TRANSITIONAL BEHAVIOUR OF PREPREGS IN AUTOMATED FIBRE DEPOSITION PROCESSES

D. Ivanov*, Yiqing Li, C. Ward, K. Potter
Advanced Centre for Innovation and Science, University of Bristol, UK

Abstract
This paper explores the compaction behaviour of modern toughened prepreg materials. An experimental programme has shown that the material compressibility is strongly dependent on the initial ply thickness, tools constraints, strain, and load history. A micromechanical deformation mechanism is suggested to explain the observed phenomena. It shows that prepreg compaction can be explained in terms of the reconfiguration of inter-fibre channels.

1 Introduction
Fibre deposition and debulking of prepregs in automated processes requires sophisticated tuning of manufacturing parameters, in order to get a defect free component. Resin rich channels, entrapped porosity, thickness variation, and fibre path deviations present major risks in composite quality, particularly for thick components.

Modern toughened prepregs are complex time-, temperature-, and strain rate-dependent systems. In the typical temperature range of deposition and consolidation used in manufacturing (~30-90°C), these prepregs exhibit a strong transition in viscosity – up to six orders of magnitude [1]. Viscosity determines the flow type: the resin can either escape from the ply without shifting the fibres (known as bleeding or percolation flow), or push fibres transversely making the system deform as an incompressible fluid (known as squeezing or shear flow). The toughened thermosets, within the temperature range used, exhibit intermediate viscosity, where a concurrent flow pattern is observed. The toughened prepregs exhibit features typical for both the traditional low-viscosity thermoplastics and the traditional high viscosity thermosets.

The flow mechanism at the fibre and ply scale determines the ability of the material to deform. In pure bleeding the through-thickness compaction is limited: it is determined by the ratio of initial fibre volume fraction (typically 40-50% after debulking) to the maximum fibre volume fraction (typically 70-75%). In the squeezing medium higher compressibility is possible due to the transverse flow of material. Understanding the transition between these flows is essential. For instance, heating to an elevated temperature prior to consolidation may forbid the closure of gaps between tows: the resin bleeds out rather than pushes fibres into those gaps. On the other hand, consolidation at low temperatures can require unrealistically high pressure levels to achieve a certain thickness.

The mechanical behaviour of squeezing fluid in a flat compaction test is a classical problem. An early review of the flow models for prepregs was conducted by Hubert and Poursratip [2]. Engman et al [3] produced a comprehensive summary of squeezing flow models for isotropic fluids. Among the rich variety of the available compaction models, analytical models present a particular interest for this study since they allow for the direct identification of material properties (from simple compaction tests). The first analytical solution, relating applied pressure to thickness for an ideal unidirectional fibre reinforced Newtonian fluid under no-slip and zero-friction conditions, was obtained by Rogers [4]. This solution was later generalised to account for ply interaction [5], partial slip [6], and rate-dependent material response such as a shear thinning power law [7]. More complex forms of material behaviour, for example the Carreau-type, present a serious
challenge for analytical integration [8]. Servais et al [9], considering Newtonian and Power Law as the limit cases of Carreau and Herschel–Bulkley behaviour, suggested a closed form solution for stochastically reinforced media. The squeezing flow models have been mostly applied to and validated against highly viscous thermoplastics such as PEEK, PS [7, 8], and PP [9].

The approaches used for the description of low viscosity thermosts are drastically different. Typically percolation flow models utilise Darcy’s law to describe the movement of resin and the rate-independent compaction model of fibrous networks to link pressure and the fibre volume fraction evolution [10, 11, 12, 13, 14]. Hubert and Poursartip [11], considering the compaction of prepreg saturated with liquid resins, demonstrated that the rate independent constituent of material reaction (fibre bed response) does not depend on the ply lay-up and laminate thickness. Commonly used additive superposition of viscous and elastic responses leads to differential equations, which show gradual pressure redistribution from resin to fibre network in the course of compaction. An alternative argument is defended by Kelly [15] who has demonstrated for some material systems, such as short fibres impregnated with low viscosity resins, that multiplicative stress superposition is better suited for the modelling of consolidation experiments. It is interesting to note that this idea conceptually agrees with the squeeze flow theories, where the apparent response of deformed media presents a product of elastic and viscous parts.

Most of the percolation and shear flow models are based on incompatible assumptions with regard to compressibility, fibre movement, and resin flow. Since these models were traditionally applied to the different classes of materials the need for a transitional model was rarely stated. Yet there are distinct experimental data showing that a transitional model is needed. For example Hubert and Poursartip [16], testing toughened and low viscosity prepregs on curved tools with bleed and non-bleed bagging conditions. They clearly demonstrated that both squeezing and percolation flows can act concurrently. Neglecting one or another may lead to significant error in thickness estimation.

