
Carbon/E–glass	3.6 kg	–
E–glass	3.8 kg	–
E–glass/foam core	2.6 kg	–

Table 1. Bracket weights.

5.2 Structural deformation.

The demonstrators, when subjected to a static cantilever test did not fail in a catastrophic way. As the load increased, so did the deformation. However at significant deformations large loads were still carried by the bracket structure. This indicates that the composite bracket is unlikely to fail in a catastrophic way as is often experienced with a metal bracket, by cracking at the junction of the pad with the foil with a loss of load carrying ability and probably propulsion. A non catastrophic failure of the composite bracket, with the only degradation of the structure being a reduction in stiffness, should secure the operational capability of the bracket in a "get you home" situation.

5.3 Stiffness and resonant frequency.

The ability to vary the resonant frequency of the brackets with identical geometry, by altering the material stiffness is possible. In the case of this application, it should be possible to reduce the effect of propeller induced vibration to both the bracket and the hull. Figure 8 shows the different resonant frequencies, of identical size and shaped brackets with different internal fibre construction.

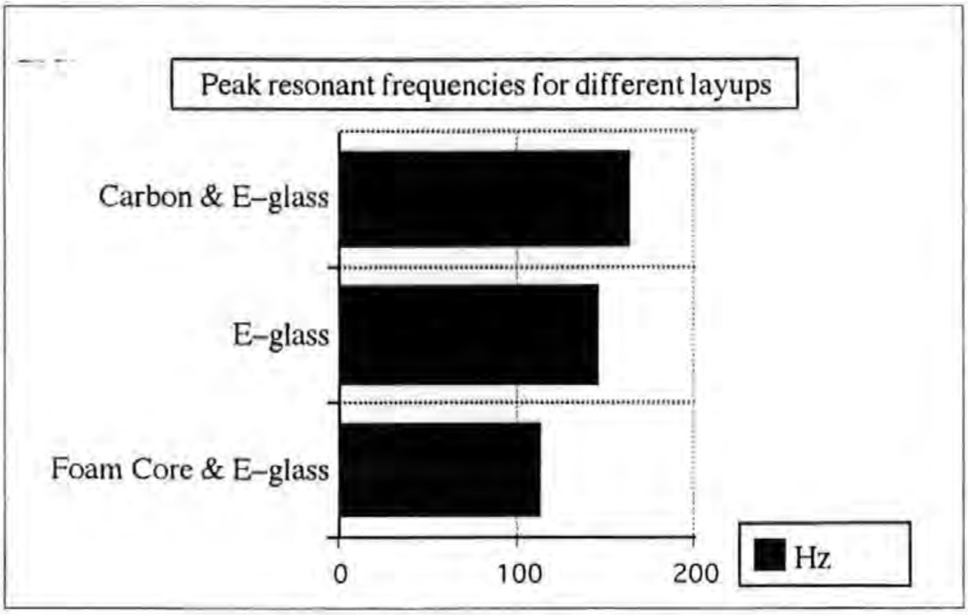

Figure 8. Resonant frequencies.

5.4 Specific Strength.

Table 2 gives the specific strengths for the composite brackets, found from a bending test together with the theoretical (and over estimated) specific strengths for the metal brackets.

Material	Failure load [N]	Density [gcc-1]	Specific Strength
Foam Core +E–glass	2100	1.16	1810
E–Glass	6000	1.7	3529
Carbon/ E–glass	7000	1.61	4350
NAB	16020	8.7	1841
Steel (AH36)	23210	7.85	2956

Table 2. Specific strengths.

6. Conclusions.

This paper has presented two propeller designs and part of a propeller support bracket made from high volume fraction continuous fibre composite by RTM. Experience at ACMC has shown that these components go a long way towards addressing many of the problems associated with high tolerance metallic items manufactured for the marine environment. The full potential of using composite materials will be realised when the whole of the stern gear is designed and built.

The indications from these projects are that composites are capable of being manufactured by cost effective processes, giving low weight and comparable performance to their conventional metal counter parts that is worthy of further development and investigation.

