9
Resin impregnation and prediction of fabric properties

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9.1 Introduction

It is apparent from the previous chapter that there is a very wide range of textile products that can be used as reinforcements for composite materials and components. Such a wide choice provides the designer with great difficulty since an appropriate reinforcement must be selected for a specific application. There is no hard and fast rule for this selection and, in many instances, factors such as ease of manufacture become dominant and reinforcements are often selected on the basis of this rather than for performance enhancement. In general, textile reinforcements for composites show good tensile strength but have poor performance in terms of compression or stiffness. This necessitates the use of a matrix to encapsulate the fibres, thus protecting them from damage but also enhancing the performance of the composite, in particular overcoming some of the weaknesses of textiles.

Structural composites can be defined as products that use fibre reinforcements (50–70% by weight) of very high strength and stiffness in combination with polymeric, metal or other matrices. This class of composite has extremely unusual properties in which the matrix binds the reinforcing fibres together, forming a cohesive structure, providing a medium to transfer applied stresses from one filament through the matrix to the adjacent filaments. When polymeric matrices are used, composite structures with relatively low densities are produced which have very high specific properties, i.e. high strength/weight and high stiffness/weight ratios.

Thus it is necessary to use a means of impregnating the reinforcements with a matrix system which can be polymeric or metallic, although the emphasis as far as this book is concerned is directed towards polymer matrix composites (PMC). The distribution of the matrix throughout the reinforcement is critical to the overall performance of the composite. Small variations in fibre volume fraction throughout the composite give rise to significant variations in properties. The simple rule of mixtures (9.1) for unidirectional tape demonstrates the influence of fibre volume fraction (v_f) on stiffness (E):

$$E_{11} = v_f \cdot E_f + (1 - v_f) \cdot E_m \qquad [9.1]$$

where the subscripts f and m refer to fibre and matrix respectively.

If there is more than one type of fibre then this relationship can be modified:

$$E_{11} = (1 - v_f) \cdot E_m + v_{f1} \cdot E_{f1} + v_{f2} \cdot E_{f2} + v_{f3} \cdot E_{f3} \ldots \qquad [9.2]$$

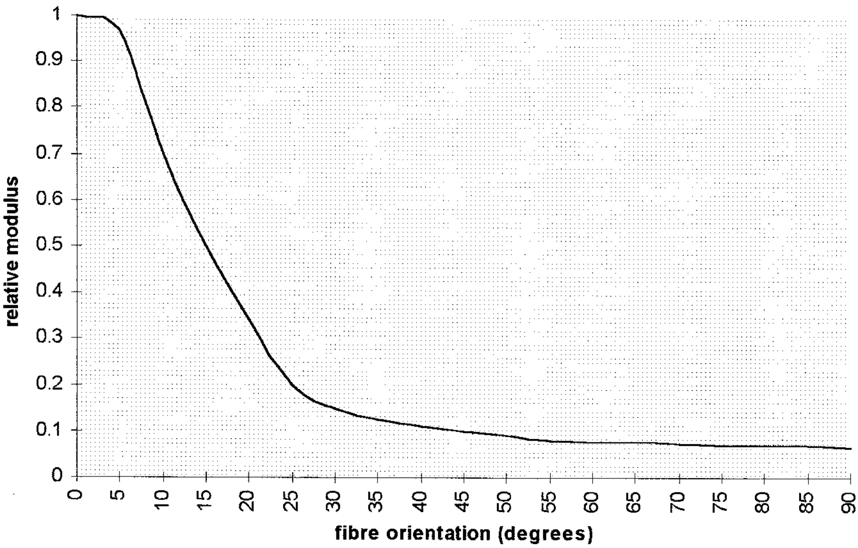
where v_f is the overall fibre volume fraction and v_{f1}, v_{f2} and v_{f3} the fibre volume fraction of the different fibre types.

In order to achieve uniformity of properties, the resin must completely fill the interstices within the fabric and also, significantly, the spaces between the filaments making up the tows. When optimum packing is achieved, the spaces between the fibres account for 9.9% but in reality this is more likely to be in the order of 20–25% since ideal packing of the fibre filament bundle is unlikely to occur under normal circumstances. Further, when more complex textile structures are employed as reinforcements, the efficiency of fibre packing will decrease even further, making fibre volume fractions in excess of 60% very difficult to realize. The filaments have to be completely encapsulated in the matrix in order to ensure effective and efficient load transfer between fibres and matrix and also to protect the filaments from damage.

To achieve this effective load transfer it is important that complete wet-out of the fibrous mass is achieved. This implies that low-viscosity resins must be used which, in turn, suggests that thermosetting resins are employed and that the performance is developed and enhanced through the crosslinking of the resin system. In general, thermoplastic resins are of higher molecular weight, and hence of higher viscosity during processing, making complete wet-out, in particular in the interfilament spaces, very difficult to achieve satisfactorily.

While the fibres dominate the tensile and stiffness properties, the matrix material influences high-temperature performance, transverse strength and moisture resistance of the composite. The resin is also a key factor in toughness, shear strength and in particular interlaminar shear stress (ILSS) resistance and oxidation and radiation resistance. Figure 9.1 demonstrates the significance of small deviations in fibre orientation on tensile modulus; these deviations also significantly reduce the tensile strength. Hence in-plane misalignment or indeed reinforcement crimp can result in significant losses in mechanical performance.

The matrix system has a significant influence on the fabrication process and associated parameters for forming the composite materials into intermediate and final components. Most carbon fibre composites are based on



9.1 Typical variation of modulus with fibre orientation.

thermosetting epoxy matrices which offer low shrinkage during processing, excellent adhesion to the fibres, good property balance, particularly mechanical to electrical performance, and ease of fabrication. They also have a good heat resistance and stability over a wide range of environmental conditions.

Typical fibre loading in high-performance composite materials is 60–65% by volume (65–70% by weight). Carbon fibres have a coefficient of thermal expansion which is a slightly negative sequence. Production of composites from fibres with a fairly broad range of coefficients of thermal expansion values permits the manufacture of components with an almost zero coefficient of thermal expansion. This feature can be exploited, particularly in aircraft, to hold critical instrumentation in a precise position as the composite properties of the supporting component can be tailored specifically at the design stage. For particular components this demonstrates the potential to design or engineer specific properties into materials to meet the performance requirements and hence optimize the structural design.

