CONSOLIDATION MODELLING FOR TEXTILE COMPOSITES

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ABSTRACT

Fibre reinforced composite materials incorporating thermoplastic matrices are gaining increasing popularity in many industrial applications. To achieve adequate mechanical properties of the final product sufficient matrix impregnation of the fibres is essential. Commingled yarn preforms incorporate matrix in fibre form into the reinforcement fibre bundle facilitating the elimination and prevention of voids and dry spots. The conditions to impregnate the bundle are dependent upon the material properties and the consolidation process parameters. The processing parameters include the applied pressure, the temperature and the time at pressure. The density of the fibre packing, the dimensions of the fibres and their arrangements as well as the viscosity, and the distribution of the matrix affect the flow of the polymer into the interstitial space of the laminate. The material used for the experiments is a balanced twill weave fabric of density 1.5 g/cm$^3$ consisting of a yarn of 60% by mass commingled E-glass and polypropylene supplied by Vetrotex International under the trade name Twintex®

1 INTRODUCTION

In this paper a consolidation model for commingled thermoplastic composites is developed. In addition, experimental analysis is performed on flat laminates consolidated by an isothermal low pressure forming process Measurements of void content are obtained, using image analysis techniques [1], and these are related to the processing parameters.

Based on general assumptions a sensitivity study is carried out. These assumptions are:

- The fluid is non-Newtonian.
- Pressure uniform and remains constant during tests.
- The width and length of the fabric are much larger than the thickness so that matrix pressures are constant in the cross section.
- A yarn is constituted of elliptical dry fibre bundles surrounded by the matrix pool. However, the flow front is considered to advance radially.
- The consolidation of the whole laminate can be described by the consolidation behaviour of a single representative yarn.
- Flow takes place in the direction orthogonal to the fibres.
- Due to the low pressure applied (vacuum pressure), capillary flow must also be considered in the impregnation model.
- No void nucleation, migration or dissolution in the matrix is assumed to occur. However, the effects of these mechanisms will be discussed in this paper.

Three submodels have to be used:
1. A compaction submodel, which predicts the deformation of the reinforcement only.
2. A permeability submodel, which determines fibre bundle permeability.
3. An impregnation submodel, which predicts the encroachment of the matrix into the fibre bundles.

2 SUBMODELS

2.1 Compaction submodel

Van West et al [2, 3] used a fibre compaction model of the following form (based on work by Hou [4]):

\[
P_{fb} = A_s \left(\frac{t_o - t}{t_o - t_\infty}\right)^n
\]

where \(P_{fb}\) is the fibresbed pressure, \(A_s\) is a fibresbed elastic constant, \(t_o\) is the initial laminate thickness, \(t_\infty\) is the minimum laminate thickness (1.53 mm for Twintex®) and \(t\) is the instantaneous laminate thickness. This expression relies on experimental compaction data to determine suitable values for \(A_s\) and \(n\). Cain et al [5, 6] carried out these experiments on Twintex to evaluate the compaction characteristics of the glass fibres within the commingled fabric in isolation. Samples were heated at 400°C for 300 seconds to burn off the polypropylene. The fabric was then soaked in mineral oil as the fibre bed would be lubricated by the molten matrix during the moulding process. The samples were then compacted between flat platens using an Instron model 1195 testing machine at 1mm/minute. Cain et al [5, 6] found that a simple power law model could represent the compaction behaviour:

\[
P_{fb} = A \left(\frac{t_\infty}{t}\right)^b
\]

The constants \(A\) and \(b\) were determined by Cain et al [5, 6] to be 0.035495 and 10.1 respectively.

In this section, two compaction models have been presented. These two models represent the deformation behaviour of the laminate for different levels of pressure. However in both cases the models were only used for experiments conducted at high pressure (significantly greater than 1 bar). Therefore an alternative way to calculate fibre volume fraction is used in this study.

It is observed from experiments that the void content is a function of the total thickness of the laminate. In fact, the void content can be calculated as:

\[
V_c = \frac{t - t_\infty}{t}
\]

Fig. 1 shows a comparison between the measured void content using microscope image analysis and the void content calculated from the measured thickness using a point micrometer. A limitation to this comparison is the changing thickness of the laminate due to surface undulations, as shown in Fig. 2.