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Manufacturing of Marine Propellers in Composite Materials

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ABSTRACT

The benefits of continuous fibre polymer composites are significant for the application of a marine propeller. Some of these advantages are discussed in the first part of this paper. Resin transfer moulding (RTM) has been used exclusively in the production of the prototype propellers. It is a cost effective process that enables high quality repeatable laminates. However, in order to be successful with RTM many of the processing parameters need to be carefully controlled. To this end experimentation is reported that has enabled the most significant parameters to be defined.

The evaluation of a number of prototype composite propellers by sea trials has been a major focus of this project. Testing over a period of 9 months has yielded important running experience that is reported at the end of this paper.

1. INTRODUCTION

The important question to ask is, how do composites materials enable better solutions to engineering problems? Composites offer the following advantages:

- high specific strengths;
- high specific stiffness;
- low coefficients of thermal expansion;
- resistance to environmental degradation;
- possibility of reduced cavitation erosion [1];
- non catastrophic failure in fatigue;
- high production rates;
- healthy production environment;
- ease of producing complex shapes;
- ease of repair and maintenance;
- specific material design for the application;
- the ability to tailor the elastic properties;
- a polymer composite material uses about half the energy to manufacture compared to steel or aluminium [2].

Experience has shown that large structures can be successfully constructed from continuous fibre composites. The exploitation of these materials for applications such as wind turbine blades, bridges and varying sizes of boat hulls have demonstrated this. There should be no restriction on the size possible for a propeller.

The longevity of composite propellers is still to be assessed; however, much evidence exists that points favourably to certain advantages with composites. Electrolytic corrosion is often a problem with metal propellers, particularly in a sea water environment where many different metals have to co–exist in the stern area of a ship or boat. An all composite propeller does not have this complication.

The life of many propellers is determined by the damaging effect of cavitation upon its surface. Experimental work has shown composites to perform well in cavitating environments and can erode significantly less than metals [1].

A frequent prejudice with composites is their apparent inability to withstand impacts. There is little evidence to support this view. Correctly manufactured composites with low void content and high fibre content have, for many applications such as ballistic panels and aircraft propeller blades, been shown to be very tough [3]. In fact composites offer a more favourable failure mechanism than metals. An impact to a composite will not result in a permanent plastic deformation or a propagating crack, instead a loss of stiffness results and the geometry can remain virtually unchanged. This is more favourable than the plastic deformation associated with metals. Where the possibility for minor chips exists, metal propellers are susceptible also, particularly high performance propellers that have delicate edges. Should damage occur to a composite propeller, be it minor scratches and chips or serious de–lamination, then repair is straight forward by bonding in place new fibres and using epoxy based fillers to restore the hydrodynamic shape.

A further prejudice with composites is water absorption. Composites do absorb water, however by the correct choice of materials and sufficient manufacturing quality this problem can be minimised [4].

2. MANUFACTURE

As well as the benefits of material properties, the manufacturing advantages are also significant. When the geometry of a component increases in complexity, so it becomes more cost effective to use particular materials. Generally an increase in component complexity favours the use of composites over metals in terms of manufacturing cost [5]. Propellers have inherently complex geometry, so this on its own gives good reason to explore composites for the manufacturing process.

Generally metal propellers are cast in sand, then machined and finished by hand, resulting in a lengthy and labour intensive manufacturing process. For high performance propellers, where a extremely high degree of geometric accuracy is required, then NC machining is employed. The alternative composite process uses a two part female tool (Figure 1).

