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Processing and Mechanical Properties of Bi-directional Preforms for Liquid Composite Moulding

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Abstract

The design and manufacture of fibre preforms for structural parts remains the major technical challenge in liquid composite moulding processes such as RTM and SRIM. This paper sets out to identify new methods for preform design based upon fibre architecture in 2.5 dimensional preforms via a drape analysis. The predicted fibre geometry is related to models for permeability and elastic properties to generate property distributions over the part. These may then be used within finite element analyses to predict mould filling and structural performance. Experimental results are presented which include fibre distribution, in-plane permeability, elastic properties and structural tests. The integration of the stages within a design framework is discussed.

1 INTRODUCTION

Composite materials based upon the use of aligned, long fibre reinforcement are in widespread use for structural applications due to their high specific strength and stiffness. While aerospace applications have made wide use of pre-impregnated materials with low volume manufacturing strategies based upon vacuum bagging and autoclaving, the opening up of new markets including structural automotive applications imposes new constraints on design and processing. Typical aerospace applications include flat or single curvature panels produced in relatively modest numbers. These contrast with higher volume automotive and "industrial" applications which often involve double curvature. Any technical challenges due to the performance specification are added to the economic constraints associated with high volume manufacture.

In the interests of reducing development and tooling lead times for composite components it is increasingly common to apply computer-aided techniques for component design. Performance prediction based upon laminate theory and/or finite element analysis has become routine for structural parts. More recent developments have taken place in the area of process simulation. This has been evident for several years for thermoplastic injection moulded parts and additional interest has been shown in resin transfer moulding (RTM) of composite parts(1), much of this work stimulated by the automotive industry. Extensive experimental work has been reported and non-isothermal RTM and the related structural reaction injection moulding (SRIM) processes have been characterised in detail with respect to thermal and pressure cycles(2,3). A number of computer simulations (eg 4) have been developed for both process. Generally, these have considered the isothermal impregnation of fibre reinforcement or preforms with Newtonian resins, although non-isothermal and non-Newtonian solutions have been demonstrated.

While numerical methods have been applied to solve the independent problems of process simulation and performance prediction, the analyses are linked in a number of aspects. Although the governing partial differential equations are different, both problems can be solved using finite element methods. Also, both solutions rely upon a knowledge of the architecture and properties of the pre-placed fibre reinforcement. For structural analysis, this will involve the elastic constants for the laminate and for process simulation the permeabilities of the preform need to be determined. Traditional design methods involve the measurement of all data from flat plaque laminates. This approach becomes less valid as double curvature is introduced into the part geometry. Preforms manufactured from high modulus fibre textiles can only accommodate such geometries by changes in the fabric architecture. Since elastic properties and permeabilities are known to be strong functions of fibre orientation and volume fraction, it follows that significant property variation over the area of the part is possible. Any such variation will influence the validity of the design analyses discussed earlier.

The study described below sets out to examine the significance of changes in fibre distribution within fabric based preforms and property variations which arise from these. This is done by performing a kinematic draping analysis, the results of which are linked to models for permeabilities and elastic properties. The properties may then be used as inputs to FE based structural analysis and process simulation. The study is based upon a prototype wheel hub (Figure 1) and experimental results are included.

Experimental Details

Experimental work, which included the measurement of properties for flat fabrics in as-received and pre-sheared states was based upon Tech Textiles E-LT 1134 Style 1047 stitch bonded glass fibre reinforcement. This contains two parallel layers of E-glass reinforcement (600 tex rovings, 15 micron filament diameter) at 0/90° which were restrained by a polyester yarn in the form of a compliant stitch, comprising approximately 1% of the fabric mass. Flat plaque mouldings were manufactured by RTM using Cray Valley Totale 6345.001 unsaturated polyester resin in aluminium tooling operated at a nominal temperature of 90°C. Preforms for the prototype wheel hub were produced using the same reinforcement in epoxy tooling mounted in a fly press. The resulting preforms were processed by SRIM using a Krauss Maffei RIMStar 40 machine with centre injection into a steel mould. The mould contained in-situ pressure transducers and thermocouples for processing monitoring purposes. The resin system was Shell Epikote DX6008 epoxy with DX6511 hardener in a 4:1 ratio. The steel mould was operated at 120°C with the resin and hardener at 117° and 86°C respectively.