In comparison with steel and aluminium, carbon fibre composites are lighter, have lower thermal conductivity, are stiffer and stronger and have superior fatigue resistance. A summary of the typical properties of high strength and high modulus carbon fibre composite materials in an epoxy resin is shown in Table 9.1. The marked differences in properties between uni-directional (0°), transverse (90°) and the quasi-isotropic (0°, ±45°, 90°) fibre orientations should be noted. The high-modulus fibre composite data

Table 9.1. Typical properties of carbon fibre composite materials

Property	High strength	High modulus
Unidirectional laminate		
Longitudinal (0°)		
Tensile strength (MPa)	1785	1165
Tensile modulus (GPa)	145	215
Ultimate strain (%)	1.2	0.55
Compressive strength (MPa)	120	840
Compressive modulus (GPa)	140	190
Ultimate strain (%)	1.1	0.45
Flexural strength (4 pt) (MPa)	1995	1335
Flexural modulus (GPa)	135	190
Interlaminar SS (short beam) (MPa)	95	80
Transverse (90°)		
Tensile strength (MPa)	49	36
Tensile modulus (GPa)	9.5	7.0
Ultimate strain (%)	0.52	0.49
Additional properties		
Density (kg/m^3)	1550	1610
Shear strength (in plane) (MPa)	72	59
Shear modulus (in plane) (GPa)	4.8	4.1
Poisson ratio (0 coupon)	0.30	0.24
Coeff. thermal expansion $\times 10^{-6}$/°C		
0 °C	0.31	—
90 °C	35.8	—
Quasi-isotropic laminate (0°, ±45°, 90°)		
Tensile strength (MPa)	537	305
Tensile modulus (GPa)	50	73
Ultimate strain (%)	1.2	0.42

reflect the lower-strength, higher-modulus properties and lower shear strengths inherent in high modulus composites associated with the much higher thermal treatments that these fibres undergo during their manufacture.

9.2 Hand impregnation

There are a number of ways in which fibres or reinforcements can be impregnated with resin. Initially, when composite materials were used for leisure goods such as sports canoes, the resin system was hand mixed and then applied by brush to each layer and consolidated using pressure applied through a hand-held roller. Chemical reaction proceeded in the presence of air to produce a crosslinked matrix. Such systems are highly labour intensive with long cure cycles and also there are significant hazards owing to the volatile products of reaction released into the atmosphere during the cure. Properties of materials produced in this way tend to be variable because of the lack of process control, in particular local variations in amount of resin applied. In addition, it is extremely difficult to occlude all the air entrapped between the plies since compaction of the layers is by hand only. With no direct escape route for this air, stress concentrations are set up during the exothermic cure reaction, creating large voids within the structure. In these applications, glass fibre, often in chopped strand mat form, and polyester resins were used and under these conditions, it is extremely difficult to achieve high fibre volume fractions and hence high performance.

Hand lay-up techniques are used with open moulds to produce components with good surface finish characteristics. This is only possible on one surface. A gel coat is applied to the tool surface and allowed to cure. Plies of textile reinforcement are laid in on top of this hard gel coat finish, each being coated with resin and compacted. In this way the composite component is assembled and allowed to cure at room temperature. This labour-intensive hand lay-up operation in open tools is used to produce large components.

9.3 Matched-die moulding

To achieve a more uniform distribution of resin throughout the reinforcement, more automated systems came into use [1]. Pre-mixed resin and hardener are injected, under pressure from a pressure pot, into the reinforcement placed in closed matched cavity tools. The resin spreads out radially from the point of injection, permeating through the reinforcement until the cavity is completely filled with resin. Under such conditions the flow paths must be fully understood and predictable, otherwise resin-starved areas are created even in very simple geometric configurations in which the resin front impinges on the cavity boundary wall when the flow front can no longer expand in the radial direction. Two such fronts on adjacent walls will result in the flow converging on a point within the reinforcement. Unless high pressures are used, this region will remain dry, i.e. not impregnated with resin. If high pressure is used, then compression of the enclosed air will occur, which will cause an increase in the air temperature. At best this temperature rise will accelerate the crosslinking reaction prematurely and at worst the temperature will rise to such a degree that thermal degradation of the resin will occur. The outcome of this will be burn marks on the component and significant loss of mechanical properties. Hence air vents must be accurately positioned in these areas to assist the removal of entrapped air and provide a quality composite.

Such problems have led to a considerable amount of effort being made to model and predict the precise position of the molten resin front with respect to time [2,3]. These approaches, applied at the design stage, have permitted fill procedures to be developed by which resin-starved areas are eliminated through the use of accurately positioned vents and/or different resin injection points. These predictive approaches require greater knowledge of the properties of the reinforcements, particularly their permeability, which, depending upon the nature of the reinforcement constriction, may be different in the longitudinal and transverse directions. Modelling of isothermal flow of resin of constant viscosity through textile reinforcements with isotropic permeability is based on D'Arcy's equation (9.3):

$$Q = -\frac{KA}{\mu} \cdot \frac{\delta p}{\delta x} \tag{9.3}$$

where K is the permeability, μ the resin viscosity and $\delta p/\delta x$ the pressure drop per unit length.

For random mat non-woven reinforcements permeability is isotropic in-plane while for other textile structures the permeability will be different in different directions depending upon the nature of the textile structure. This differential permeability will result in complex flow patterns in the tool, making flow prediction even more important, although the use of D'Arcy's equation then becomes an over-simplification.

The vast majority of the tows employed in woven, braided or knitted reinforcements comprise low twist or untwisted continuous filament yarns. The pressure flow of the low viscosity resins can be assisted by capillary flow in the parallel channels between the filaments and control of the filling operation must be exercised to ensure resin 'racing' or 'tracking' does not occur. If this is not controlled the resin flow front will race ahead (or fall behind) before rejoining the pressure flow front, leading to unimpregnated enclosed dry regions. Hence variations in fibre volume fraction will result.