This paper sets out to investigate toughened material in the state where both flow types are possible, and to explore the applicability of different concepts for the description of compaction experiments. The major question of this paper is the relationship between the rate dependent and rate independent constituent of a materials response. The available data indicates that the transition between bleeding and squeezing states is governed not only by temperature, and as a consequence by resin viscosity, but also by the geometrical parameters of the compacted media. Thin and thick plies appear to have different compaction limits, different apparent viscosity, and different levels of bleeding. Thus the paper attempts to summarise the key features of compaction of thin and thick plies, and explain the observed phenomena based on micro-mechanical considerations. The primary purpose of this exercise is to form a basis for formulating a pragmatic phenomenological constitutive equation at the ply level that can be used in modelling of automated manufacturing of toughened systems.

2 Experimental programme

Investigated parameters

An experimental programme was undertaken to explore material behaviour as subjected to the conditions typical for fibre deposition, hot debulking, and pre-curing consolidation. In a typical automatic fibre placement (AFP) process, multiple slit tapes (linear density 12 K, approximately 6-12 mm in width) are deposited by a soft elastomeric roller at up to 1 m/sec [17]. Lukaszewicz and Potter [18], taking into account the deformability of a soft silicone roller, estimated the contact time between a 60 mm diameter roller and the material to be 0.03 sec at the maximum deposition rate. Load applied to the roller for nip-point control, may be set at 0-1000N. Typical values (for a 32 tape head AFP) are translated to pressure of 0.1-0.2 MPa [19].

In the course of deposition the material in front of the roller (so-called “nip point”) is heated to increase tack at the nip point and so aid deposition quality. Once laid down, the deposited material is regularly debulked at room or at elevated temperature (30-90°C) to evacuate air and close the tolerance gaps between slit tapes. Hence, there are three major compaction programs of interest:
(1) High speed deposition of thin tapes at relatively low temperature and moderate pressures

(2) Slow debulking of stacked laminates at elevated temperature and atmospheric pressure

(3) Consolidation of thick parts in an autoclave at high temperature, high pressure, and low load rates

This experimental program is set to understand the material behaviour in the range of varied parameters covering all these areas.

**Materials and samples**

Toughened Hexply M21/ T700 prepreg, with an areal density of 294 gsm (nominal ply thickness 200-250 μm) was chosen for testing. M21 is a high performance resin system designed by Hexcel for aerospace structures, with a focus on post-impact performance. The morphology of this material was previously characterised in detail by Lukaszewicz and Potter [20].

To explore size effects, unidirectional (UD) and cross-ply (CP) samples were prepared. UD samples present a simple 15 by 15 mm block of 18 plies stacked in the same direction. The purpose of using CP samples is to investigate the flow of isolated plies and to represent the ply interaction conditions. The major concern of testing simple square shape CP is the loss of material from underneath the pressurised area as the plies are squeezed in perpendicular directions and load is only transmitted through the area shared by neighbouring plies. To enable a consistent comparison between CP and UD configurations, the CP samples were modified so that ‘short’ 90° plies alternated with ‘long’ 0° plies, Figure 1. The benefit of this arrangement was in the fact that the 90° plies were homogeneously loaded over all the expanding area, since ‘long’ 0° plies transfer the load through the thickness. As a result, CP samples represent behaviour of thin constrained plies whereas the UD samples show the deformation of thick non-constrained system. For brevity the CP and UD samples are referred further as “thick” and “thin” sample although the nominal sample thickness, and consequently the resolution of displacement measurements, is the same.

Figure 1. Cross section view of compacted cross-ply prepreg with alternating long and short plies

Plies were cut from feedstock material using a B&W Genesis 2100 and lay-up was undertaken in standard clean room conditions following standard lay-up procedures. During lay-up a 10 minute debulk cycle was employed every four plies, aiming to minimise any possible inter-ply error associated with initial sample roughness and entrapped air. Special care was taken to avoid closing the gaps between the 0° plies in CP samples during debulking by inserting paper interleafs of approximately the same thickness as the plies. The initial fibre volume fraction for the tested samples was estimated to be in the range of 43-53%.