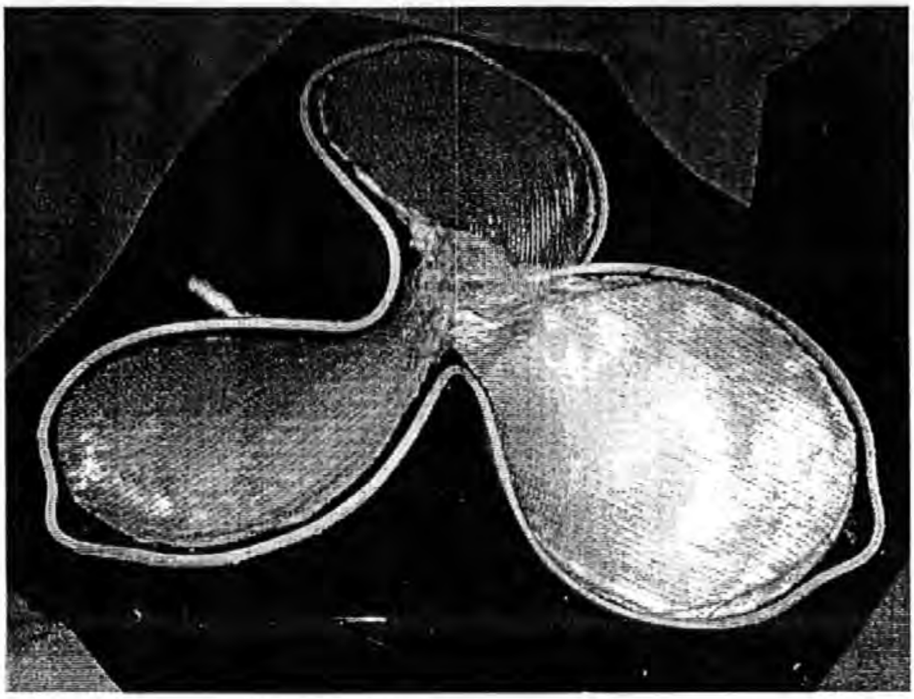

Figure 1. A Mould For the Production of Propellers by RTM

The composite mouldings that are produced are geometrically accurate, repeatable and require virtually no subsequent finishing other than trimming a thin flash from the mould split line. Whilst this does require the manufacture of a tool at a greater expense than a sand mould for casting a metal propeller, a number of GRP moulds have been made for this project relatively inexpensively. Although at this stage one off composite propellers have marginal economic feasibility, as the numbers increase in the order of five or six, manufacture rapidly becomes cost effective [6].

Development work to integrate the design and manufacture of tooling to a seamless CAD/CAM process should allow in the near future tooling to be produced at a very much reduced cost. The NC machining required for propellers, where the tolerances are strict, should be better applied to the production of the mould for one blade. From this the appropriate number of composite blades would be produced which are then joined at the hub.

In order to define and mould accurately the surface of the propeller, a closed mould is required. This limits the process to either compression or RTM. RTM has been used to date for the following reasons:

- low void content;
- good control of properties;
- repeatable results;
- flexibility of mould design;
- reduction in labour and material waste;
- clean process, handling of dry fibres;
- good for volume production;
- good for large components;

- quick process;
- tooling cost need not be high.

3. EXPERIMENTATION

3.1 Processing Parameters and Fibre Lay-up.

In order to achieve high quality mouldings with RTM, it is essential that the processing parameters are correct. This becomes more critical as the fibre volume fraction of the component increases. High volumes of fibre reinforcement have low permeabilities and reduce the ability of the resin to permeate through the fibre pack. Crucial parameters include the following:

- correct resin viscosity;
- fibre weave style that is conducive to resin flow;
- accurate tooling;
- careful loading of fibres.

Well made, accurate tooling that seals, maintains a vacuum and consistent dimensions of the mould cavity is essential. If either the mould does not close to the same position each time it is used, or the plies are not accurately positioned in the mould, large changes in the fibre volume fractions can occur. A small error in loading fibres into the mould can lead to a large change in local fibre volume fraction. A sizable increase in local volume fraction can lead to dry patches. Areas of inconsistent low volume fraction should be avoided as this creates an easy path taking resin past and away from areas of fibre not already permeated by resin, giving lack of wetting of the fibres, voids and shrinkage defects in the resin rich areas.

Loading the fibres into the mould for the propellers manufactured at the University is assisted by pre–forming with a thermoplastic binder allowing accurate placement. For development purposes glass fibres have been considered the most appropriate reinforcement on the grounds of cost. These are aligned to absorb the major loads the propeller is subjected to. Therefore the predominant alignment is from the root to the tip, although several tows are placed around the blade edges to absorb local impacts.

3.2 Equipment and Experimental Procedure.

In order to carry out the experimentation, a RTM mould tool was produced that enabled small wedge shaped test specimens to be produced. This shape was chosen as its tapered wedge section is in some respects similar to a propeller blade. As a consistent number of plies were placed throughout the tool, a wedge specimen of variable fibre volume fraction was produced. The mould was substantially built so that any distortion of the mould during resin injection was insignificant. A straight edge was placed across the top surface of the tool on a number of occasions, there was no detectable distortion.