Permeability measurements were carried out using a radial flow arrangement according to the method described in our earlier paper(5). Elastic properties for the flat plaques and test coupons from the prototype wheel hubs were measured using a computer controlled Instron 1195 Universal Testing Machine to a method encompassing BS 2782. The same testing machine was used to carry out structural testing of prototype parts. Diametral compression or pinch tests were made by holding the prototype wheel hub mouldings between 10mm diameter rollers which located in a corresponding notch in the perimeter of the part. The force required to produce deflections up to a maximum 10mm were recorded via a load cell.

2 DRAPE PREDICTION

The problem considered is that of determining the orientation and distribution of fibres in a generally curved, two-dimensional preform. This is solved by the application of the kinematic draping algorithm which is described in detail in our earlier paper(5). Briefly, the analysis consider the fabric as a pin-jointed net of inextensible fibres. No slip is provided for at the tow intersections and the only mode of deformation considered is that of fabric shear. This reduces the problem to one of co-ordinate geometry and has been found to provide a useful description of fabric behaviour for stitch-bonded, warp knit or so called zero-crimp fabrics. One of the objectives of the present study is to ascertain the limits of accuracy for this approach to deformation modelling.

The part geometry was represented by a surface composed of bi-linear patches (Figure 1). This offers the advantage of an explicit solution to the location of the tow intersections. The use of curved patches(7) implies an iterative solution which require more intensive computation. The tow patterns were generated by fixing the initial contact point for the fabric on the male mould (the centre of the hub). The fabric orientation (+/-45) was then used to fix the path of two initially perpendicular fibres across the surface patches to the edge of the part. Intermediate fibre paths could then be calculated from these generators. The output from the completed drape analysis is shown in Figure 2. It is evident that substantial re-orientation of the fibres is predicted in order to conform to the part geometry. The nominal fibre separation angle of 90° is reduced to a minimum of 28° at the perimeter of the part with associated changes in preform properties which are discussed in detail below. A parallel experimental study was made to verify the drape model. A preform was prepared from five layers of Tech Textiles E-LT 1134 0°/90° fabric according to the projected net-shape from the drape analysis(6). Warp and weft tows on the outer layer were marked at 18mm intervals to highlight the fibre paths. The preform was then impregnated as described above and qualitative assessment of the resulting moulding (Figure 3) indicated good agreement with the model. Due to the difficulties in achieving accurate local measurements of fibre orientation, it was decided to investigate the property variations arising from the fibre distribution.

While the major, visible effect of fabric shear is that of fibre re-orientation it is also clear that any shear will modify the spacing between adjacent tows with consequent changes in the fibre volume fraction. This can be deduced by trigonometry and the local fibre volume fraction can be estimated using the following relationship:

$$V_f = \frac{nS_0}{\rho h \sin\beta}$$

The circumferential variation in fibre volume fraction for the prototype wheel hub arising from the drape analysis is shown in Figure 4. This is compared with the results from burn-off tests on specimens cut from the rim of the moulded parts and shows close agreement with the predictions. The local fibre volume fraction can be seen to depart from the nominal value of 40%, reaching local maxima of 60-70%. It is likely that further increases were prevented by attainment of the so-called "jamming angle"(10) during preform manufacture.

3 PROCESS SIMULATION

Process simulation has been demonstrated by several authors (eg 4) to predict the impregnation phase. While this offers a number of potential benefits, the main purpose is often to determine a satisfactory position for the injection and vent points, such that impregnation times and the danger of air entrapment are minimised. Previous workers have reported simulations based upon global values for permeability data. Due to the substantial reinforcement variations suggested by the drape analysis, the in-plane permeabilities were related to the fibre architecture to predict the variation over the component resulting from preform manufacture. The permeability data were determined for quasi-unidirectional stitch bonded fabric reinforcement over the range 37% to 53% fibre by volume and the results are shown in Figure 5. These gave rise to the following empirical relations between principal permeabilities and fibre volume fractions:

$$k_1 = 50.85.10^{-9}\ \phi^{7.18}$$
$$k_2 = 4.50.10^{-9}\ \phi^{9.05}$$

The local permeability values for the stack was then calculated by summing the flow in individual layers, based upon the off-axis values for individual plies:

$$k_{eff} = \frac{1}{h}\sum_{i=1}^{i=n}(k_1\cos^2\theta_i + k_2\sin^2\theta_i)\ t_i \quad (3)$$

This equation was then applied to the output from the kinematic drape model to predict average permeabilities for each patch in the geometric model. The distribution of permeability values for the prototype wheel hub is shown in Figure 6 which exhibits a wide variation from the equivalent (uniform) value for the nominal +/-45° fibre architecture of $0.72.10^{-9}$ m^2, reducing to a local minimum of $0.0008.10^{-9}$ at the rim. This is the net effect of the changes in both fibre orientation and volume fraction. The radial re-orientation tends to increase radial permeability while the local compaction will counter this effect. The results suggest that the fibre volume fraction effect dominates in this case, as shown by the substantial reduction in radial permeability which is calculated. Due to the difficulties involved in making permeability measurements for the deformed part, validation of these effects was attempted by combining a flow analysis with impregnation trials for the deformed fibre structure.