The current thickness can be obtained from Eqn. 3, hence the current fibre volume fraction can be calculated as:

\[
v_f = v_{f\infty} \frac{t_\infty}{t}
\]

where \(v_{f\infty}\) is the fibre volume fraction of a fully consolidated laminate (\(v_{f\infty}=0.35\) for Twintex®).
2.2 Permeability submodel

Gutowski et al [7] developed a modified form of the Kozeny-Carman equation to predict the transverse fibre bundle permeability coefficient:

$$K = \frac{r_f^2}{4k'} \left( \frac{v_a}{v_f} - 1 \right)^3 \frac{v_a}{v_f + 1}$$

The value of $v_a$, fibre volume fraction at zero permeability, was calculated to be 0.91 assuming hexagonal close packing of fibres. For glass fibres used in Twintex® the fibre radius is $r_f = 9.25\mu m$.

There are no data available that represent the permeability behaviour of the material used in this experiments, so the constant the Kozeny constant, $k'$, has to be obtained empirically. Fig. 3 shows how different values of $k'$ affect to the permeability.

**Figure 1** Comparison between void content measured using microscope image analysis and void content calculated using the current thickness of the laminate.

**Figure 2** Cross-section of a 3 ply glass/PP laminate consolidated by vacuum pressure.

$$\text{Eqn. (3)}$$

$$\text{Measured}$$
2.3 Impregnation submodel

Bernet et al [8, 9] stated that neglecting flow in the fibre direction and considering the fibre impregnation rate to obey Darcy’s law, the time increment $\Delta t$ necessary for the resin to advance a distance $\Delta r_i = R_i - r_i$, where $R_i$ and $r_i$ are the positions of the resin flow front before and after $\Delta t$, is calculated from:

$$
\Delta t = \frac{\eta(1 - v_f)}{K(P_a + P_c + P_v)} \left[ \frac{r_i^2}{2} \ln \left( \frac{r_i}{r_0} \right) - \frac{R_i^2}{2} \ln \left( \frac{R_i}{r_0} \right) - \frac{r_i^2}{4} + \frac{R_i^2}{4} \right]
$$

(6)

where $\eta$ is the non-Newtonian resin viscosity, $v_f$ is the fibre volume fraction, $r_0$ is the initial agglomeration radius, $K$ is the permeability, $P_a$ is the applied pressure (transmitted hydrostatically by the molten resin to the boundary of each fibre agglomeration), $P_c$ is the capillary pressure and $P_v$ is the internal void pressure (for a vacuum pressure process, $P_v$ is assumed to be zero). It is assumed that small fibre bundles tend to gather within the yarns. Each of these groups is known as an agglomeration.

Assuming that the commingled yarn contains $N_a$ agglomerations with an initial radius $r_0$, the total void content of the yarn at a given time step is given by:

$$
V_c = \frac{N_a r_i^2(1 - v_f)}{A_t + N_a r_i^2(1 - v_f)}
$$

(7)

where $A_t$, the cross sectional area of the fully consolidated yarn, can be expressed as:

$$
A_t = \frac{N_t \pi r_f^2}{v_f}
$$

(8)

where $N_t$ is the number of reinforcing fibres in the total commingled yarn and $R_f$ is the fibre radius. For Twintex® the number of fibres per in a yarn is $N_t = 1600$.

2.3.1 Capillary pressure

$P_c$ is the capillary pressure, defined here as positive when it enhances resin flow. Following Bernet’s model [8, 9], the capillary pressure can be estimated theoretically using the Young-Laplace equation:
where $\gamma_l$ is the surface tension of the polypropylene and $\theta$ is the contact angle between the solid and the liquid. Capillary pressure can be estimated using $\gamma_l = 0.029 \text{Jm}^{-2}$ and $\theta = 89^\circ$ [10]. Typical values of capillary pressure are between 75 Pa and 100 Pa for fibre volume fraction between 0.3 and 0.35 respectively.

2.3.2 Shear Thinning

Polypropylene is widely known to behave in a non-Newtonian manner so Cain et al [5, 6] incorporated a facility for shear-strain rate dependent viscosity into their model. The scheme suggests that at ultimate compaction, the reinforcing fibres will assume a hexagonal close packing configuration, Fig. 4. At intermediate stages the fibres will lie in a proportionately packed hexagonal array. This allows construction of a triangular unit cell, with the inter-fibre spacing being denoted by $x$.