A variation of this process is to vacuum assist the resin into the tool. The cavity, with the reinforcement *in situ*, is evacuated and the resin is forced under pressure into the tool, thus wetting out the fibre. This approach is known as *vacuum assisted resin injection* (VARI) [4].

9.4 Degassing

One of the major difficulties associated with composite manufacture is that of void formation during impregnation and cure [5]. When these become entrapped within the matrix, stress concentrations can be established within the matrix. These may originate:

- during mixing of the resin formulation;
- during the complex chemical reactions that take place during the cure of thermosetting resins, when volatile gases are released and become encapsulated in the crosslinked resin;

- during filling of the cavity as described above;
- owing to the complex nature of the textile reinforcement, since air can become entrapped in the interstices of the fabric structure. This can be particularly evident when coarse yarns (or tows) are used or in complex 3-D braided or woven structures and may be most prevalent at the solid tool/composite interface.

During the formulation stage of the resin system, mixing is necessary to ensure that the hardeners, the crosslinking agents or any other additives are uniformly distributed and dispersed. The agitation during this formulation draws air into the uncured polymer along with the air already absorbed within the low viscosity fluid. As indicated above, these 'volatiles' are potential problem areas and must be eliminated in high-performance composites.

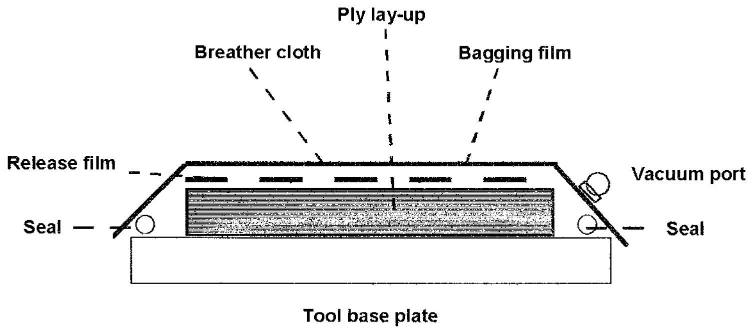
After rigorous mixing, the resin mixture is degassed, under full vacuum, giving a deaerated fluid ready for application to the reinforcement. This deaeration can be assisted by heating the resin, to reduce its viscosity, although great care must be exercised to ensure that crosslinking is not initiated.

9.5 Preimpregnation

One of the limitations of producing high-performance composite materials lies in the difficulty of achieving uniformity of fibre/resin distribution with low void content. Instead of relying on the pressure flow to force the resin throughout the reinforcement, dip coating and lick roll technology are used to apply a controlled and uniform amount of uncured resin to the reinforcement. The resin bath contains both the base matrix resin and the hardeners in a partially cured resin system. The rolls of 'prepreg' are wrapped in release film and can be stored under refrigerated conditions for a period of time before the shelf-life of the product expires (normally 90 days at –18 °C for aerospace quality materials). Adoption of this route ensures uniformity of resin distribution in the reinforcement and eliminates the need for the processor to handle resin systems but does require that low-temperature storage facilities are available on the production site.

9.6 Vacuum bagging

The vacuum bagging system is used for producing non-critical components. Plies of thawed out and conditioned prepreg are cut into the appropriate shape either by hand or by an automated process such as a Gerber® cutter system. Plies are placed in a precise order and orientation on a tool surface. The lay-up sequence and orientation of the plies is critical to the performance of the composite. A layer of release film is laid on top of the ply lay-



9.2 Vacuum bagging process for the production of composites.

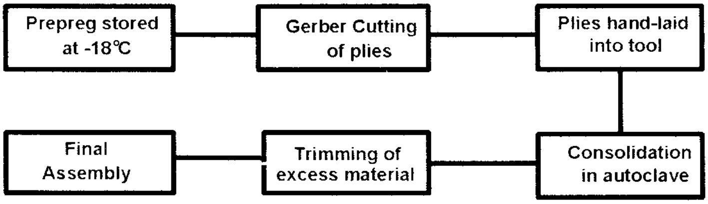
up to prevent the resinous stack of plies from adhering to the fibrous breather cloth. This cloth is used to absorb any excess resin and distributes the applied pressure evenly over the lay-up. The complete assembly is enclosed in a sealed bag or the bagging layer is sealed to the surface of the tool surround beyond the boundaries of the component as shown in Fig. 9.2. A vacuum connector is inserted into this bagging film so that the ply stack can be consolidated under approximately one atmosphere of vacuum. This complete assembly, while still under vacuum, is placed in an oven at an elevated temperature to cure the resin system.

While this route uses prepreg material, which should ensure an even distribution of resin throughout the reinforcement, it is only operated at a maximum pressure of approximately 1 bar to consolidate the plies into a 'homogeneous' layer. This low pressure is insufficient to compact the layers adequately to produce a high performance component with high fibre volume fraction and low void content.

9.7 Autoclave

For high-performance composites, high fibre volume and low void contents are essential. It is also important that distribution of both fibre and resin is uniform throughout the component. This is achieved by taking the vacuum bagging process one stage further. As previously described, prepregs in the form of unidirectional tows or woven fabrics impregnated with a partially cured resin system are used. The process follows the stages outlined in Fig. 9.3.

A number of the steps in this process are similar to those used in the vacuum bagging process. In these steps care must be exercised both from the point of view of health and safety and to ensure that the lay-up is contamination free. Such contamination can seriously impair the performance of the composite component. A clean room is required and protective cloth-



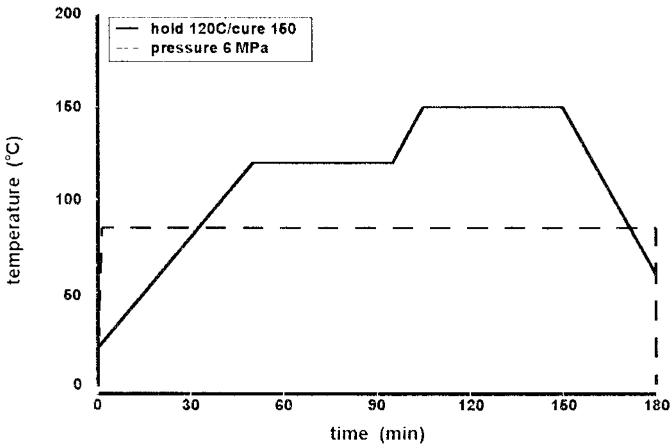
9.3 Route for composites production using the autoclave process.

ing should be worn at all times for the production of both defect-free components and health and safety reasons.