**Test program**

Samples were tested in Metravib 2000 Dynamic Mechanical Analyser, following a flat isothermal load-controlled compaction programme as described in [21]. Samples were loaded in two regimes: a slow monotonic loading, and a ramp-dwell regime where the fast application of load is followed by long creep intervals. In both these cases samples were loaded to 60 N in 1200 seconds, although the ramp-dwell program included five steps with the increment load of 10 N starting with 20N at the first step. Due to peculiarities of the DMA machine, the load rate during ramping is not uniform. At the ramp onset the load rate reaches 24.5 N/s which for the given sample dimensions translates to ~0.1 MPa/s which is comparable to the load rates seen in AFP deposition. At 0.83 seconds the load reaches 70% of the dwell level and it then takes another 4-7 seconds to approach the pre-set value in an asymptotic fashion. Once the load application is levelled off it is kept to ±0.37% variation of the defined level. The time interval for the creeping at the pre-set dwell was set to be 240 seconds.

Correction to machine compliance was made when processing the experimental results. An additional correction was needed to take into account of high uncertainty of the initial thickness. Assuming that elastic deformations are very small compared to irreversible ones, the displacement-force curves
were shifted to match sample thickness as measured immediately after the test.

To measure the transverse expansion of plies in CP samples, the tested samples were cured with no applied pressure, then cross-sectioned and polished. The final width of each ply was measured using optical microscopy. The results of width measurements are only indicative due to the fact that considerable scatter between the expansions of individual plies was observed.

A thin resin release film was applied between the DMA loading plates and the samples. This film minimises friction which leads to different constraints experienced by thick blocks (close to zero friction) and thin plies constrained by alternating plies of transversed fibre direction (close to no-slip).

Results and key experimental observations

Transverse widening and through-thickness compaction

Comparing the post-compaction thicknesses and widths, and neglecting the elastic response (if any), the incompressibility assumption can be judged. Figure 2 shows different deformation patterns for thin-isolated (CP) and thick-blocked (UD) samples. The CP (thin) samples showed no significant widening with the transverse expansion of the same order of magnitude as experimental scatter. By contrast UD samples show significant widening above 40%. The largest through thickness deformation of a UD sample can be seen to take place at 70°C.

![Figure 2](image)
Figure 2. a) Relative expansion of UD and CP samples ply widths, as measured and estimated based on thickness measurements and the incompressibility assumption; b) Cross sectional view of a UD sample compacted at 70°C; c) Top view of a CP sample tested at 80°C.

UD samples are clearly incompressible up to 60-70°C, which approximately corresponds to the observed onset of resin bleeding and clear traces of resin being squeezed out along the fibres are detected at the sample edges, Figure 2b.

Compaction limit

Figure 3 shows thickness-time diagrams, and demonstrates that at sufficiently high pressure and/or temperature, a certain apparent compaction limit can be reached. Every consequent step generates less displacement increments both on ramping and dwell/creep stages. This trend is much more explicit at higher temperatures (60-90°C). The observed deformation pattern of UD samples suggested that compaction limit is independent of resin viscosity, and that even at low temperatures the samples can approach a compaction limit if sufficiently high pressure is applied. The presence of such a limit could be interpreted as a rate-independent (elastic) constituent of the material response. However, the compaction limits of the thick-blocked and thin-isolated samples appear to be drastically different (10% v’s 40% deformation), even above the bleeding-squeezing transition. This does not agree with the elastic nature of the compaction limit and thus an additive superposition of elastic and viscoelastic constituents appears to be inapplicable for this case.

Measurements of transverse widening clearly indicated that through-thickness compaction response is related to the ability of the material to flow transversely. Isolated plies in CP’s exhibited much less capacity for in-plane expansion, and hence cannot be deformed as easily as the thicker preforms.
Transitional behaviour of prepregs in automatic fibre deposition processes

Figure 3. Thickness evolution in the ramp-dwell program for UD-18-ply samples, CP - with thin isolated expanding plies. The same level of applied force is reached at the end of the program for all the samples.

The squeezing fluid theory predicts strong inhomogeneity of strain rate distribution in no-slip plate-sample conditions and, as a consequence, the strong dependence of the apparent viscosity on the sample dimensions (width-to-thickness ratio). Thin samples were found to be two orders of magnitude times less viscous than thicker ones. Yet the viscosity alone, does not explain the convergence of the compaction curves to a particular limit values. The flow theory does not foresee any compaction limit other than the case when sample thickness approaches zero and the apparent viscosity becomes infinite. This observation evidences that the transverse flow has a strain limiter. This limit appears to be constraint and thickness dependent.

