FLOW VISUALISATION IN RESIN TRANSFER MOULDING

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Abstract

This paper will present and discuss a range of flow characteristics which have been observed in different fibre configurations and under different operating conditions, in both vacuum-assisted and pressure RTM. It is concluded that flow is inhomogeneous at every scale. At the scale of the component, flow is affected by geometrical factors such as fabric cutting and lay-up which may result in 'easy paths' for the resin. At the scale of fibre tows or bundles, there may be movement either within or between layers resulting in local variations in permeability. At the scale of the individual filaments, there are competing processes of viscous and capillary flow which may affect microstructural composite properties if fibre wet out is incomplete.

Small variations of this nature may be beyond the control of normal manufacturing processes, and can have a large effect on the way in which the mould fills. However, this does not preclude the production of quality RTM parts if these variables are understood and taken into account at the process design stage.

INTRODUCTION

Resin Transfer Moulding is an increasingly common process for the manufacture of reinforced plastic components. A pre-catalysed thermosetting resin is injected at low pressures (up to 7 bar) into a closed mould containing dry reinforcement. Impregnation may be assisted or driven by evacuating the mould; the process is the sometimes known as VARI (Vacuum Assisted Resin Injection).

The process originated in the mid 1940's when the US Navy used it to fabricate patrol boats [1]. In the last 10 years, the process has become of considerable commercial interest in the composites industry, both for 'reinforced plastics' (using relatively low amounts of randomly oriented glass reinforcement and polyester resin) and 'advanced composites' (high volume fraction, oriented glass, carbon or aramid reinforcement and epoxy resin).
RTM requires a matched mould of adequate stiffness built to high tolerances. Careful attention has to be paid to sealing arrangements, particularly if vacuum is used. The process has therefore encouraged developments in tooling design and automation [2-4] which are crucial to its commercial success in the production of high performance, load bearing engineering components.

Of equal importance is the interaction between raw material selection, mechanical properties/part quality and process cycle times. Of particular interest is the permeability of the reinforcement (i.e. the ease with which the flowing resin is able to impregnate the fibres and fill the mould). There is now a considerable literature on both empirical [5-7] and theoretical [8, 9] studies of permeability measurement, as well as numerical models of resin flow [10-13]. Resin and fabric suppliers are now marketing raw materials specifically designed for RTM [14].

In common with many other academic groups, we have measured the permeabilities of a range of different reinforcements. The experiments and some typical results are briefly described in this paper. The twin objectives of this work are to provide basic data which can be used in flow simulation models [15], and to attempt to correlate permeability with the detailed fibre 'architecture' (i.e. the microscopic details of fibre arrangement - filament diameter, tow size and orientation, weave style, etc.) [16, 17].

Almost all experimental work assumes that the flow of resin through a reinforcement can be described by Darcy's law [18] - this is a linear relationship in which flow velocity is proportional to pressure gradient and inversely proportional to fluid viscosity. The apparent permeability is essentially the constant of proportionality in the Darcy equation. As described below, permeability is measured by observing the progress of a resin of known viscosity (in a transparent mould) as it flows under a controlled pressure gradient.

Experience over several years with this type of experiment, plus prototype production of real components, has indicated that Darcy's law is only a crude approximation. Within a real fabric, there are local inhomogeneities; flow takes place on different scales, from the relatively large gaps between tows (of the order of a few mm) down to micron-sized spaces between individual filaments. Both capillary and viscous forces may be significant in determining the overall flow pattern [11]. Flow may be 3-dimensional, especially near inlet ports and in thick composites.

The second part of the paper offers a purely qualitative description of some of these 'departures' from predictable flow according to Darcy's law. Some of these variables could (at least in principle) be eliminated by careful experimental design, preparation and process control, but others are inherent in the nature of the process and need to be taken account of for successful component production by RTM.

EXPERIMENTAL MEASUREMENT OF PERMEABILITY

The 'permeability' of a porous medium refers to the ease with which a fluid passes through it. Darcy's original work [18] was based on the flow of domestic water through porous rock, and has been used widely since then to classify particulate media in the petroleum industry. Darcy has lent his name to a unit of permeability; 1 darcy is the permeability of a medium in which a fluid of dynamic viscosity 1 centipoise flows with a velocity 1 cm/s under a pressure gradient of 1 atmosphere/cm. In SI units, permeability is expressed as an area, and 1 darcy = 1.01325×10^{12} m^2.

As indicated above, measurement of permeability requires monitoring the rate of progress of a fluid (resin) as it impregnates the porous medium (reinforcement). Fig. 1 shows a schematic of the type of experiment used at the University of Plymouth, in which the mould comprises a steel base plate to which is clamped a glass or Perspex cover. Resin flow is recorded either manually by tracing successive positions of the flow front, or photographically. Permeability is then deduced from the ratio of flow velocity to pressure gradient. Table 1 gives some typical values for measured permeability, obtained over a number of years on several different fabrics. As can be seen, there are considerable differences between different types of reinforcement, and permeability is very sensitive to volume fraction.

One result of this sensitivity is that repeatability between experiments is difficult to achieve, due to the natural variations in local volume fraction which occur in commercial fabrics and accidental fibre disturbance which may be introduced through handling. Typical experimental scatter is illustrated in Fig. 2.

SOME OBSERVATIONS OF RESIN FLOW

Easy Paths. In a closed mould, any gap between the edge of the reinforcement and the sides of the cavity will result in a high permeability 'easy path' for resin flow. The effect of this is seen in Figures 3 & 4,where the position of the resin front has been recorded at 5 min. intervals during injection of a solution of glycerol under vacuum only. The initially circular front becomes straighter as time progresses, but the shape is dominated by much faster flow around the edges. In extreme cases, fluid which has 'race-tracked' around the edge can reach the vent port in advance of the main flow front, and lead to large unfilled areas and/or resin wastage.