![Figure 4 Hexagonal packing and triangular unit cell geometry.](image)

Hence, an expression relating $x$ to the instantaneous fibre volume fraction $v_f$ can be derived:

$$
\left( \frac{x}{r_f} + 2 \right)^2 = \frac{\pi}{v_f \cos \frac{\pi}{6}} \tag{10}
$$

Eqn. (10) can be solved for $x$, giving a measure of the inter-fibre spacing within the bundle. The flow path between fibres can be represented as a rectangular channel, thus Eqn. (11) can be easily used to determinate the matrix shear-strain rate attributable to flow between fibres.

$$
\gamma_a = \frac{2n+1}{n} \left( \frac{2V}{x} \right) \tag{11}
$$

Here, $n$ appears in the exponent of the power law, which is fitted to the viscosity and $V$ is the flow velocity, which can be determined from the flow front radius $r_i$, the flow front radius at the previous time step $R_i$, and the duration of the time step $\Delta t$.

A generalised Newtonian model [11] describes the shear rate and temperature dependence of the viscosity. The viscosity model is fitted by the Carreau-Yasuda model:

$$
\eta = \eta_{\infty} \left[ 1 + \left( \lambda \dot{\gamma} \right)^n \right]^{(m-1)/\lambda} \tag{12}
$$
where $\eta$ is the viscosity, $\eta_0$ is the zero shear rate viscosity and $m$, $a$ and $\lambda_{cy}$ are additional fitting parameters. It was observed from the experiments that $m$ has approximately the same value as $n$ in Eqn. (11) for the range of shear strain rate predicted in the consolidation model. The shift factor $a_r$ is calculated by

$$\log(a_r) = A \left( \frac{1}{T} - \frac{1}{T_{ref}} \right)$$  \hspace{1cm} (13)

With $A = \Delta H / 2.303R$, $\Delta H$ is the ‘flow activation energy’, $R$ the Boltzmann gas constant and $T_{ref}$ the reference temperature (in °K).

Parameter values used in the Carreau-Yasuda model are given in Table 1 along with the parameters for Arrhenius equation. These parameters were obtained from steady shear rate sweep experiments carried out in The University of Cambridge. Experiments were performed on a Rheometrics RMS 800 using parallel plates of 25 mm diameter. Polypropylene pellets were formed into 1 mm thick circular discs at 200°C under 8 MPa pressure for about 10 minutes then cooled. The discs were loaded between the heated plates and squeezed to a gap of 0.8 mm. Tests were performed at 170 to 220°C in steps of 10°C. The shear strain rate range was from 0.0156s$^{-1}$ to 100s$^{-1}$.

### Table 1 Parameter values for fitted Carreau-Yasuda model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Carreau-Yasuda</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_0$ (Pas)</td>
<td>840</td>
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<tr>
<td>$\lambda_{cy}$</td>
<td>0.16</td>
</tr>
<tr>
<td>$m$</td>
<td>0.4</td>
</tr>
<tr>
<td>$a$</td>
<td>2</td>
</tr>
<tr>
<td>$\Delta H$ (mole°K/KJ)</td>
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</tr>
<tr>
<td>$T_{ref}$ (K)</td>
<td>473</td>
</tr>
<tr>
<td>$R$ (KJ/mole°K)</td>
<td>8.31 $10^{-3}$</td>
</tr>
</tbody>
</table>

3 RESULTS

The aim of this model is to predict void content as a function of processing parameters. A comparison between measures and predicted void content is shown in Fig. 5 and Fig. 6, where the effect of different Kozeny constants and the number of agglomerations is observed.

When the Kozeny-Carman constant equals 125 and the number of agglomerations is between 10 and 15, the predicted void content shows acceptable correlation with the measured void content. However, the assumption that the number of agglomeration is constant during the process is not entirely clear. From experiments, see Fig. 7 and Fig. 8, it is observed that voids tend to migrate towards the vacuum outlet, thus voids close to the surface of the laminate will disappear as time at pressure increases due to migration.

Shear strain rates range from 33.3s$^{-1}$ to 3.2s$^{-1}$ from the beginning to the end of the experiment, which correspond to viscosity values between 380 Pas and 970 Pas.
A glass/PP commingled thermoplastic was consolidated and void content was quantified using microscope image analysis techniques. Void content was predicted as a function of processing parameters such as pressure, time at pressure and processing temperature. An existing model based on Darcy’s law flow front progression was modified to account for the effect of shear thinning. Sensitivity studies revealed the

4 CONCLUSIONS

Figure 5 Comparison between predicted and measured void content.

Figure 6 Effect of number of agglomerations on void content.

Figure 7 Laminate consolidated for 60 seconds.

Figure 8 Laminate consolidated for 120 seconds.
effect of the number of agglomerations on the predicted void content. Disagreement on the predicted void content may be due to migration of the voids towards the surface of the laminate as shown in micrographs.

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6 REFERENCES