The various steps in the manufacturing route are as follows.

1 Prepreg material is stored under refrigerated conditions at –18 °C. Prior to processing, rolls are removed and allowed to thaw and condition. After reaching room temperature, the fabric is cut into shaped plies, taking fibre orientation into account. Computer-based nesting is used to optimize fabric utilization. These plies are labelled.
2 The plies are hand laid into the thoroughly degreased and clean moulding tool in the correct sequence and orientation. Constant inspection and signing-off of the lay-up at each stage is necessary to ensure performance and quality. Where the component comprises a large number of plies, frequent debulking is required, i.e. the lay-up is compressed under vacuum, after which a further series of plies are laid-in. A balanced lay-up, i.e. symmetry of lay-up about the neutral axis, minimizes the extent of springback. Once the lay-up is completed, a layer of release film is placed on top of the plies, the breather cloth placed on top of the release film and the whole assembly is bagged and sealed. A vacuum nozzle is attached to the complete assembly. These steps are identical to those shown in Fig. 9.2 for vacuum bagging. Vacuum is then applied to the assembly.
3 After confirming the integrity of the seal, the bagged assembly, while still under vacuum, is placed in a computer-controlled autoclave which is programmed to follow a particular processing cycle of both temperature and pressure. A typical cycle is as shown in Fig. 9.4.

   The cycle is designed so that the maximum flow is achieved up to and including the hold period so that the fabric can be completely wetted-out and the interstices and the interfilament regions in the fabric structure completely filled with resin. The application of pressure, through inert nitrogen gas at a very early stage in the cycle, consolidates the composite structure and the nitrogen minimizes the risk of fire and explosion. On ramping up the temperature to the maximum, the resin commences to crosslink through an exothermic chemical reaction. Heat-



9.4 Autoclave cure cycle.

up rates, typically at 2–5 °C/min, are slow, to ensure that the exothermic reactions are kept under control.

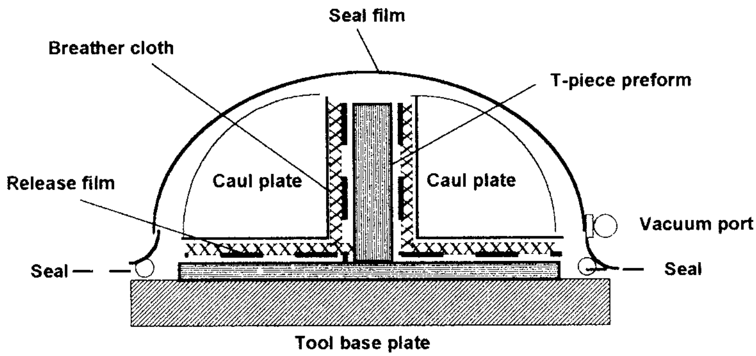
4 Once the cure cycle has been completed and the component cooled, also at a slow rate, the excess resin around the periphery is trimmed off and holes drilled, etc., where necessary.

5 Finally, the various components are put together to form the final assembly.

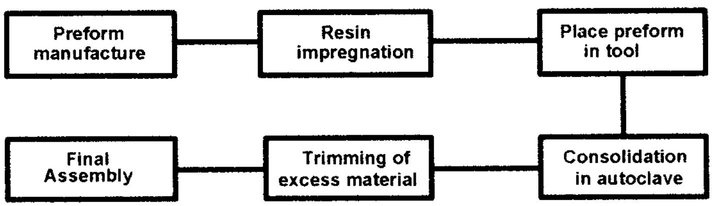
This route is used to manufacture high-quality composites mainly for aerospace applications. The fibre volume fraction for carbon fibre composites should be in the region of 60% and the void content <1%. Non-destructive quality control is performed using ultrasound scans or X-ray micrographs to confirm this. The autoclave can often form a bottleneck for composites manufacturing since commercial autoclaves are large and to be viable, full loads have to be assembled. Components of similar thickness are processed under the same cure cycle and hence production scheduling is crucial to the success of this operation.

Since a single tool surface is utilized, a good finish is only secured on one surface of the component, the other surface being in contact with the release film. However, caul plates can be used to produce a good surface finish on both sides of the component, even for reasonably complex shapes. The example in Fig. 9.5 shows how T-pieces can be manufactured. These caul plates solve the additional problem of consolidating both the web and the flanges simultaneously once the pressure is applied during the cycle.

While autoclave processing provides high-performance composites, the operation of the autoclave has associated high running costs. This route can



9.5 Tooling for production of T-pieces.

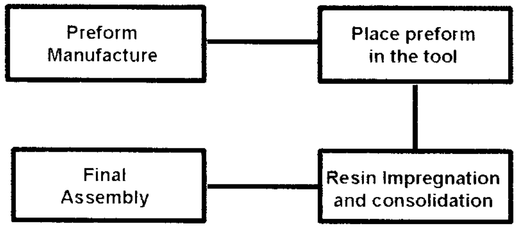


9.6 Route for composites production using preforms.

also take advantage of preforming of reinforcements. Three-dimensional technical textiles, produced by weaving [6], knitting [7], braiding [8] or as non-crimp fabrics (NCF) [9] as dry near net shape fabrics, can be placed directly in the tool, thus reducing considerably the labour intensity of the operation. Resin, applied either by brush or in film form (see later), is heated to make it less viscous, and wets-out the fabric under pressure. This is followed by cure in a heated tool. The basic process is shown in Fig. 9.6.

9.8 Liquid moulding with vacuum assistance

Alternative routes have been investigated to provide more flexible processes [10], both to eliminate the bottleneck in the autoclave process and to address the problems of mass production of quality components particularly for automotive applications. The major drawback to the autoclave route, apart from the large capital outlay required, is the high cost associated with the operation of the process. Low-temperature storage space is costly to operate, the ply cut-out is time consuming and wasteful. The manual ply lay-up procedure is labour intensive in terms of both implementation and inspection to guarantee the quality of the component.