In an idealised, symmetric mould, edge effects would be reduced (and fill times decreased) by the simple expedient of injecting resin at the centre of the mould. However, practical tooling is rarely so straightforward, and edge effects have to be controlled by accurate cutting and/or preforming and placement of the reinforcement. Even accurately cut fabric may be relatively unconstrained at the mould edges, and suffer movement as the resin front advances, particularly if injection pressures are high. In 'leaky' moulds (working without vacuum) it may be possible to clamp the reinforcement through the seal. Alternatively, the mould tool could incorporate an edge feature near the seal locally to compress the fabric - this would ensure high volume fraction and low permeability at the mould edges, but the part may then require additional finishing after moulding.

A different approach is to use edge effects to advantage, by designing 'galleries' to assist rapid mould filling.

Fibre Orientation and Anisotropy. Many advanced reinforcement fabrics are anisotropic in terms of fibre orientation, and this will be reflected in the nature of resin flow - permeability parallel to unidirectional fibres may be of the order of 6 times higher than in the transverse direction. Figs. 5 and 6 illustrate these orientation effects. In Fig. 4, a plain weave fabric is aligned with warp and weft at ± 45° to the mould edges; the rates of flow are similar to those in Fig. 3, although edge effects are less pronounced. In Figures 5 & 6 a unidirectional fabric was aligned at 45° and 0° respectively. The combination of anisotropy and easy paths results in a very different pattern of mould filling such that the resin reaches the outlet long before all the reinforcement is impregnated.

It should be noted that flow-enhancing fabrics are highly anisotropic in permeability. One such fabric in undergoing evaluation at the University of Plymouth [16, 17]. Flow enhancement is achieved by spirally wrapping a thermoplastic fibre around a proportion of the warp tows.

This maintains a roughly circular cross section, even when the fabric is compressed, and ensures that a larger inter-tow gap is maintained. Fig. 7 shows experiments with these fabrics in which resin was injected at the centre of a flat plate. When an 'isotropic' lay up is used, a succession of circular flow fronts is produced; changing the orientation of individual plies introduces anisotropy of permeability, and the flow front becomes elliptical rather than circular. In these cases, a tensor description of permeability is required [19] and Darcy's law is modified appropriately. Just as mechanically anisotropic reinforcements enable the designer to tailor laminate stiffness and strength, so anisotropic permeability can be exploited for optimum RTM process design.

Fingering. Local inhomogeneities in fibre distribution result in regions of high and low permeability within the reinforcement. The resulting flow front is far from smooth, as seen in Figs. 5,6 & 7. In these illustrations the inhomogeneities may arise from 'natural' variations in fibre orientation or from disturbances introduced by handling. Under some circumstances, the flowing resin may displace fibres laterally, and we have observed that the degree of fingering increases with injection pressure.

Many fabrics are inherently inhomogeneous, comprising stitched or woven tows or bundles of fibres which may be several mm apart. Close inspection of the flow front during injection reveals different rates of flow *between* the tows compared to *within* the tows (Fig. 8). At low pressures, the capillary flow within tows can lead the viscous flow in the spaces between them; at high pressure the situation is reversed, and the observed flow front does not indicate the extent of the wetted-out fabric.

The interaction of these complex mechanisms has been demonstrated in the manufacture of a rectangular test panel from a quadriaxial (0°, ±45°, 90°) non-crimp fabric. This fabric has well defined gaps between the stitched tows in the 0° direction, but evenly spread unidirectional fibres in the other 3 layers. Permeability is thus highly anisotropic. In this experiment, half the required volume of epoxy resin was pigmented yellow and injected in the normal way; the injection was completed with a second batch of black-pigmented resin. The result in shown in Fig. 9, in which the lighter coloured resin appears to occupy the tows, while the second batch of dark resin remains in the tow spaces. It is believed that the first batch of resin will have rapidly filled the spaces between the 0° tows, then subsequently impregnated the tows themselves, leaving the spaces relatively clear once again for the second batch. Whatever the precise details of resin flow, it seems unlikely that a single value of permeability as derived from a Darcy flow experiment will provide an adequate characterisation of this fabric.

Three-Dimensional Flow. Most composite components comprise thin, shell laminates, in which the lateral dimensions are several orders of magnitude greater than their thickness. In this case, the problems of materials characterisation and flow simulation can be considered in two dimensions. A few components, such as panels for ballistic protection, are required to be of considerable thickness - at the University of Plymouth monolithic GRP test panels for such applications of up to 60 mm thickness have been manufactured from a range of non-crimp fabrics [20]. In the quadriaxial fabric referred to above, the continuous 90° fibre layers offer a high resistance to through-thickness flow (Fig. 10). In-plane flow is relatively rapid due to the inter-tow gaps in the 0° plies. It was found that injecting thick laminates from one face of the tool resulted in resin flowing laterally and around the edges of the reinforcement to reach the far side of the tool (a distance of the order of 1 m) before resin had penetrated vertically through the fabric (a distance of only 60 mm). Unwetted plies were therefore located within the laminate typically a few mm from the back surface. Subsequent experiments on biaxial (0°/90°) non-crimp fabrics (in which both warp and weft fibres comprise stitched tows) have proved more successful, due to the higher through-thickness permeability.

DISCUSSION

In most experiments, the initial shape of the flow front reflects the geometry of the inlet. For example, an isolated port produces a circular flow front, while linear injection from the mould edge produces a straight line. During the first few cm of mould filling, the flow appears to be in transition, and Darcy's law is inapplicable.

At the highest level, flow is subsequently influenced primarily by fibre orientation and anisotropy, and this determines the overall way in which the mould is filled. Location of inlet and vent ports should take this into account to avoid wastage of resin. At a lower level (smaller scale), any 'fingering' due to fabric design or irregularities will be superimposed on this pattern. In extreme cases, resin may progress rapidly towards the outlet without fully wetting the fibre bundles. At the lowest (microstructural) level, capillary forces affect flow within fibre tows. The magnitude of capillary forces will depend on the packing of fibres within the tow, and this in turn could be affected by the overall fibre volume fraction and the pressure gradients in the resin. Local movement of fibre in response to excessive pressures has been observed both in discontinuous and continuous reinforcements. In the latter case, resulting regions of high volume fraction and hence low permeability will restrict resin flow.