The permeability distributions described were used as input data to the CFILL code described by Owen et al(4). This is a commercial FE code known as PAFEC which was modified to include a control volume method for the solution of moving boundary problems such as impregnation during liquid composite moulding. This is made possible by the Laplacian nature of porous media problems, where the element stiffness matrix is assembled from the individual viscosity/permeability terms, enabling a linear elasticity solution to be used. The model is subject to boundary conditions of constant volume flux at the centre node representing the injection gate and atmospheric pressure at the flow front. The analysis in this case is isothermal since the reactants are injected at an effective bulk temperature of approximately 110°C, with the mould at 120°C. The viscosity change for the resin system between these temperatures in negligible. Mould filling times in the range 3-5 seconds permit the impregnation and cure phases to be considered independently. The finite element mesh used corresponds to the surface model shown in Figure 1.

The output from the analyses are shown in Figure 7. These are presented as isochrones or contours of equal fill time and demonstrate the preferential flow which is predicted as a result of the fibre re-orientation. Figure 7(a) shows the predicted fill fronts for the nominal (0°/90°) reinforcement architecture. The isotropy of the preform is reflected in the circular flow fronts depicted. Figure 7(b) shows the same model using permeabilities generated from the local fibre orientations in each element but maintaining the fibre volume fraction uniform throughout the domain. This was done in order to isolate the effects of fibre volume fraction and orientation. The results show a clear displacement from the isotropic case towards the rim of the cavity. This is attributed to the increase in radial permeability arising from the radial re-orientation of the fabric. Comparison with Figure 7(c) shows that the effect becomes less marked when the change in volume fraction arising from the re-orientation effect is also taken into account, although a clear flow leader exists in the same region, despite the local reduction in permeability. This effect is explained by the local decrease in porosity which implies a reduced volume of resin required for impregnation.

Short shots were carried out at intervals corresponding to the isochrones in Figure 7 in order to validate the permeability predictions. An example of these is given in Figure 8 which shows the position of the flow front after injection for 2.8s under the conditions described in Section 1. The photograph shows that the maximum principal flow axis corresponds to the axis of maximum shear and *minimum* permeability (arising from local compaction effects), thus confirming the predictions described above.

4 PERFORMANCE PREDICTION

Elastic properties can be related to fibre orientation via conventional laminate theory. This can be applied simply using the type of analysis suggested by Krenchel(11) as applied to angle ply laminates in our earlier paper(9). The problem is complicated slightly for fabric shear, (compared to a simple stress transformation) since the shear induces changes in fibre volume fraction, in addition to ply angle. The efficiency factor (compared to a group of unidirectional fibres) is given by:

$$\eta = \sum_{1}^{n} a_i \cos^4 \alpha_i$$

This can then be used within the modified rule of mixtures to estimate the modulus referred to the laminate axes:

$$E_c = E_m(1-V_f) + E_f V_f \eta$$

This relationship was investigated by subjecting fabric samples to varying degrees of pre-shear (up to 30% nominal shear strain) prior to manufacture of flat plaque mouldings, as described above. The fabric samples were clamped rigidly to a laboratory bench using one side of a two bar linkage mechanism. The opposite edge of the fabric was then displaced by a predetermined amount to induce the desired shear strain in the fabric. Fabric samples were subjected to 0,5,10,20 and 25% shear strains prior to testing. Specimens were cut and tested in the laminate reference (0° and 90°) directions. The results are shown in Figure 9 and compared with the estimated moduli showing very close agreement.

The relationship between elastic constants and fabric shear strain was then applied to the results of the drape analysis, providing the property distributions shown in Figure 10. The results suggest local variations in laminate modulus from the nominal maximum value of 15.6 MPa for the 0°/90° patches to a predicted maximum of 40MPa at the rim where the local ply angle has been reduced to 28°. The variation in this case is more dramatic than in the case of the in-plane permeability, since the combined effects of the decrease in ply angle and the increase in local fibre volume fraction both work to increase the laminate "modulus" in the radial direction.