9.7 Liquid moulding of composites using preforms.

As discussed above, resin impregnation under pressure also has its performance limitations but by using vacuum assistance, first of all to evacuate the cavity and then to draw the degassed resin into the reinforcement, high-performance composites can be produced. Adoption of such a route, as shown in Fig. 9.7, removes many of the disadvantages of the autoclave process, namely:

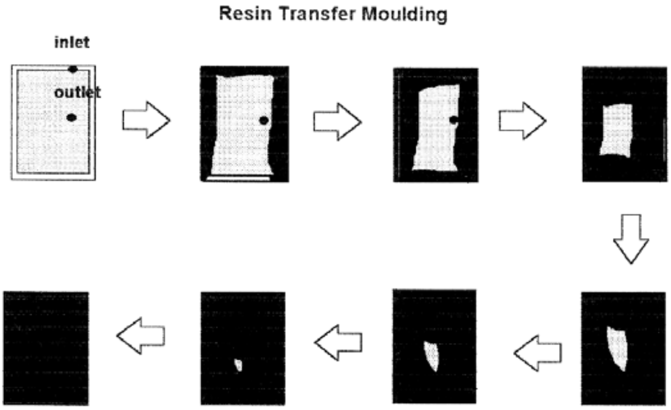
- Low capital investment, although mould costs may be higher if matched tooling is used.
- Cold storage areas are not necessary and hence high value added products are not held in stock.
- Shelf-life constraints are eliminated.
- When preforms are used, expensive cutting out and wastage are minimized and the labour-intensive hand lay-up is dispensed with.

The removal of these offers a much more viable operation, although there may be some restrictions on the level of pressure that can be applied and hence the degree of consolidation of the composite.

Investigations [7] into different combinations of gating and pressure/vacuum injection have shown that peripheral gating and vacuum injection provide the most effective route to achieve high-performance composites. Under this arrangement, the flow surrounds the reinforcement and then the flow front converges towards the vacuum exit point. The position of this is not critical since initial vacuum, removing all the air from the sealed tool, encourages the in-flow of resin throughout the reinforcement. The progression of the fill of a rectangular plaque with the exit point deliberately off-set is shown in Fig. 9.8 [11]. Hence under these circumstances, venting, if at all necessary, is much less critical.

The liquid moulding route with vacuum assistance is used to produce structural composites with high fibre volume fraction and low void content using either ply lay-up or more complex 3-D reinforcements. Clearly, the latter is a much less costly process particularly if near net shape textile reinforcements are employed.

One of the objectives of adopting the resin transfer moulding route as a



9.8 Sequence of mould filling using peripheral gating and off-centre vacuum exit.

manufacturing process is to reduce costs. However, utilization of matched tooling increases mould costs and indeed great care must be exercised to ensure that both sides of the tool are sufficiently stiff to resist plate deflection, thus introducing thickness variations in the component. Such variations will result in fibre volume fraction and performance variations throughout the composite structure. Stiffer tooling also has a large thermal mass which will, in turn, necessitate longer cycle times to complete the cure of the component.

The use of 'soft-top' tooling, i.e. using a base metal tool and bagging the complete assembly as previously described, and applying vacuum, overcomes the problem of thickness variation. For good surface finish on both sides of the component, a caul plate with a release film can be placed on top of the preform. Under these conditions, the pressure applied between the caul plate and tool surface holds the reinforcement in position. This allows the resin to flow in the space around the outer edge of the reinforcement before being drawn into the reinforcement, completely wetting it out. Thickness variations, using this technique, are much less pronounced than for matched tooling under pressure unless very stiff tooling is used.

9.9 Resin film infusion

To overcome the time-consuming process of deaerating the resin system to ensure void-free composite manufacture, layers of resin, in film form, are laid into the ply assembly. When heat, pressure and/or vacuum are applied, the resin becomes less viscous and flows to fill the interstices in the reinforcement and the spaces between the filaments. This is a much more rapid method of manufacture and can be used for mass production of components. When complex 3-D reinforcements are used, resin film layers can be placed on the top and bottom surfaces, allowing resin, when heated, to be drawn throughout the reinforcement by vacuum before further consolidation.

9.10 Pultrusion

For constant cross-section composite components, the pultrusion method of impregnation offers a relatively low-cost operation for composite manufacture. A preformed 3-D reinforcement is drawn through a heated die, not dissimilar to a conventional extrusion die. Heated polymer is forced into the reinforcement as it is hauled at slow speed through the shaped die. The impregnated textile is passed through either a second die or an oven to cure the resin system. This process produces, for example, I-beams or hollow rectangular tubes of uniform section which can be used in construction applications.

9.11 Conclusion

With this large number of permutations and combinations of reinforcements and resins systems it is necessary to provide the designer with some means of assessing the potential of some of these alternatives. This must be by a means that predicts the volume of fibre in different directions within the composite material. Hence a modelling system has been devised that calculates the amount of fibre making up the reinforcement within a known composite volume. Using a modified Rule of Mixtures, which takes into account contributions from the transverse fibres, the composite modulus can be predicted. This will provide the designer with a means of selecting an appropriate reinforcement for a particular application without a costly trial and error experimental assessment.

9.12 Prediction of fabric properties

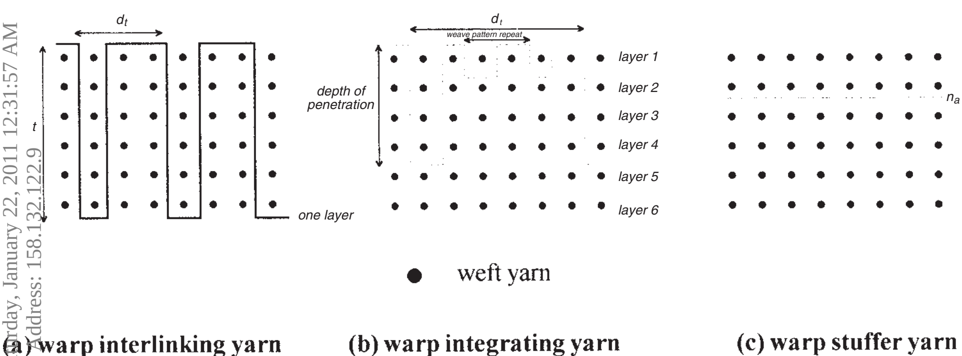
The thickness, and thus the fibre volume fraction, of the composite, together with the engineering properties of the reinforcement, which are a function of the proportions of yarn in each of the three mutually perpendicular directions, can be derived from the mass (areal density) of the textile reinforcement. Therefore the prediction of the areal density is important in the determination of composite properties.