CONCLUSIONS

Darcy's law has been widely used as a model of resin flow during RTM. However, a number of observed features have been described in this paper which illustrate that the interaction between a fluid and advanced fabrics containing aligned fibres is considerably more complex. While many of these effects may be difficult to quantify, it is suggested that the use of flow visualisation can give an important insight into the various flow mechanisms, their interactions and likely influence on mould filling. An appreciation of these aspects is crucial to the meaningful characterisation of the raw materials used in RTM, and hence to the success of flow prediction and efficient process design and control.

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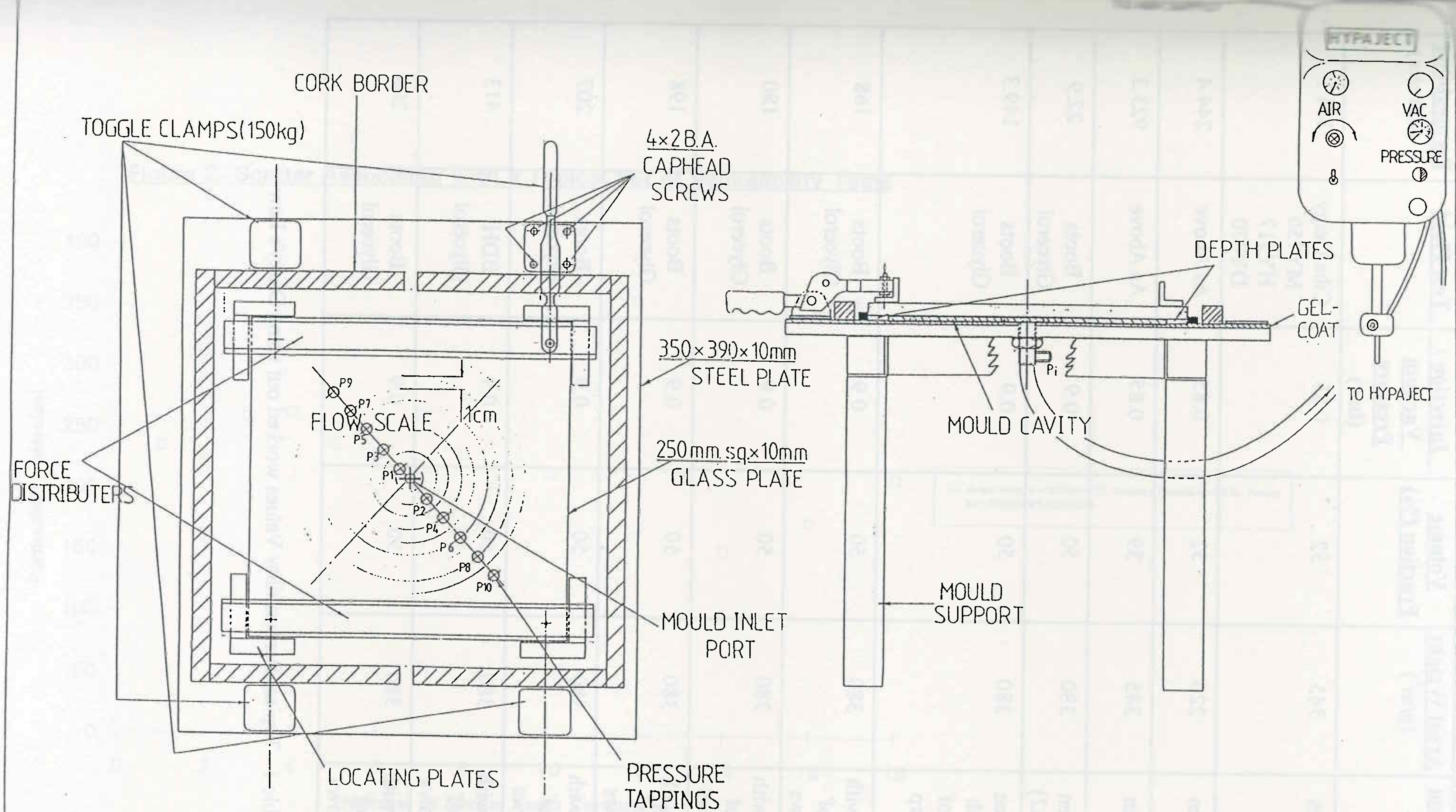
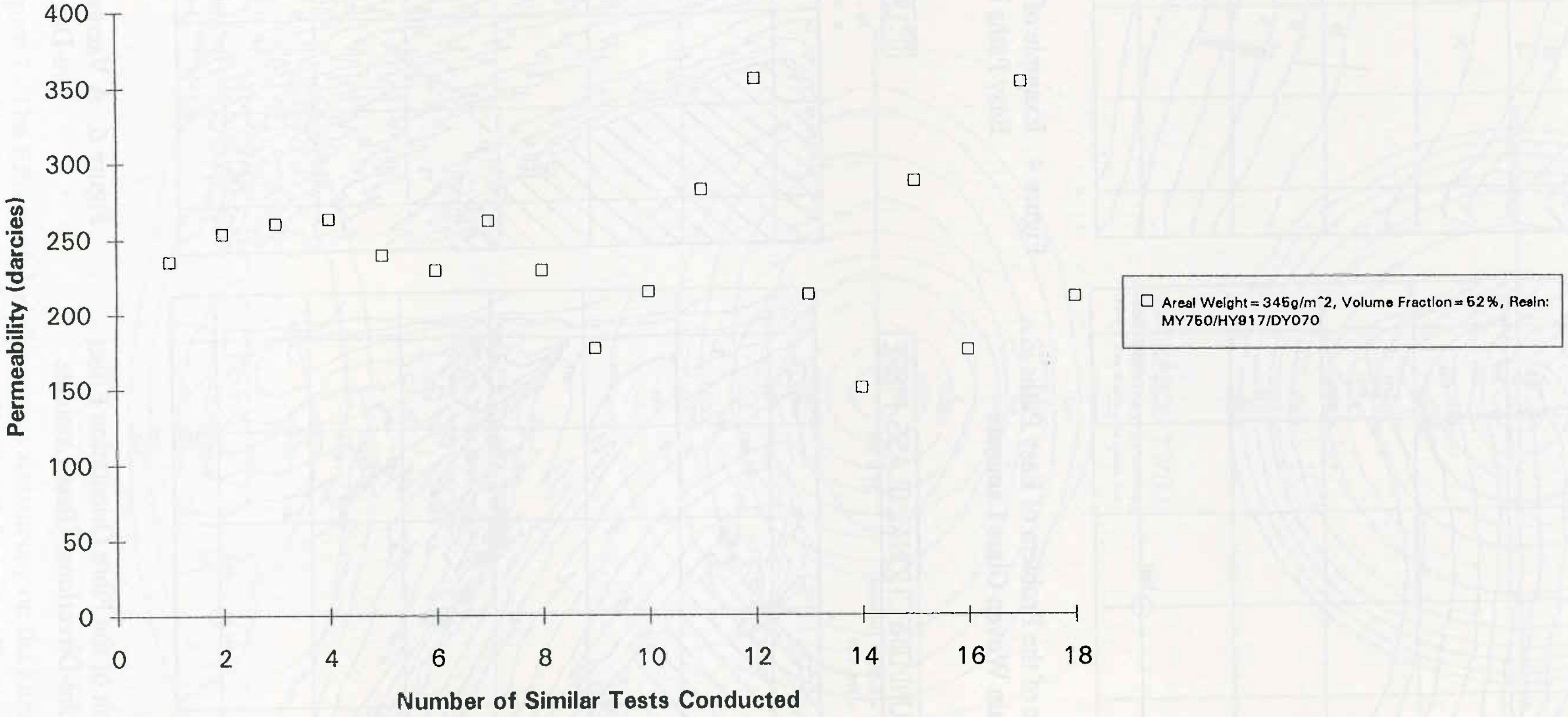