Structural Testing

To study the effects of fibre re-orientation on mechanical performance, pinch tests were used (as described above) on wheel-hubs made with five layers of Tech Textiles E-LT 1134 0°/90° reinforcement. This involved the compression of components between two points, as illustrated in Figure 11. Tests were carried out at various positions around the component, denoted by the angle from the constrained paths. Figure 11 shows the relationship between force and deflection for each test. At 0° to the constrained path, a force of 412 N was required to achieve a 10mm deflection. This was 31 % higher than the force required to achieve the same deflection at 45°, ie mid-way between the constrained paths. This difference is thought to be caused by the fact that at 0° the reinforcement is unsheared and has a significant proportion of fibres perpendicular to the direction of loading. The test at 45° corresponds to the region of maximum shear, where fibres are aligned towards the loading axis and hence the component has a reduced transverse stiffness. As with the flow simulation described earlier, it should be possible to simulate the effect of reinforcement shear within an FE structural analysis. This possibility is currently under investigation and will be reported in the near future.

5 SUMMARY

Preforming operations on fabric reinforcements require changes to the reinforcement architecture to accommodate compound curvatures. This results in changes in fibre volume fraction and orientation compared to the nominal fabric. The kinematic drape model used appears to provide reasonable estimations of fibre orientation and distribution for the reinforcement fabric and part geometry considered. Although the local fibre orientations have not been measured, the property distributions arising from these have been shown to provide close agreement with the predictions. For the component geometry studied, the major effect of the fabric deformation is modification of the elastic properties of the composite. Substantial changes in preform permeability have been identified also, although these have been shown to be less significant in practice (as shown by flow modelling) due to the accompanying reduction in porosity.

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Nomenclature

E_m	Matrix modulus
E_c	Composite Modulus
S_o	Superficial density
V_f	Fibre volume fraction
h	Stack thickness
$k_{1,2}$	Principal in-plane permeabilities
k_{eff}	Effective stack in-plane permeability
ρ	Density
α	Fibre angle wrt reference axes
δ	Fibre separation angle
θ	Ply angle
η	Reinforcement efficiency