The areal density, expressed in g/m^2, of the textile reinforcement can be determined by the summation of the masses of all the yarns within a measured area of the complete 3-D reinforcement which is large enough to contain sufficient weave pattern repeats to be representative of the structure.

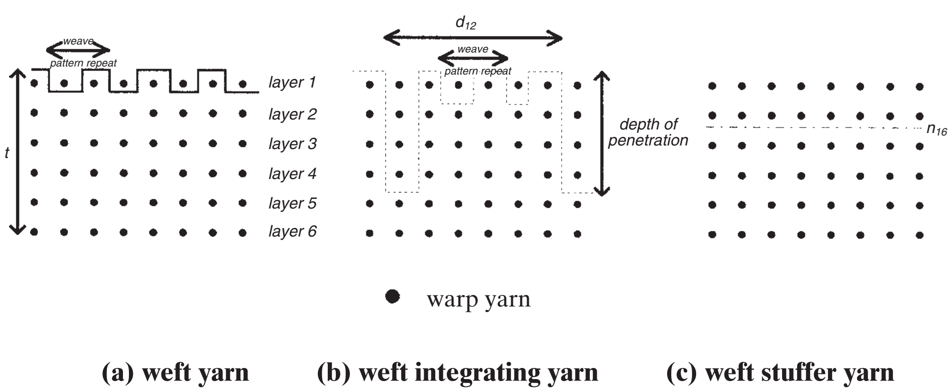
Consider the different yarn paths that can be located in a 3-D woven textile reinforcement (Figs. 9.9 and 9.10). In each of the warp and weft directions a yarn can play one of three roles and in Fig. 9.9 the role of each of the warp yarns is shown.

For the purposes of calculation it is assumed that each yarn follows a rectilinear path, as shown in Fig. 9.9 and, that the role of the yarn is consistent during the weaving process. Therefore, the 'straight' length of each yarn in the warp or weft direction is equal to the length of the reinforcement in that direction and the vertical elements contribute either to the through-the-thickness portion and/or to the 'normal' crimp content.

To calculate the total areal density of the reinforcement, the mass of each of the constituent yarn elements in 1 m^2 of the reinforcement is determined.



9.9 Geometric representation of possible warp yarn paths.



9.10 Geometric representation of possible weft yarn paths.

9.12.1 Mass of warp interlinking yarn (W_1) in 1 m^2 of reinforcement [12]

The warp interlinking yarns are relatively crimp free and lie on the top and bottom surfaces of the reinforcement. They bind the structure together by linking through the entire thickness of the reinforcement. The path of a typical warp interlinking yarn is shown in Fig. 9.9(a).

The mass of the warp interlinking yarn (W_1) is calculated using Equation 9.4.

$$\begin{aligned} W_1 &= \text{mass of the 'straight' section of yarn } (W_2) \\ &\quad + \text{mass of the interlinking section } (W_3) \end{aligned}$$

$$\begin{aligned} W_1 &= \left(e_1 \times 100 \times \frac{\text{tex}_1}{1000} \times n_1\right) \\ &\quad + \left(\frac{t \times 2}{100} \times \frac{e_1 \times 100 \times f_1 \times 100}{d_1} \times n_1 \times \frac{\text{tex}_1}{100}\right) \end{aligned} \qquad [9.4]$$

where: e_1 = ends/cm/layer of interlinking yarn,
tex_1 = yarn count of the interlinking yarn,
n_1 = number of layers of the interlinking yarn (usually 1 or 2),
t = thickness of the reinforcement in (cm),
f_1 = picks/cm/layer,
d_1 = number of picks between consecutive interlinks.

9.12.2 Mass of warp integrating yarn (W_4) in 1 m^2 of reinforcement [13]

The warp integrating yarns are woven in the structure in a specific weave pattern and all of the warp yarns are engaged in binding the structure together. At predetermined and regular intervals the linking is accomplished by a yarn transferring from its original layer to another layer before returning to its original layer. Within a reinforcement, the depth of penetration of the interlinking yarns into the structure is the same, in order to give symmetry about the mid-plane and to reduce the possibility of spring back. In Fig. 9.9(b) the integrating yarn follows a plain weave pattern with the yarns interlinking every six picks and transferring from their original layer to one three distant from it. Thus layer 1 links to layer 4 (as illustrated), layer 2 to layer 5, layer 3 to layer 6, layer 4 to layer 1, layer 5 to layer 2 and layer 6 to layer 3.

The mass of the warp integrating yarn (W_4) is determined using Equation 9.5.

W_4 = mass of the 'straight' section of yarn (W_5)
+ mass of the integrating section (W_6)
+ mass of the crimp element (W_7)

$$W_4 = \left(e_4 \times 100 \times \frac{\text{tex}_4}{1000} \times n_4\right) + \left(\frac{\varphi_4 \times t \times e_4 \times f_4 \times \text{tex}_4 \times n_4}{5 \times d_4}\right) + \left[\frac{t \times e_4 \times f_4 \times \text{tex}_4 \times (d_4 - \omega_4)}{5 \times d_4 \times \omega_4}\right] \qquad [9.5]$$

where: e_4 = ends/cm/layer of integrating yarn,
tex_4 = yarn count of the integrating yarn,
n_4 = number of layers of the integrating yarn,
t = thickness of the reinforcement (cm),
f_4 = picks/cm/layer,
d_4 = number of picks between consecutive interlinks,
φ_4 = is a factor related to the depth of penetration of the interlinking yarn and is equal to the number of yarns the integrating yarn passes vertically when forming the link plus one divided by the total number of yarns in one column in the cross-section,
ω_4 = number of picks in one weave pattern repeat (for a plain weave ω equals 2, for a 2 × 1 twill $\omega = 3$ and 8-end satin $\omega = 8$).