Figure 1. Permeability Test Apparatus

Reinforcement	**Areal Weight (g/m^2)**	**Volume Fraction (%)**	**Injection / Vacuum Pressure (bar)**	**Test Fluid**	**Permeability (darcies)**
Plain Woven 'E' Glass	345	52	0.85	Ciba Geigy MY750 HY917 DY070	244.1
Plain Woven 'E' Glass	220	52	0.85	As Above	244.4
Plain Woven 'E' Glass	345	39	0.85	As Above	923.3
Twill Woven Carbon (2x2)	380	50	0.9	Boots Glycerol	22.9
Twill Woven Carbon with 1:7 Ratio of Bound Warp Tows	380	50	0.9	Boots Glycerol	149.3
As above with 1:6 Ratio of Bound Tows	380	50	0.9	Boots Glycerol	168
As above with 1:5 Ratio of Bound Tows	380	50	0.9	Boots Glycerol	180
As above with 1:4 Ratio of Bound Tows	380	50	0.9	Boots Glycerol	198
As above with 1:3 Ratio of Bound Tows	380	50	0.9	Boots Glycerol	207
As above with 1:2 Ratio of Bound Tows	380	50	0.9	BDH Glycerol	413
As above with 1:1 Ratio of Bound Tows	380	50	0.9	Boots Glycerol	208

Table 1. Typical Permeability Values worked out using Darcy's Law

Figure 2. Scatter Associated with a Typical Set of Permeability Tests



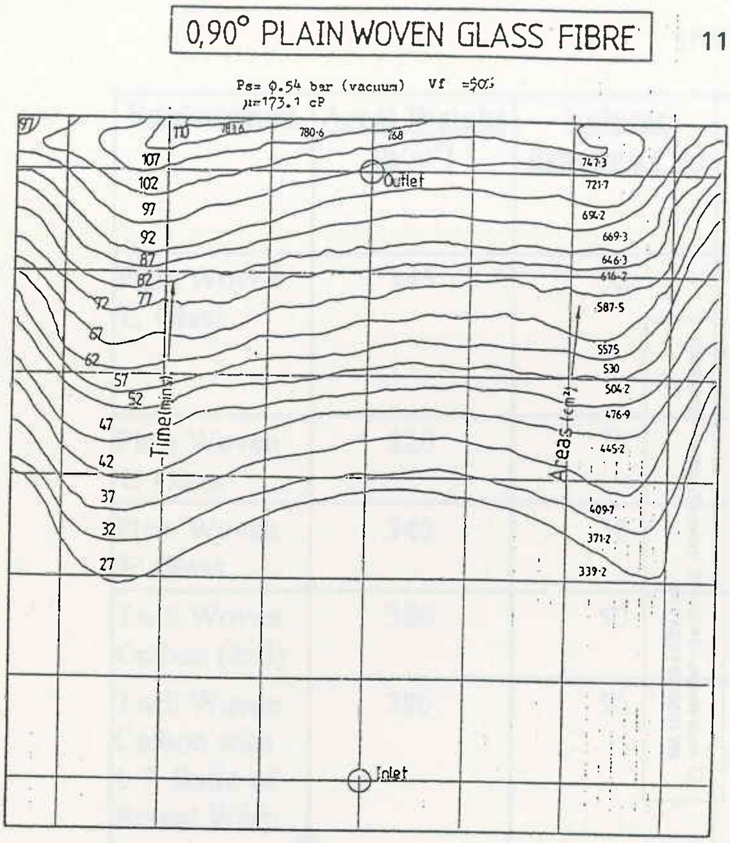


Figure 3. Example of the Problem of Easy Paths in a 0,90° Plain Woven Glass Laminate