History and strain-rate effects

The compaction experiments clearly showed the history and strain-rate dependence. Figure 4 summarises the pressure-thickness curves for the samples loaded slowly and the samples loaded in a ramp-dwell (hit-creep) fashion. The total time of the experiments and average load rate are the same, but there is a dramatic difference in both the transverse expansion and the through-thickness compaction of these samples. These observations point towards the shear thinning nature of prepreg behaviour. The strain rate at the ramp intervals of the step loading samples was much higher than the strain rate during monotonic loading. Low viscosity at the ramps promotes transverse squeezing flow, and as a result a much higher through-thickness deformation than in the case of slow loading. This effect is explicit for UD (thick) samples and much less pronounced for the CP (thin) ones.

Figure 4. Comparison of thickness evolution in ramp-dwell and slow monotonic loading programmes. The total time for the test, and the average load rate, is the same for all the samples.

Apparent viscosity

In order to explore major trends in viscosity evolution, the experimentally measured force-thickness curves were transformed into strain-rate: real-stress dependencies. The experimental thickness-time \( h(t) \) curves were approximated by the Prony series at each ramp-dwell intervals (5 terms, 95 % confidence interval). The obtained functions were analytically differentiated and then the logarithmic strain \( \varepsilon_h \), strain rate \( \dot{\varepsilon}_h \), and real stress \( \sigma \) functions were calculated using the following relationships:

\[
\varepsilon_h = \ln \left( \frac{h}{h_0} \right) \quad \dot{\varepsilon}_h = \frac{\dot{h}}{h} \quad \sigma = \frac{F \exp \varepsilon_h}{l w_0}
\]

(1)

where \( w_0 \) is the initial width of samples (across the fibre direction), \( l \) the sample lengths (along the fibre direction), and \( F \) the applied force. The apparent viscosities \( \eta_a \) were then calculated for two incompressible Newtonian fluid under two
conditions: (a) zero-friction: \( \eta_a = \frac{1}{4} \frac{\sigma}{\dot{\varepsilon}_h} \) and (b) no-slip: \( \eta_a = \frac{\sigma}{\dot{\varepsilon}_h} \left( \frac{W_0}{h_0} \exp(-2\varepsilon_h) \right)^{-2} \). Figure 5 shows the results of this data conversion.

![Figure 5. Apparent viscosity evolution of thick UD stacks during four cycles of the ramp-dwell loading, defined for (left) zero-friction thick plies, (right) no-slip thin plies. Curve thickness is proportional to the test temperature (30-80°C). The 90°C UD sample is excluded due to a singular spike in the viscosity at the third step.](image)

From Figure 5 it is clear that the material exhibits a pronounced strain-rate dependent viscosity. After a peak in strain-rate during the ramping phase the strain decelerates and the viscosity grows considerably towards the end of the dwell interval. Apart for the first step, viscosity evolution of the samples tested at 30-60°C follow a characteristic trend: fast growth in ramp and slow down to the end of dwell. It can be seen that viscosity drops as the test temperature grows. At 70-90°C (and at the forth step of 50-60°C) the trend suddenly changes. The viscosity start to grow in an asymptotic fashion; for example the apparent viscosity of the 80°C sample approaches the viscosity of the 30°C one. At 90°C a singular spike (constant stress at zero strain rate) occurs at the third step, i.e. elastic response – zero strain rate at non-zero stress.

Even though the squeeze compaction model explicitly accounts for size effects, the comparison of the apparent viscosity of UD (thick) and CP (thin) plies show differences by two orders of magnitude. This suggests that the theory of squeezing fluid cannot adequately describe thin and thick samples as the same material.

**Summary**

The experiments show that classical visco-elastic or (non-) Newtonian squeezing fluid models demand different input properties for thick and/or thin laminates. In order to better describe the compaction limit phenomena and the scale-effects, a new model is needed, and has to:

1. describe samples of arbitrary thicknesses by the same governing equation (s)
2. explicitly include the geometrical size effects in the formulation
3. capture the compaction limits both for squeezing and bleeding material states
4. incorporate criterion for the switch from squeezing to bleeding flow
5. take into account the strain-rate dependency
6. utilise the constants identifiable in conventional rheological tests
7. be at the ply scale, and be designed for the finite elements of a ply dimension

The next section presents an effort to address some of these challenges, by considering the reconfiguration of inter-fibre channels. The compaction limit is explained by the fast rise of the effective viscosity associated with the closure of inter-fibre channels. These structural considerations can give grounding for a convenient phenomenological formulation of a material model at the ply scale.