It should be noted that in the equation for W_4, the term relating to the mass of the crimp element does not contain a factor for the number of layers. This is because the crimp depth within a layer is defined as the thickness (t) divided by the number of layers (n) and therefore the total crimp element for n layers is equal to $t \times n/n$, i.e. t.

9.12.3 Mass of warp stuffer yarn (W_8) in 1 m^2 of reinforcement [12]

These yarns are crimp free and are in-laid into the structure, as illustrated in Fig. 9.9(c) to give improved engineering properties to the composite component. The mass of the warp stuffer yarn (W_8) is calculated using Equation 9.6:

$$W_8 = e_8 \times 100 \times \frac{\text{tex}_8}{100} \times n_8 \qquad [9.6]$$

where: e_8 = ends/cm/layer of stuffer warp yarn,
tex_8 = yarn count of the stuffer warp yarn,
n_8 = number of layers of the stuffer warp yarn.

9.12.4 Mass of weft yarn (W_9) in 1 m^2 of reinforcement [14]

These weft yarns take no part in binding the structure together and are part of the basic weave structure within each layer. In Fig. 9.10(a) the weft yarn follows a plain weave pattern. The mass of the weft yarn (W_9) is determined using Equation 9.7:

W_9 = mass of the 'straight' section of weft yarn (W_{10})
+ mass of the crimp element (W_{11})

$$W_9 = \left(f_9 \times 100 \times \frac{\text{tex}_9}{1000} \times n_9 \right) + \left(\frac{t \times e_9 \times f_9 \times \text{tex}_9}{5 \times \omega_9} \right) \qquad [9.7]$$

where: f_9 = picks/cm/layer,
e_9 = ends/cm/layer of warp yarn,
tex_9 = yarn count of the weft yarn,
n_9 = number of layers,
t = thickness of the reinforcement (cm),
ω_9 = number of picks in one weave pattern repeat.

9.12.5 Mass of weft integrating yarn (W_{12}) in 1 m^2 of reinforcement [12]

These yarns, illustrated in Fig. 9.10(b), have an identical role to the warp integrating yarns and their mass is determined using Equation 9.8:

W_{12} = mass of the 'straight' section of yarn (W_{13})
+ mass of the integrating section (W_{14})
+ mass of the crimp element (W_{15})

$$W_{12} = \left(f_{12} \times 100 \times \frac{\text{tex}_{12}}{1000} \times n_{12} \right) + \left(\frac{\varphi_{12} \times t \times e_{12} \times f_{12} \times \text{tex}_{12} \times n_{12}}{5 \times d_{12}} \right) + \left[\frac{t \times e_{12} \times f_{12} \times \text{tex}_{12} \times (d_{12} - \omega_{12})}{5 \times d_{12} \times \omega_{12}} \right] \qquad [9.8]$$

where: f_{12} = picks/cm/layer of integrating yarn,
tex_{12} = yarn count of the integrating yarn,
n_{12} = number of layers of the integrating yarn,
t = thickness of the reinforcement (cm),
e_{12} = ends/cm/layer,
d_{12} = number of ends between consecutive interlinks,
φ_{12} = a factor related to the depth of penetration of the interlinking yarn and is equal to the number of yarns the integrating yarn passes vertically when forming the link plus one divided

by the total number of yarns in one column in the cross-section,
ω_{12} = number of picks in one weave pattern repeat.

9.12.6 Mass of weft stuffer yarn (W_{16}) in 1 m^2 of reinforcement [1]

These are the non-crimp yarns incorporated in the reinforcement to improve the composite performance and are illustrated in Fig. 9.10(c). They perform the same function as the warp stuffer yarns and their mass is determined using Equation 9.9:

$$W_{16} = f_{16} \times 100 \times \frac{\text{tex}_{16}}{1000} \times n_{16} \qquad [9.9]$$

where: f_{16} = picks/cm/layer of stuffer weft yarn,
tex_{16} = yarn count of the stuffer weft yarn,
n_{16} = number of layers of the stuffer weft yarn.

The total mass (areal density) (W) of 1 m^2 of reinforcement is determined by the summation of the above values, using Equation 9.10:

$$W = W_1 + W_4 + W_8 + W_9 + W_{12} + W_{16} \qquad [9.10]$$

Most woven reinforcement constructions will contain only some of these elements and therefore only those that are relevant would be included in the calculations to determine the total areal density and subsequently the fibre proportions.

9.12.7 Determination of the percentage of yarn in the *X*, *Y* and *Z* directions

Once the overall mass has been determined then the proportions of yarn in each of the three mutually perpendicular directions can be determined. At this stage the ‘normal’ crimp is not considered as contributing to the *X*, *Y* or *Z* proportions even though it has been included in the determination of the overall weight. This is because the crimp elements do not lie in the principal stress directions and therefore do not contribute to either *X* or *Y*. In the *Z* direction, the crimp elements do not link the layers together; however, if nesting of the layers within the structure does occur then, under compaction during composite manufacture, the crimp undulations will fit into one another and provide resistance to interlaminar shear, thus aiding the *Z* component performance, and this may have to be taken into account later.