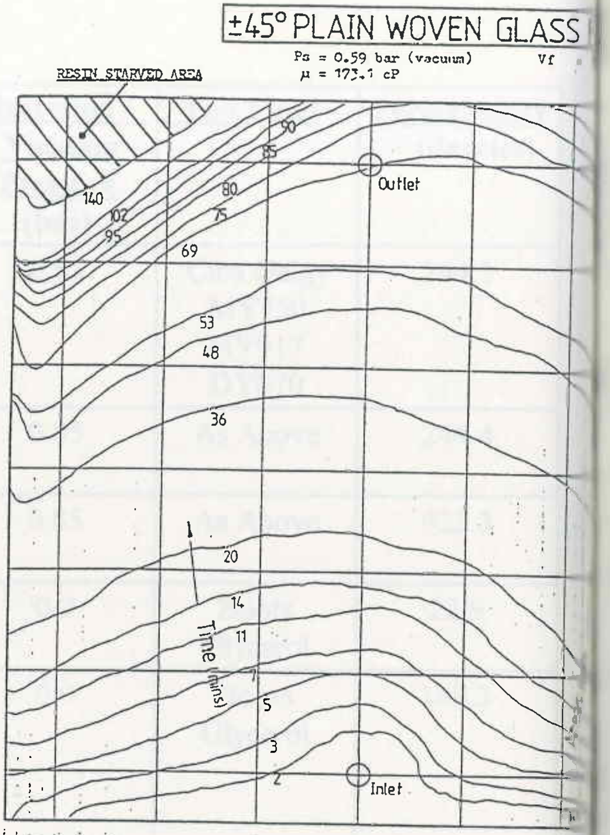


Figure 4. Example of the Resin Starved Area
Easy Paths in a ±45° Plain Woven

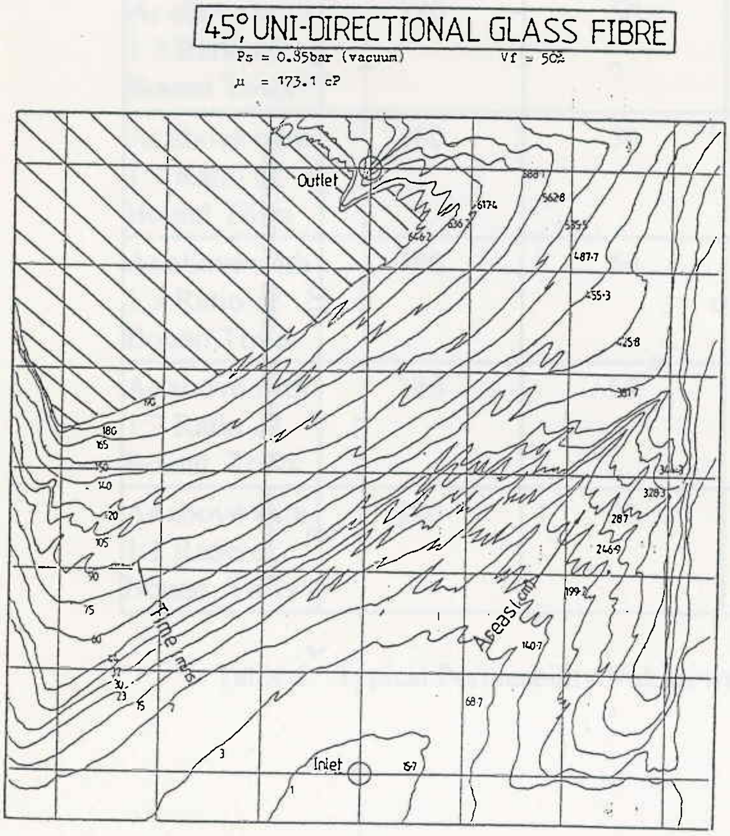


Figure 5. Illustration of the Fibre Orientation Effect in a 45° Uni-Directional Glass Laminate

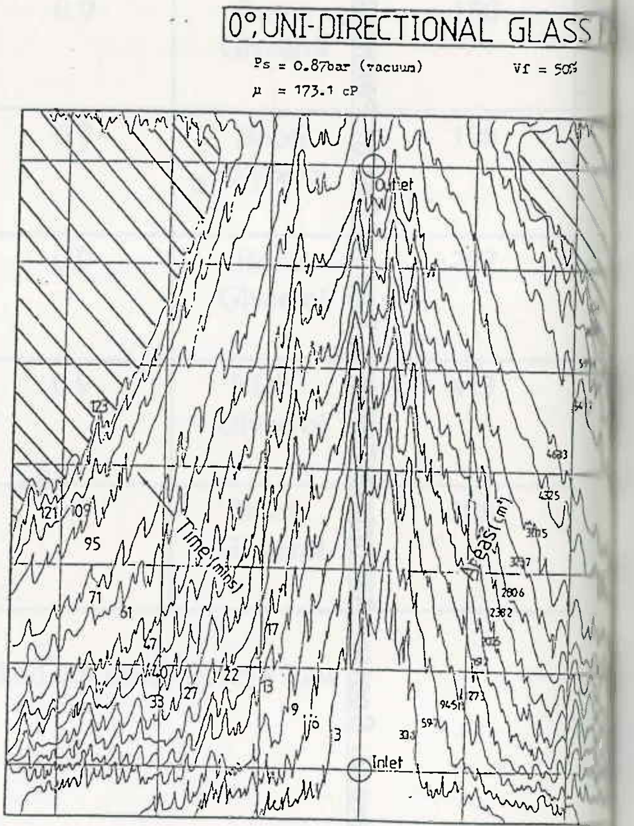
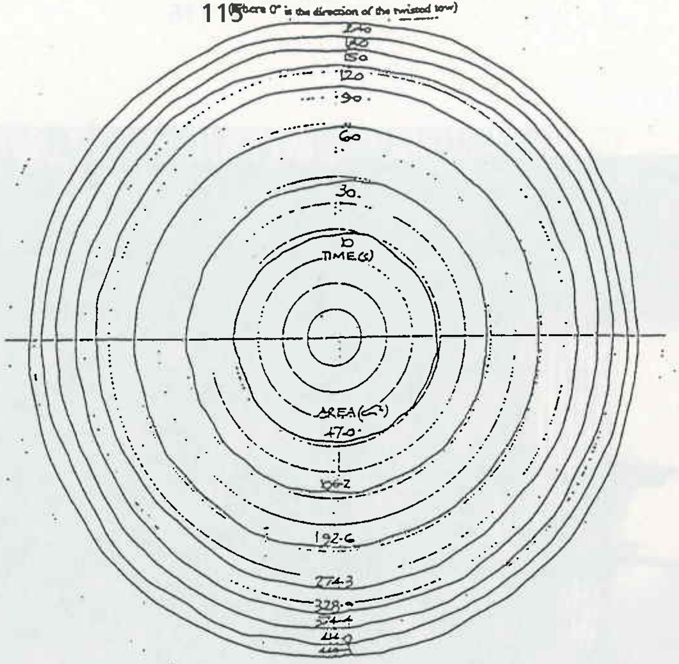
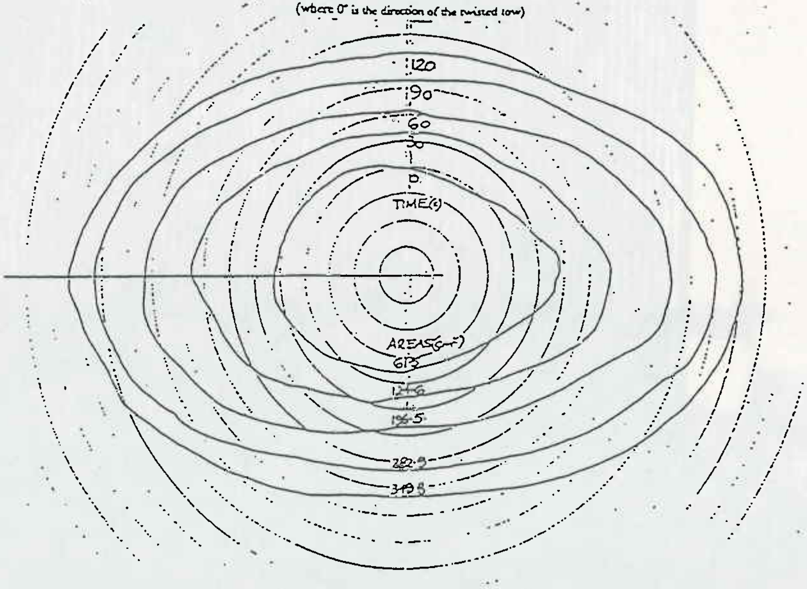