The experimental aim was to attempt to measure some of the effects of varying the resin viscosity, the fibre architecture and the fibre volume fraction. The later was conveniently varied by the wedge shape geometry of the test mould between 0.3 and 0.65 in each experiment.

The dimensions of the tool were chosen so that for the two different fabric types under consideration, of different areal weights the same volume fractions could be achieved. These were 200mm by 130mm. Table 1 gives details of the two fabric types used.

Fabric	**Fibre Orientation**	**Areal Wt. gm^{-2}**	**No. of Plies per Plate**	**Volume Fraction**	**Fibre Type**
Fabric A	Quadraxial	2200	4	30-65%	E Glass
Fabric B	Biaxial	1458	6	30-65%	E / R Glass

Table 1. Fabrics used for the experimentation.

Epoxy resin was injected into the mould tool at low pressure through an injection port at the centre of the tool. One outlet port was placed at either end of the tool. The mould was made from Perspex so the resin flow fronts were easily seen and were recorded at given times. Figures 2 to 5 show four experimental results with the fibre volume fractions indicated.

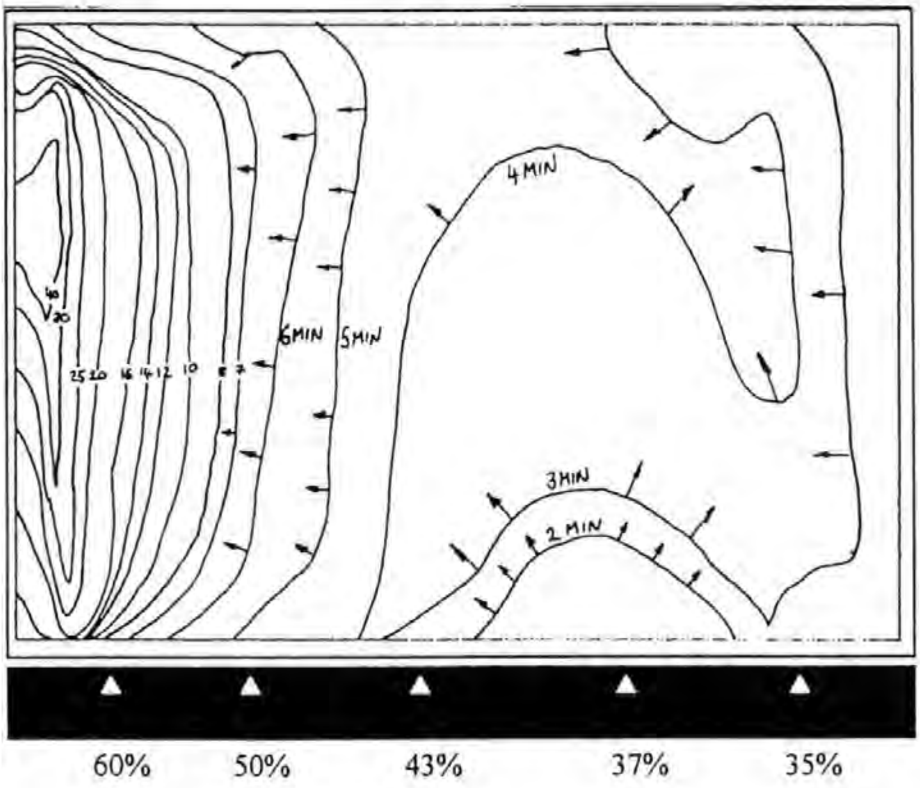

Figure 2. Experiment 5, fabric A, 1 bar injection pressure at 14 °C.