The *X* proportion has three elements W_2 (from Equation 9.4), W_5 (from

Equation 9.5) and W_8 (Equation 9.6). These are summed together (Equation 9.11) to give the total mass of yarn contributing to the X direction. This value is expressed as a percentage of the total areal density (W) (Equation 9.12). Therefore

$$W_X = W_2 + W_5 + W_8 \tag{9.11}$$

and

$$X\% = \frac{W_X}{W} \times 100 \tag{9.12}$$

The Y proportion is also made up of three elements W_{10} (from Equation 9.7), W_{13} (from Equation 9.8) and W_{16} (Equation 9.9). These too are summed together (9.13) to give the total mass of yarn contributing to the Y direction. This value is expressed as a percentage of the total areal density (W) (Equation 9.14). Therefore

$$W_Y = W_{10} + W_{13} + W_{16} \tag{9.13}$$

and

$$Y\% = \frac{W_Y}{W} \times 100 \tag{9.14}$$

The Z proportion is also made up of three elements W_3 (from Equation 9.4), W_6 (from Equation 9.5) and W_{14} (from Equation 9.8). These equations are summed together (9.15) to give the total mass of yarn contributing to the Z direction. This value is expressed as a percentage (9.16) of the total areal density (W). Therefore

$$W_Z = W_3 + W_6 + W_{14} \tag{9.15}$$

and

$$Z\% = \frac{W_Z}{W} \times 100 \tag{9.16}$$

Thus, from the design concept of a woven reinforcement structure it is possible to predict the areal density, thickness and proportions of fibre in each of the three mutually perpendicular directions.

From the total areal density (W), the fibre volume fraction (v_f) can be determined if the thickness (t) of the proposed composite is known using Equation 9.17:

$$v_f = \frac{W}{10\,000 \times t \times \rho} \tag{9.17}$$

where ρ = fibre density (g/cm^3).

9.12.8 Prediction of the composite modulus

Known values of E_f and E_m and calculated values of v_{fx}, v_{fy} and v_{fz} can be substituted into a modified rule of mixtures, Equations 9.18, 9.19, 9.20, and the composite moduli in the three mutually perpendicular directions determined thus:

$$E_x = E_f v_{fx} + (1 - v_f)E_m + \frac{E_f E_m v_{fy}}{E_m v_{fz} + (1 - v_f)E_f} + \frac{E_f E_m v_{fz}}{E_m v_{fz} + (1 - v_f)E_f} \quad [9.18]$$

where E_f is the modulus of the fibre and E_m is the modulus of the resin matrix.

Similarly,

$$E_y = E_f v_{fy} + (1 - v_f)E_m + \frac{E_f E_m v_{fx}}{E_m v_{fx} + (1 - v_f)E_f} + \frac{E_f E_m v_{fz}}{E_m v_{fz} + (1 - v_f)E_f} \quad [9.19]$$

$$E_z = E_f v_{fz} + (1 - v_f)E_m + \frac{E_f E_m v_{fx}}{E_m v_{fx} + (1 - v_f)E_f} + \frac{E_f E_m v_{fy}}{E_m v_{fy} + (1 - v_f)E_f} \quad [9.20]$$

The directional fibre volumes (v_{fx}, v_{fy} and v_{fz}) are fractional values of v_f based on the percentage of fibre in the specified direction and, for example, v_{fx} can be determined using Equation 9.21. Therefore

$$v_{fx} = \frac{v_f x X\%}{100} \quad [9.21]$$

and similarly for v_{fy} and v_{fz} are determined using the values of $Y\%$ and $Z\%$.

In the particular case when the mass of the yarn making up the crimp element is not taken into account in determining the overall areal density, then v_f can be calculated from the summation of the directional fibre volumes (9.22):

$$v_f = v_{fx} + v_{fy} + v_{fz} \quad [9.22]$$

9.13 References

1. Kendall, K.N., Rudd, C.D., Owen, M.J. and Middleton, V., 'Characterisation of the resin transfer moulding process', *Composites Manufacturing* **3**(2), 235–249, 1992.
2. Lui, B., Bickerton, S. and Advani, G., 'Modelling and simulation of resin transfer moulding-gate control, venting and dry spot prediction', *Composites Part A*, **27a**(2), 135–141, 1996.
3. Ferland, P., Guittard, D. and Trochu, F., 'Concurrent methods for permeability

measurement in resin transfer moulding. Modelling and simulation of resin transfer moulding', *Polymer Composites*, **17**(1), 149–153, 1996.

4. Matthews, F.L. and Rawlings, R.D., *Composite Materials: Engineering and Science*, Chapman and Hall, London, 1995, p. 184.
5. Lowe, J.R., Owen, M.J. and Rudd, C.D., 'Void formation. Resin transfer moulding', in *Proc. of the 4th International Conference on Automated Composites, ICAC95*, Nottingham, Institute of Materials, pp. 227–234, 1995.
6. Hill, B.J., McIlhagger R., Harper C.M. and Wenger, W., 'Woven integrated multilayered structures for engineering preforms', *Composites Manufacturing*, **5**(1), 25–30, 1994.
7. Gommers, B. and Verpoest, I., 'Tensile behaviour of knitted fabric reinforced composites', in *Proc. 10th International Conference on Composite Materials (ICCM10)*, Whistler, Canada, 1995, Vol. IV, pp. 309–316.
8. Li, W., Hammad, M. and El-Shiek, A., 'Structural analysis of 3D braided preforms for composites. Part 1 The 4 step process', *J. Text. Inst.*, **81**(4), 491–514, 1990.
9. Chou, T.W. and Ko, F.K., *Textile Structural Composites*, Vol. 3, Composite Materials Series, Elsevier, Oxford, 1989, pp. 140–142.
10. Abraham, D. and McIlhagger, R., 'A review of liquid injection techniques for the manufacture of aerospace composite structures', *Polymers Polymer Composites*, **4**(6), 437–443, 1996.
11. Abraham, D. and McIlhagger, R., 'Vacuum assisted resin transfer moulding for high performance carbon fibre composites', in *Proc. of the 4th International Conference on Automated Composites, ICAC95*, Nottingham, 1995, pp. 299–306.
12. Hill, B.J. and McIlhagger, R., 'The development and appraisal of 3D interlinked woven structures for textile reinforced composites', *Polymers Polymer Composites*, **4**(8), 535–539, 1996.
13. Hill, B.J. and McIlhagger, R., 'The development and appraisal of 3D fully integrated woven structures for textile reinforced composites', *Polymers Polymer Composites*, **5**(1), 49–56, 1997.
14. Hill, B.J., McIlhagger, R., Soden, J.A., Hanna, J.R.P. and Gillespie, E.S., 'The influence of crimp measurements on the development and appraisal of 3D fully integrated woven structures', *Polymers Polymer Composites*, **5**(2), 1–10, 1997.