Figure 6. A Vacuum Impregnation of
Uni-Directional Glass with Glyce

2x2 CARBON TWILL
ISOTROPIC LAY-UP 0-90-90-0
(where 0° is the direction of the twisted tow)



2x2 CARBON TWILL
ANISOTROPIC LAY-UP 0-90-0-0
(where 0° is the direction of the twisted tow)



2x2 CARBON TWILL
ANISOTROPIC LAY-UP 0-0-0-0
(where 0° is the direction of the twisted tow)

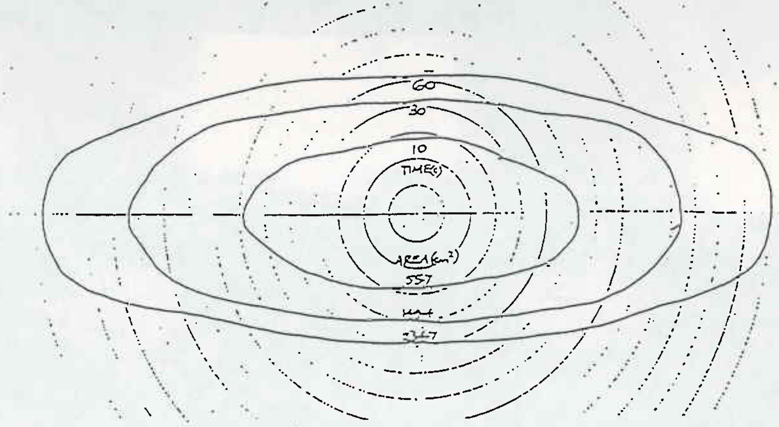


Figure 7. The Effects of Reinforcement Anisotropy on the Flow Front Profile in a 0,90° Carbon Twill Fabric with a Flow Enhancing Tow in the Warp Direction.