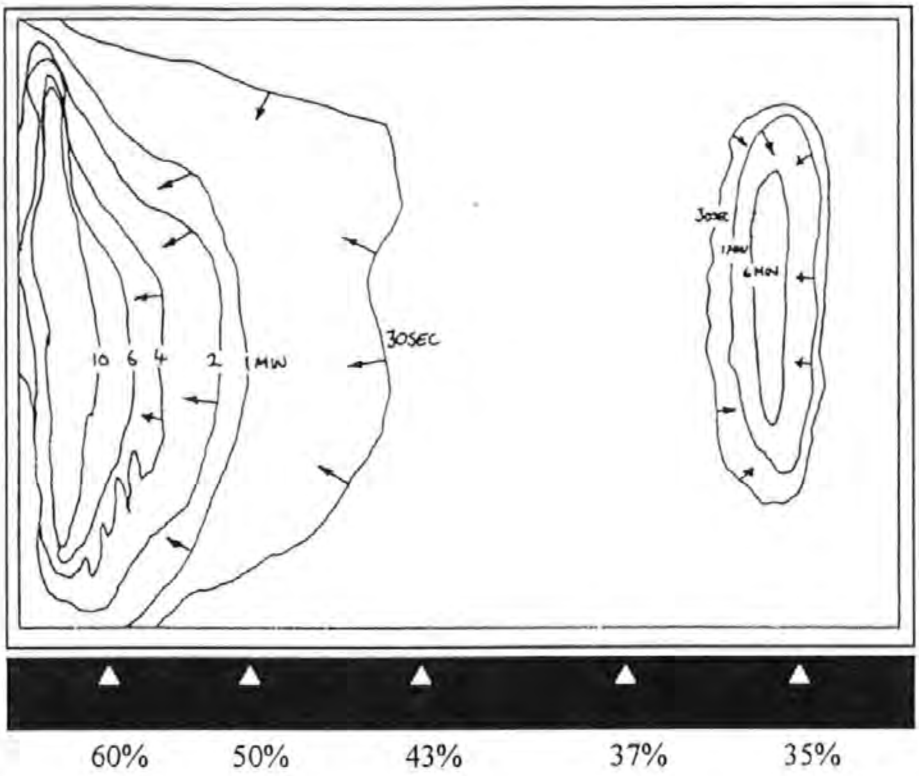

Figure 3. Experiment 7, fabric A, 1 bar injection pressure at 24 °C.

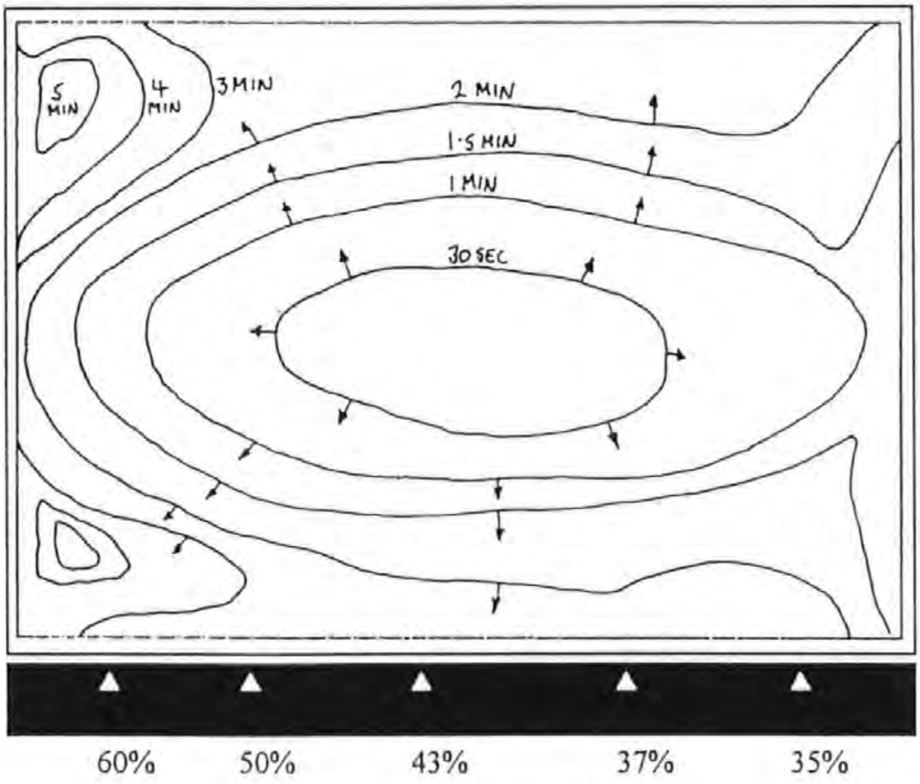

Figure 4. Experiment 9, fabric B, 1 bar injection pressure at 14 °C.