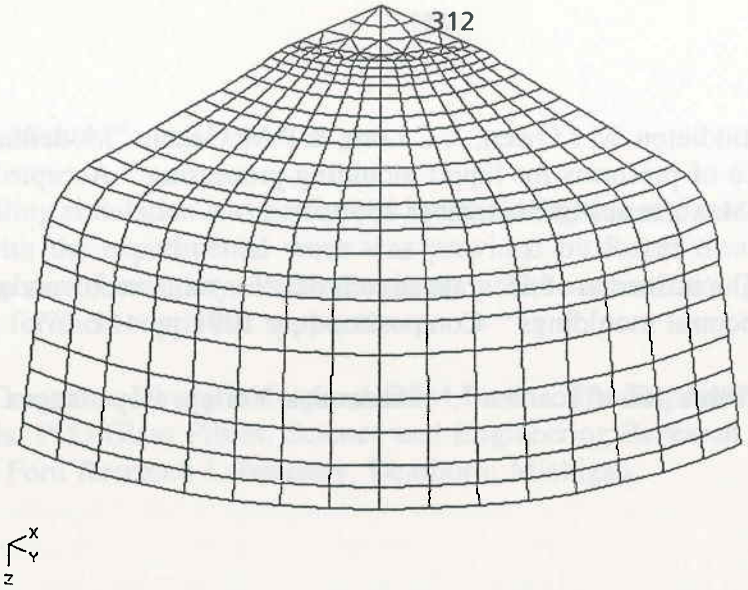


Figure 1 Surface model of prototype wheel hub

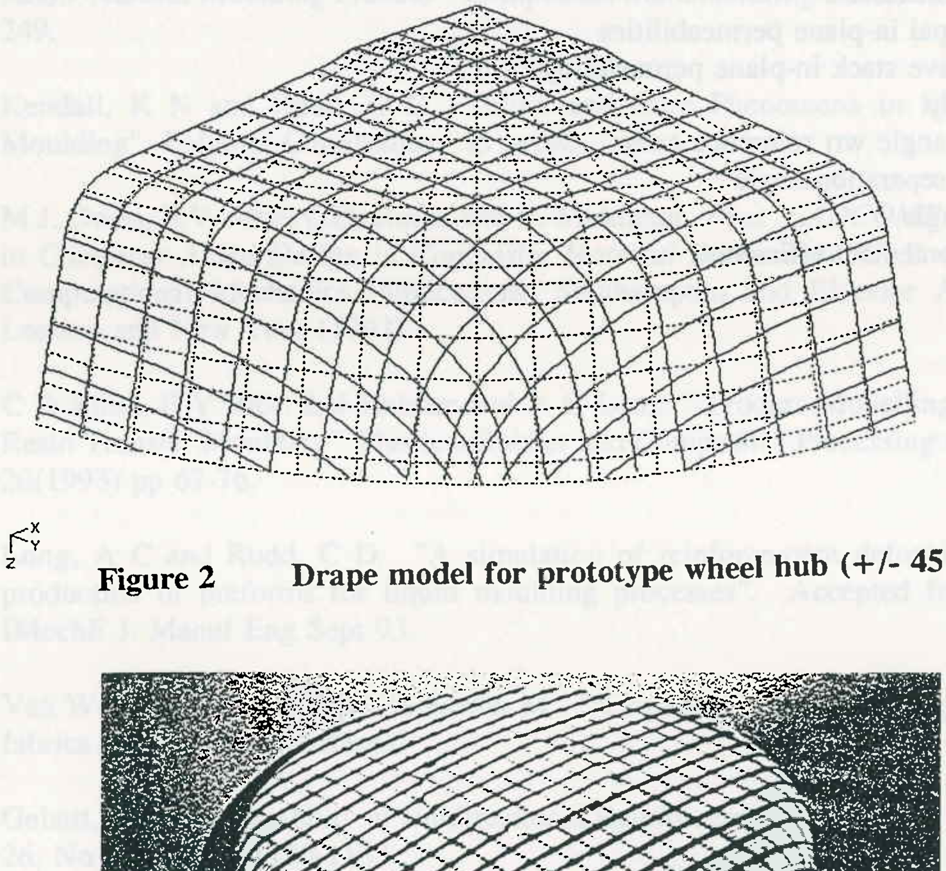


Figure 2 Drape model for prototype wheel hub (+/- 45 fabric)