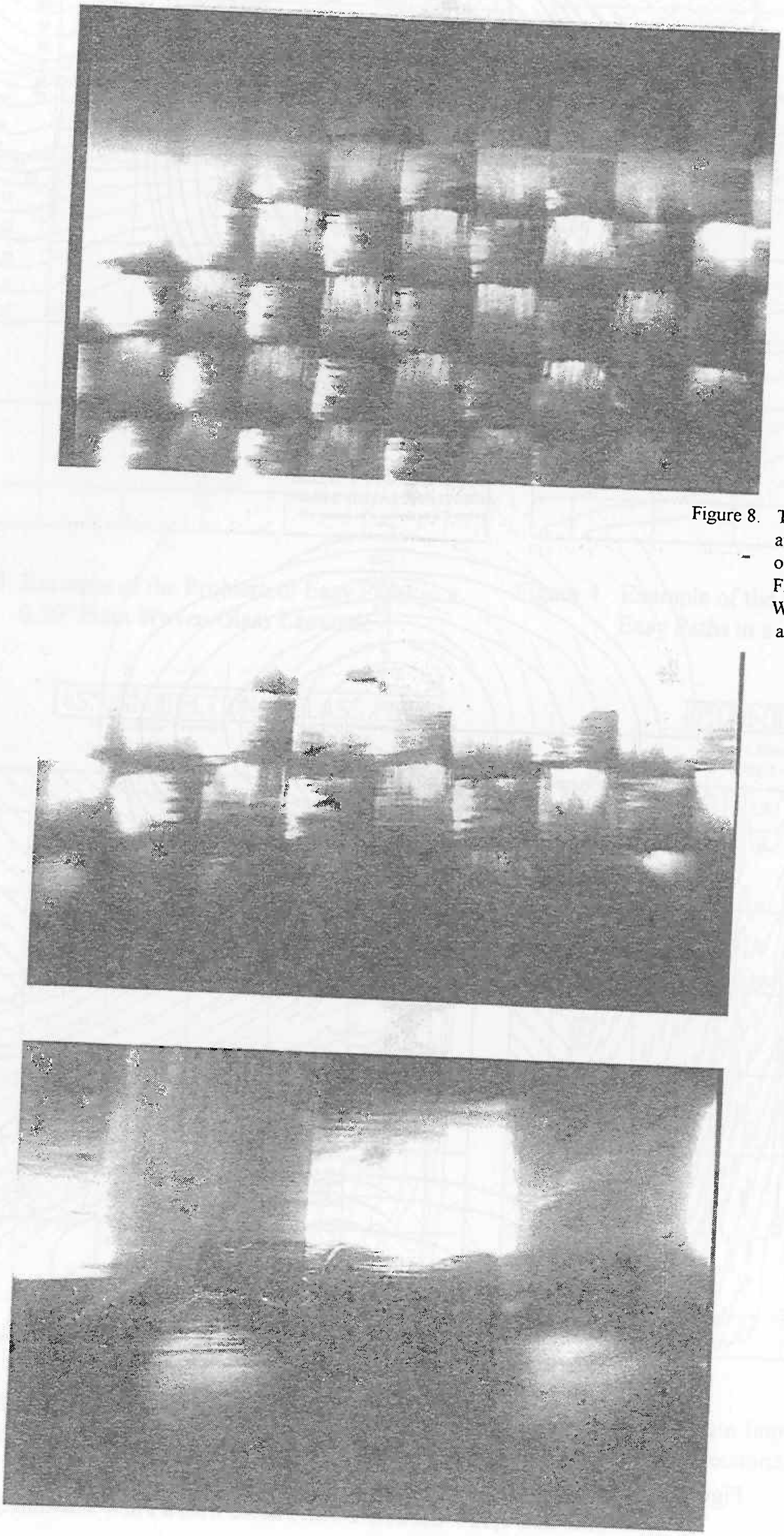


Figure 8. Three Macrophotographs at Varying Magnifications of the Edge of the Flow Front Showing Differing the Wet-out Rates of the tows and Inter-tow Spacings

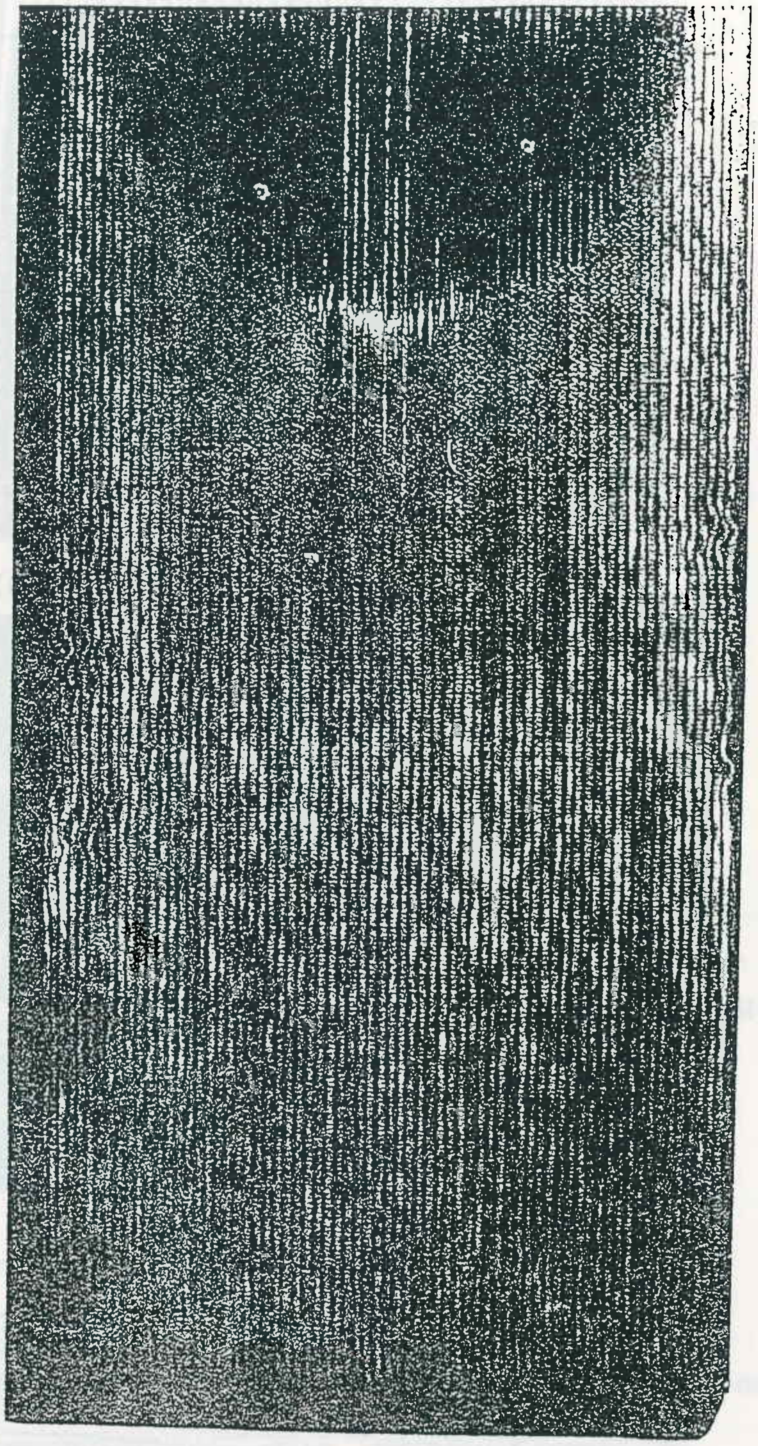
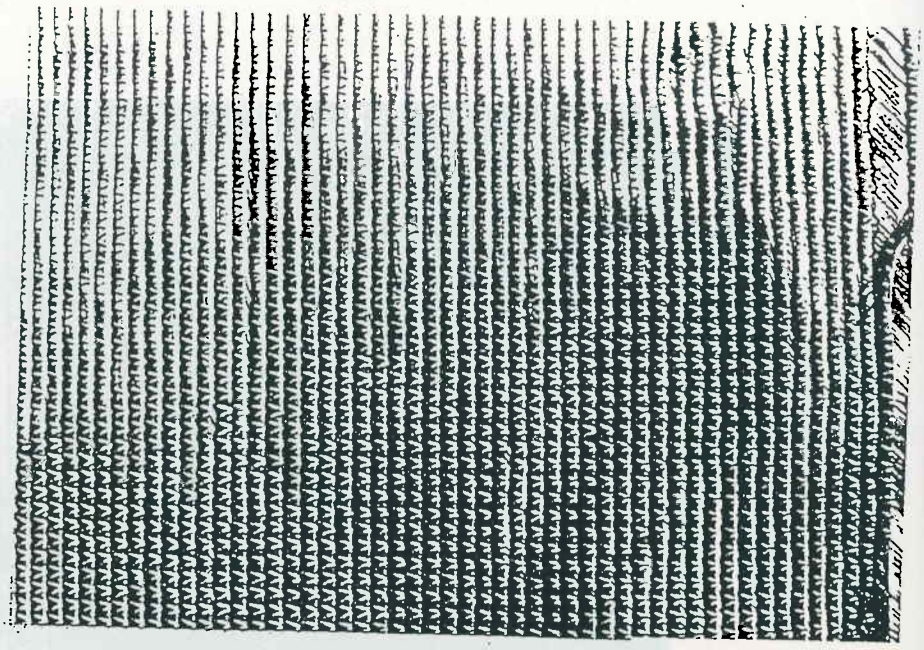
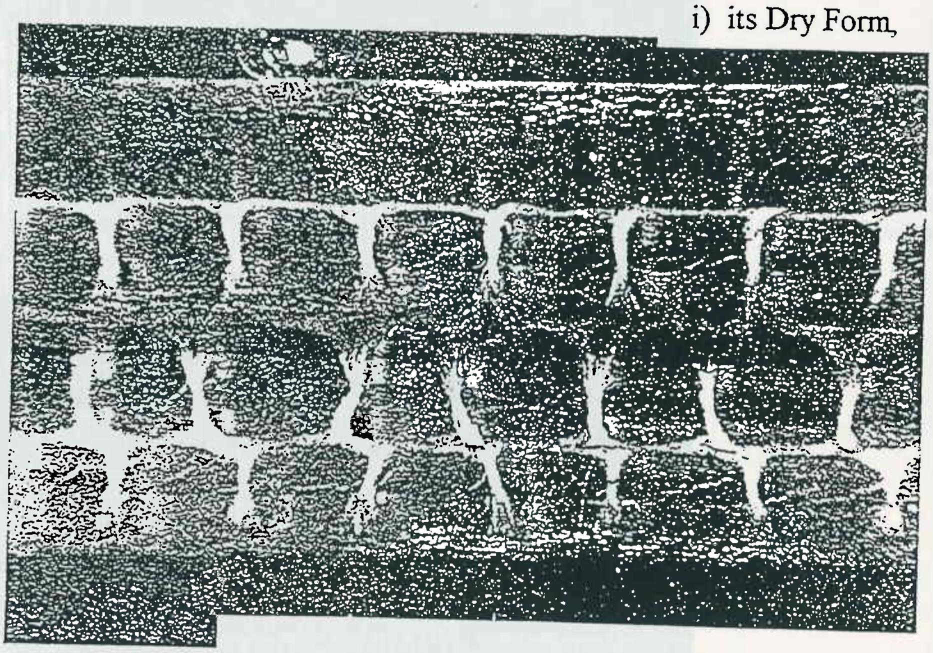