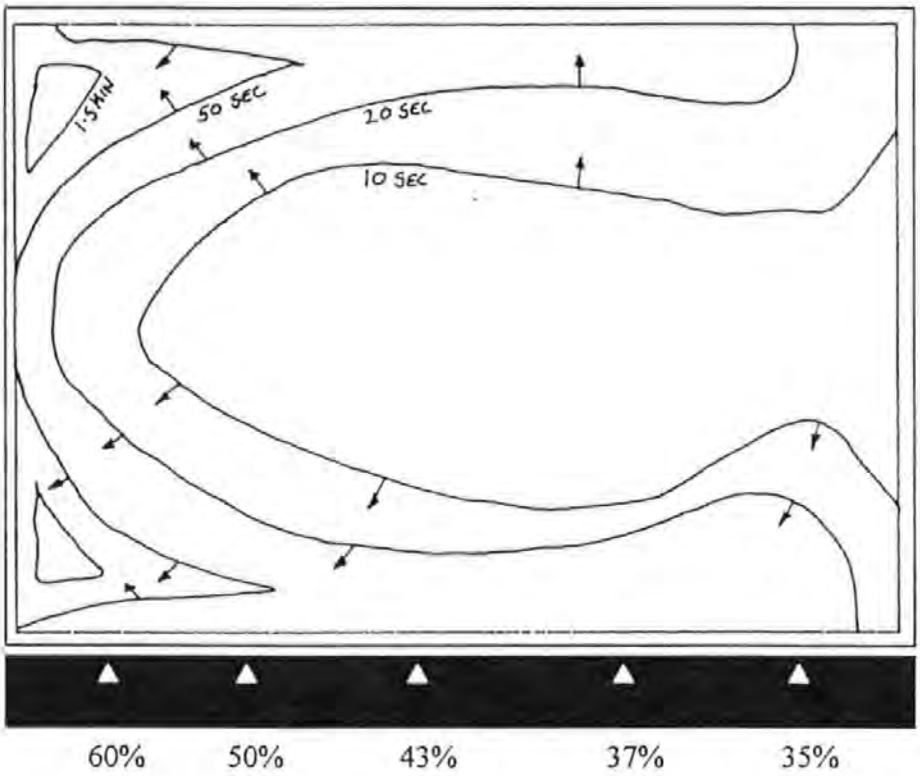

Figure 5. Experiment 11, fabric B, 1 bar injection pressure at 24 °C.

3.3 Analysis of the Results.

Twelve experiments were carried out. In order to express graphically the information shown by the previous four figures, a planimeter was used to measure the areas represented by each flow front. It was assumed at this stage that since the plates were thin, (between 4.5 and 8 mm), the areas measured were representative of the volumes occupied by the resin. From these areas the following three graphs, figures 6 to 8, are shown.