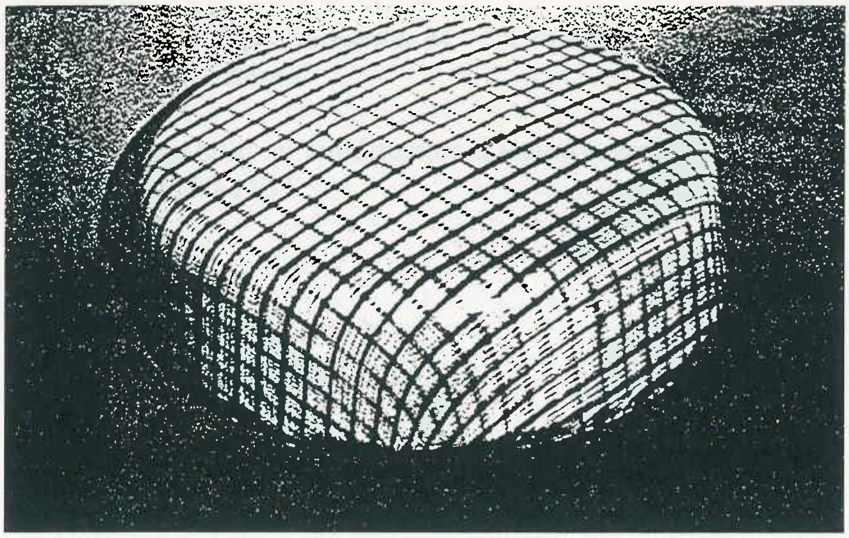


Figure 3 Photo showing fibre orientations in prototype wheel hub

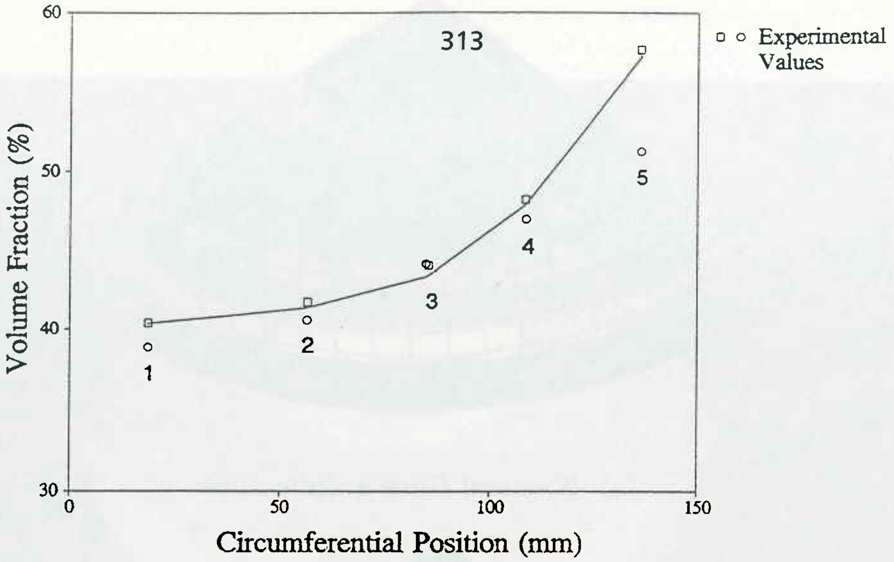


Figure 4 Circumferential variation in fibre volume fraction of prototype wheel hub