Figure 9. 'E' Glass / Epoxy Panel showing the Yellow (light) Fibre Tows and the Black Inter-Tow Flow Gaps

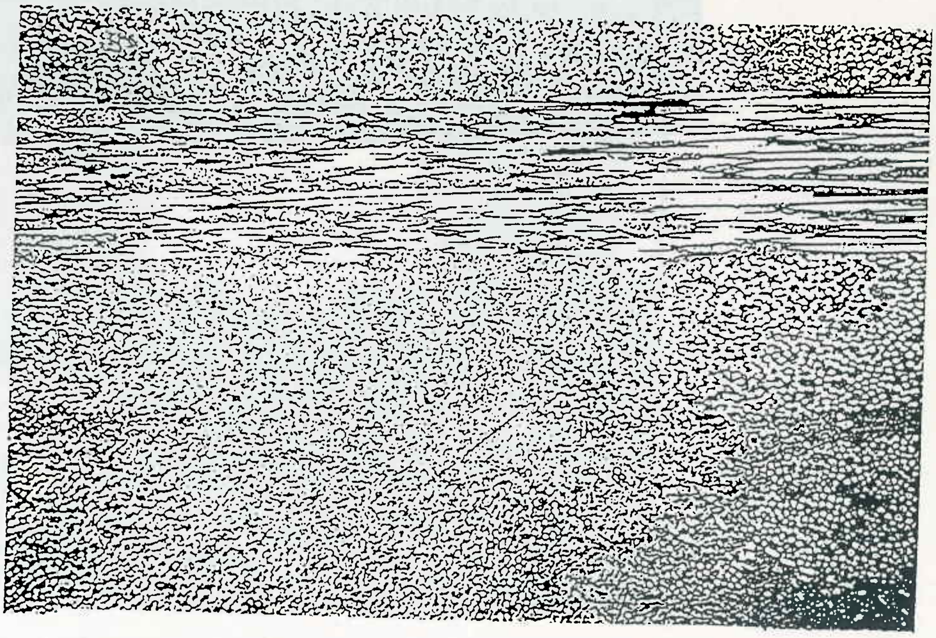
Figure 10. Quadraxial Stitched Fabric ('E' Glass) in



i) its Dry Form,



ii) a Microsection showing 4 layers in an Epoxy Laminate



iii) a Section of one layer illustrating a Deficiency

in Large Through-Thickness Flaw Channels