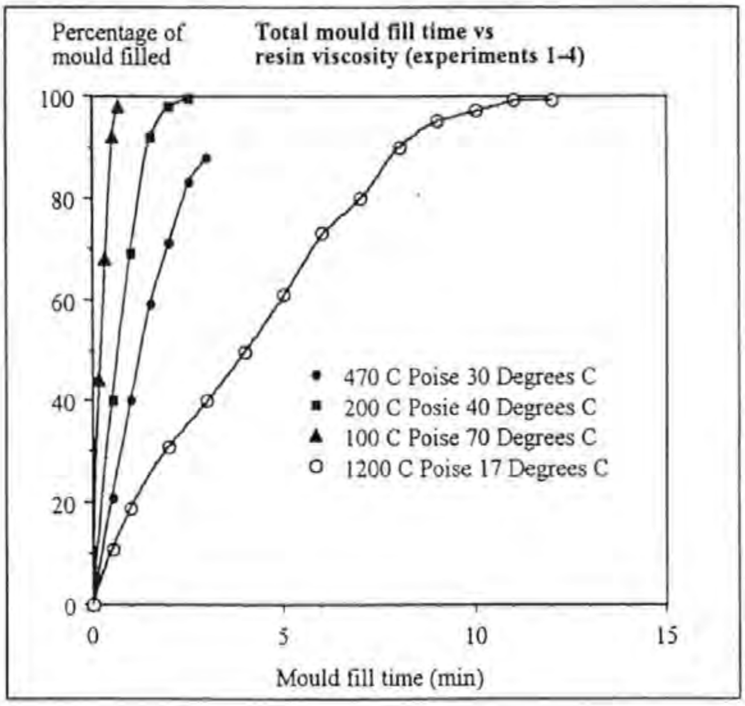

Figure 6. Total mould fill times vs. resin viscosity(fabric B).

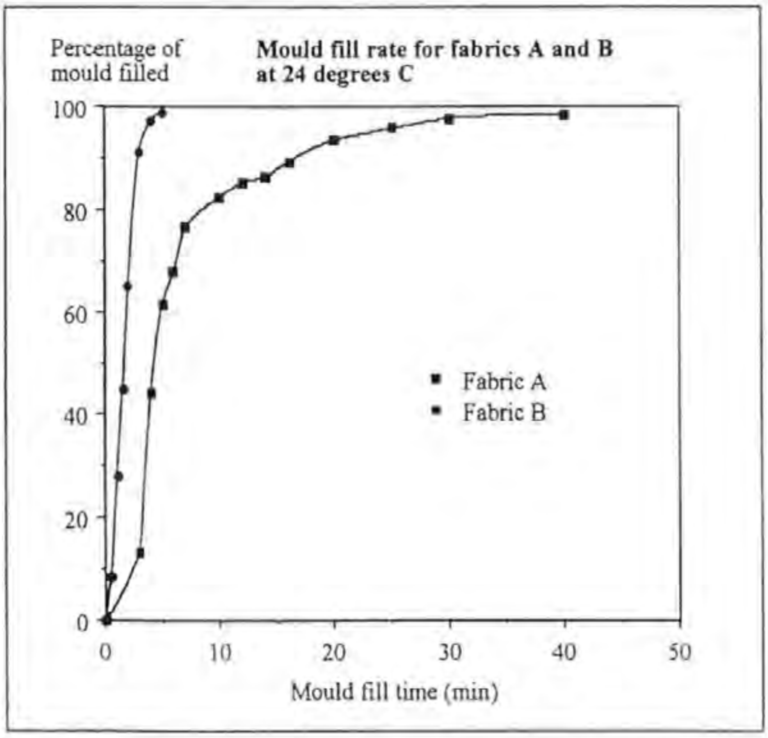

Figure 7. Total mould fill time for fabric A and B.