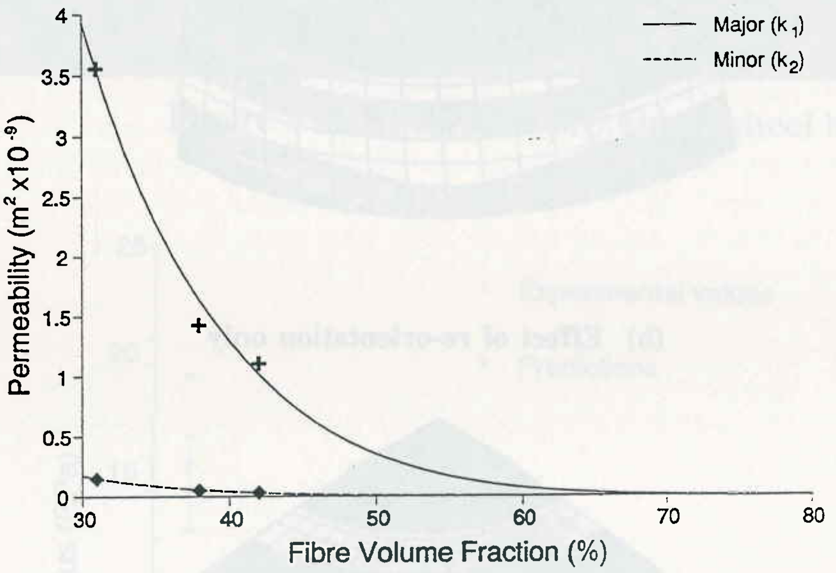


Figure 5 In-plane permeability data for quasi-unidrectional stitch bonded fabric reinforcement

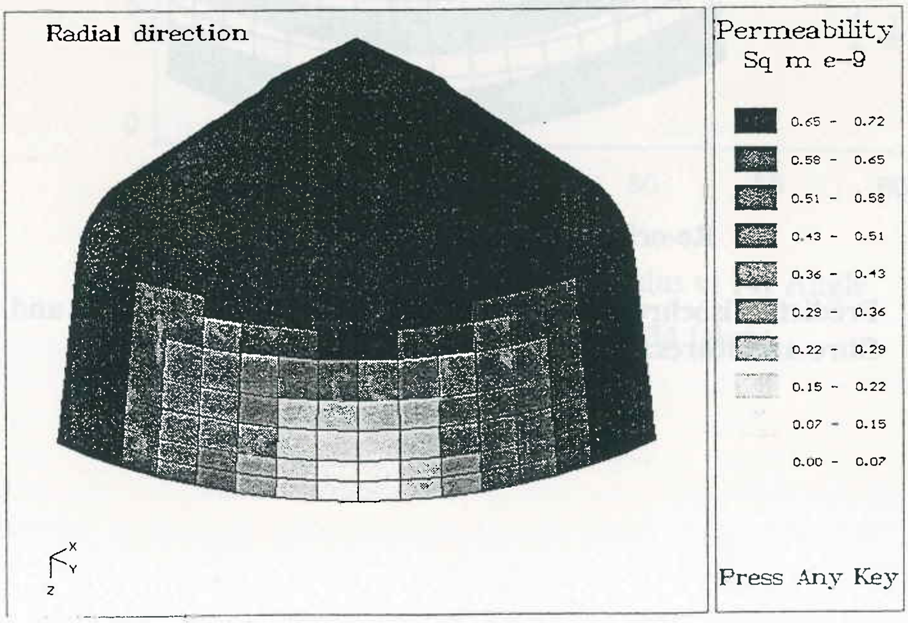
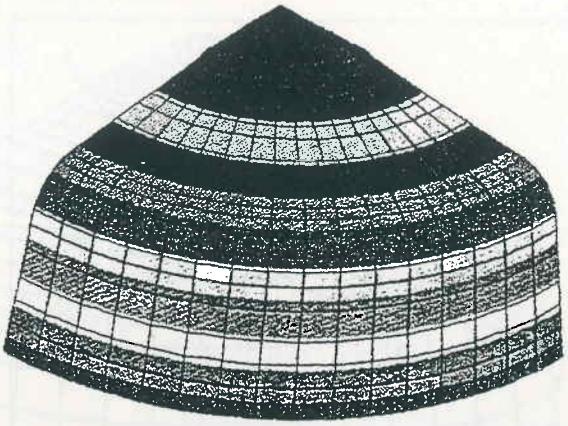
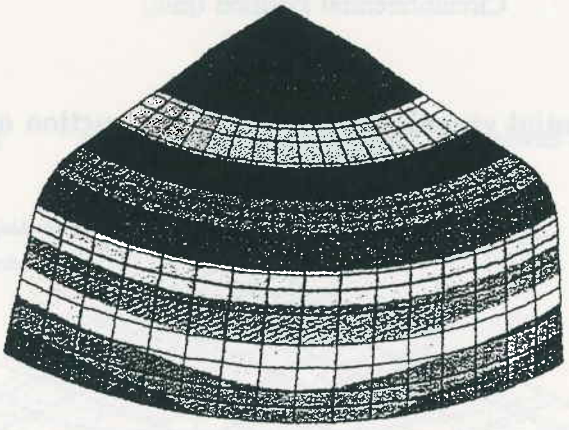