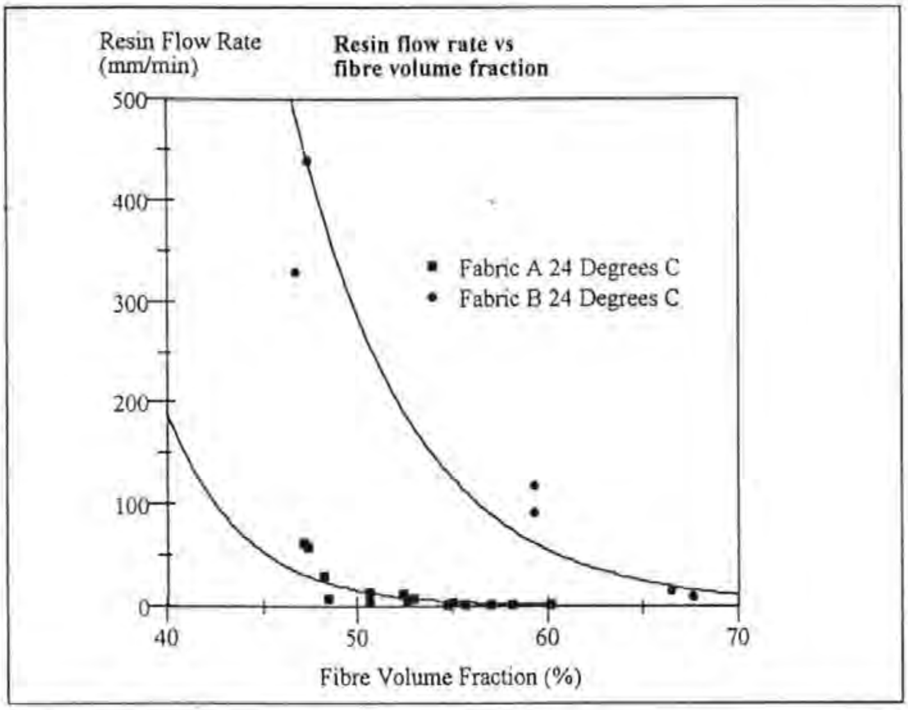

Figure 8. Resin flow velocity for fabric A and B

3.4 Discussion

Figure 5 shows how fill time varies with resin temperature. Since the relationship between temperature and viscosity is not linear it can be seen that the most significant increases in injection time occur at lower temperatures. This has implications for production purposes, as the required moulding temperature increases, so the cost of tooling and processing also increases. However, this experiment shows how, for example, an increase from 20 to 30 °C speeds up injection significantly, however, the jump from 40 to 50 °C has a smaller effect and may not be worth the extra cost. It can be seen that an increase in resin temperature from 17 °C to 40 °C exhibits a 75% reduction in injection time from 10 minutes to 2.5 minutes.

Figure 6 demonstrates the very significant difference in resin injection time brought about by the different architectures of fabrics A and B. At 24 °C, fabric B is filled in approximately 2 minutes and fabric A in approximately 12 minutes, giving a 6 fold increase in fill time. Thus it is shown how much more conducive to resin flow is the fibre architecture of fabric B, at the same volume fraction.

Fabric B is characterised by good inter-tow spacing in both of the 0/90 degree non crimp fibre plies. This inter-tow spacing does reduce as the fabric is compressed in the mould, although the spaces do remain. Generally the inter tow spacing is approximately 10% of the tow diameter (uncompressed). Fabric A on the other hand is made up of 4 layers of non crimp fibres plies, only one of these layers has good inter-tow spacing and slow capillary flow dominates, which is only adequate to fill individual tows once the resin has arrived at that point. A by product of the arrangement of fibres in fabric B is that consistent 3 dimensional resin flow is possible, this is also a contributory factor in enabling quick uniform flow of resin into the mould.

Although difficult to quantify, the erratic nature of the flow front exhibited by fabric A can be seen in figures 2 to 5. (This was mainly brought about because of the poor 3D flow properties of this material.) With fabric B, as soon as the injection was started, resin flowed quickly through the thickness of the fibre pack. However this was not the case with fabric A.

4. EVALUATION AND RUNNING EXPERIENCE

Having carried out the manufacture, an ongoing programme of testing has been initiated. Bollard pull, top speed and open water tank tests have confirmed the hydrodynamic performance of the composite propeller to be the same as the equivalent metal one, with potential for an improvement. However, the test that is considered to be of the most critical importance at this stage is the longevity.

The following list summarises the practical experience to date:

- installed on the vessel for 6 months;
- during this time the propeller has remained immersed in sea water and has only come out of the water for inspection and routine boat maintenance;
- total running time accumulated is 150 hours;
- a rope and a thick electrical cable have become entangled around the propeller causing no significant damage;
- fouling on the blade is no more than would be expected for a comparable composite boat hull, this is to be addressed shortly with an anti–fouling additive to the propeller surface;
- a 75% weight saving has been shown over the metal propeller.

6. CONCLUSIONS AND FUTURE WORK

Work reported in this paper is pre–market, however, preliminary studies have indicated that potentially, significant benefits exist by manufacturing marine propellers this way. Future work is beginning to focus in on three diverse areas.

- The economic production of hydroelastic propellers for the domestic market, providing low cost alternative propellers that will give fuel savings for fishing boats, work boats and pleasure craft.
- Replacement outboard propellers are currently being manufactured.
- Investigating the design of sophisticated, high performance, high cost, multi part propellers.

The competitive manufacturing process, reduction in weight, the ability to tailor the elastic behaviour and reduced corrosion should give composite propellers a firm sector of the market in the near future.

7. REFERENCES

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