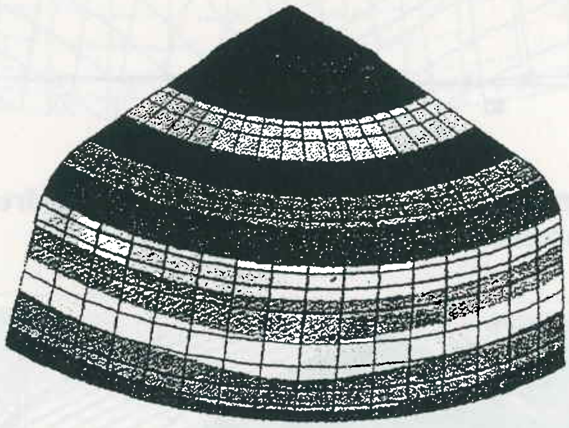
Figure 6 Predicted permeability distributions in prototype wheel hub comparing "draped" architecture with nominal fibre archíture.



(a) Nominal fibre architecture



(b) Effect of re-orientation only



(c) Re-orientation plus volume fraction change

Figure 7 Predicted isochrones during impregnation for "draped" and with nominal fibre architures.

Figure 8 Short shot for prototype wheel hub

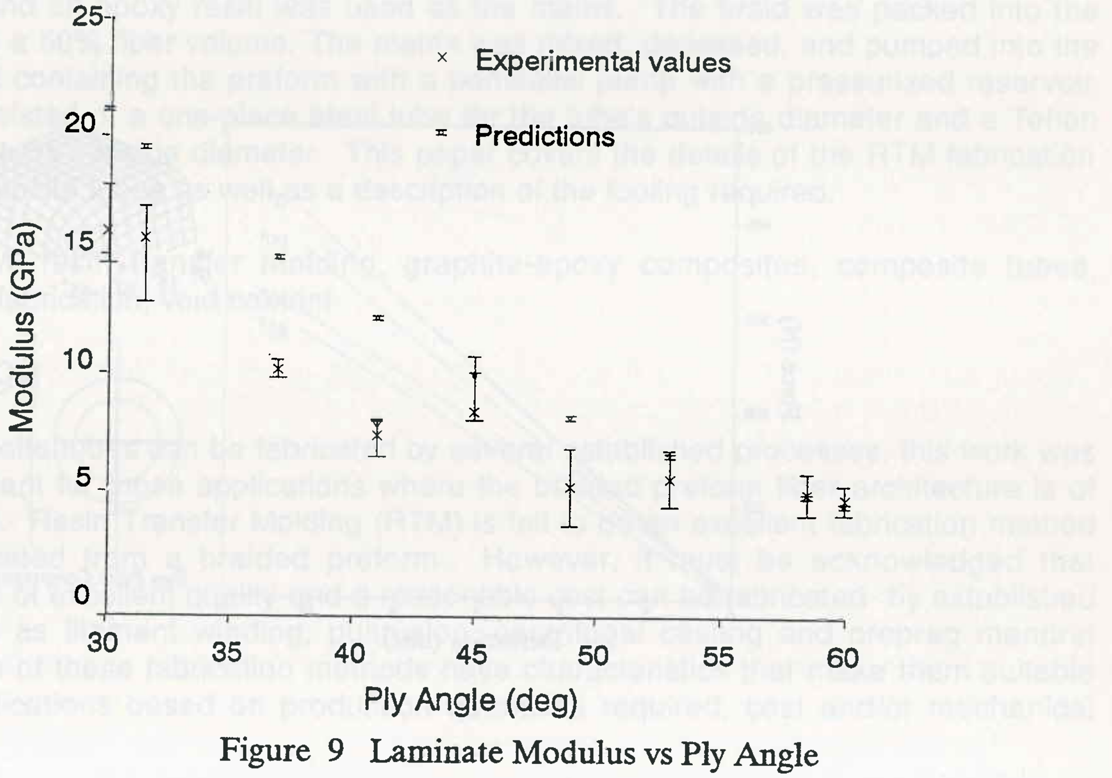


Figure 9 Laminate Modulus vs Ply Angle

Tech Textile ELT1134 fabric

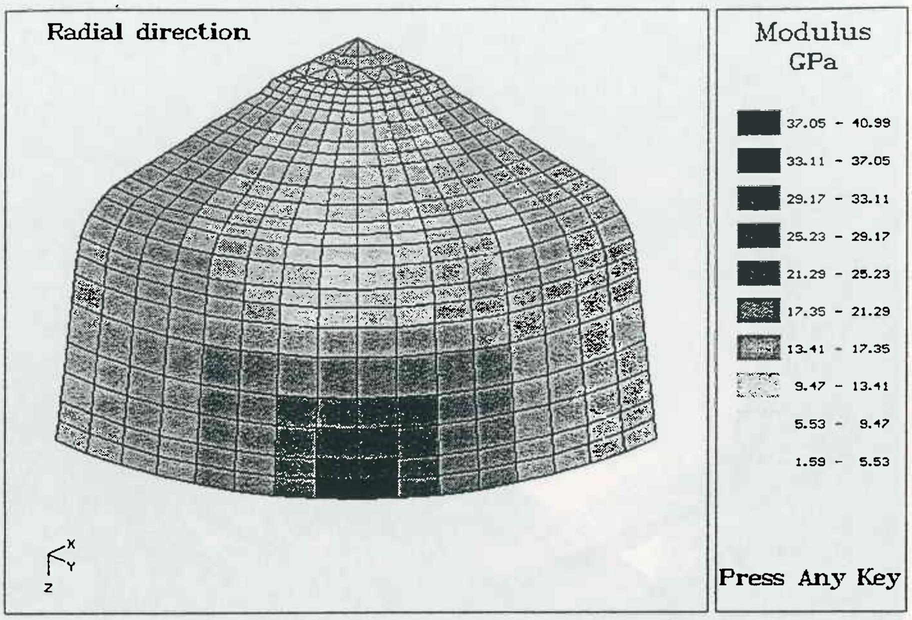


Figure 10 Predicted modulus distributions for prototype wheel hub

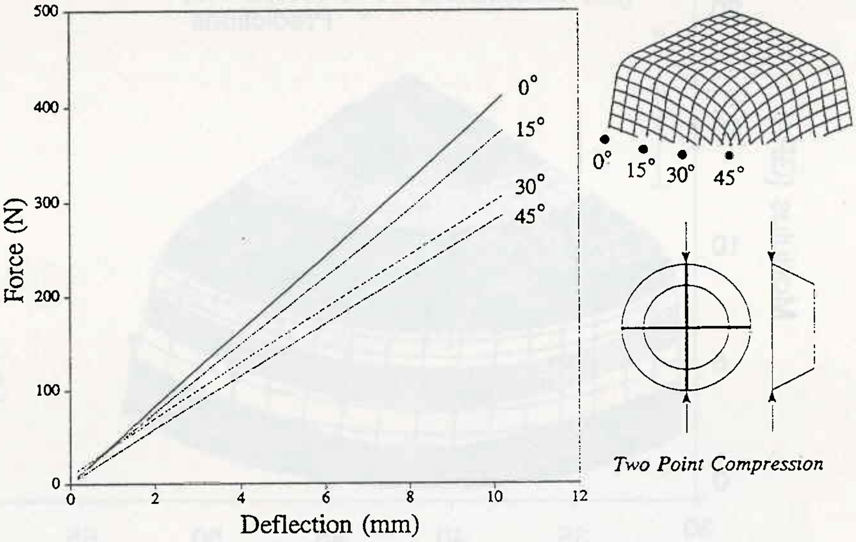


Figure 11 Pinch test results for prototype wheel hub