3. **Analysis**

**Ply scale deformations**

Distribution of the squeezing media deformations with no-slip boundary conditions is not homogeneous. Shear is the dominant deformation mode at the ply-tool interface close to the expanding ply edges, but it decays to zero at the ply mid-plane due to the deformation symmetry. At the laminate mid-plane the material is subjected to pure hydrostatic compression, and the maximum in-plane extension and through-thickness contraction deformations take place in the centre of the samples cross-section.

As follows from the analytical solution for squeezing incompressible Newtonian media [4], the through-thickness strain rate is a quadratic function...
with through-thickness coordinates and the shear strain rate is a bi-linear function with cross-sectional coordinates. The maximum shear rate at the edges \( \dot{\gamma}_{\text{max}} \), and maximum through-thickness strain at the bulk of material \( \varepsilon_{\text{max}} \), can be expressed in terms of the applied strain \( \varepsilon_{\text{h}} \) as follows:

**No-slip:**

\[
\dot{\gamma}_{\text{max}} = -3\dot{\varepsilon}_{\text{h}} \frac{w}{h} \varepsilon_{\text{max}} = \frac{3}{2} \dot{\varepsilon}_{\text{h}} \quad (2)
\]

**Zero friction:**

\[
\dot{\gamma}_{\text{max}} = 0 \quad \varepsilon_{\text{max}} = \dot{\varepsilon}_{\text{h}} \quad (3)
\]

where \( h \) is the current thickness of the squeezing medium, and \( w \) the sample width. On suggesting that there is an internal mechanism to block or slow down the resin flow, upon reaching a particular value of strain then, integrating (2) and (3) over time gives the values of applied strain at locking onset \( (\varepsilon^l_{\text{h}}) \):

**No-slip:**

\[
\varepsilon^l_{\text{h}} = \max \left\{ -\ln \left( \frac{2 h_0}{3 w_0} \gamma_1 + 1, \right. \frac{2}{3} \varepsilon_1 \right\} \quad (4)
\]

**Zero friction:**

\[
\varepsilon^l_{\text{h}} = \varepsilon_1 \quad (5)
\]

where \( h_0, w_0 \) are the initial thickness and width of squeezing medium respectively, and \( \gamma_1 \) and \( \varepsilon_1 \) are the shear and through-thickness strain at which the locking begins. This expression shows that to achieve a particular level of strain in a no-slip flow, the thick and thin laminates must undergo different shearing at the flow front.

**Sketch for squeeze-bleed switching mechanism**

Consider a hypothetical structure where fibres are arranged in a perfect rectangular grid as Figure 6a. The major purpose of this geometrical sketch is to capture the evolution of the average dimensions of inter-fibre channels. In reality the regularity of the structure is a very strong simplification of real world states as the position of fibres in real architectures are more random and this may carry important mechanical implications such as inter-fibre friction.

Consider a volume subjected to the maximum shear in the vicinity of the sample edge. At some deformation level the reconfiguration of the fibre position will close the inter-fibre channels. The fibres (initially placed diagonally with respect to each other) come into contact and so form a column locking-in the shear driven flow, Figure 6b. To impose further shearing, a massive inter-fibre friction between every single fibre in the structure must therefore be overcome. Equally when neighbouring fibres approach each other the squeeze flow of resin between them causes a rapid increase in the stress required to push the fibres further together. In either case the material appears to be locked-out to further extensions of shear flow.

![Figure 6. Shear-driven squeezing (b) and bleeding (c) of fibres initially packed in an idealised square grid (a). Due to the inhomogeneity of the through-thickness shear, lock-out at sample corners will trigger a cascade of shear-locking through the sample thickness. It can be described as the process of reduction of deformable volume. Once the entire flow front is shear locked, there can be different scenarios encountered. If resin viscosity is high, build-up pressure may lead to explosive fibre jet-out as observed for thermoplastics by Barnes and Cogswell in the compaction of carbon-reinforced PEEK [22]. For moderate viscosity resins, flow directions may be reoriented. Resin bleeding also causes a drop in pressure and so a reduction in shear force at the flow front. For low viscosity resins, bleeding may cover the entire deforming volume, including the flow front. In this case reversed fibre movement may be encountered, Figure 6c. Flow continues until the next locking configuration stops the flow-driven deformations, and the second locking configuration occurs when all the fibres are fully engaged in a friction-based contact. The experiments conducted on the toughened prepreg show that resin bleeding occurs both along the fibres (Figure 2b) and on the sample edges across the fibres (Figure 2c). The edge bleeding evidence is in favour of the likelihood of deformation sketch. In the no-slip condition the flow.](image)
theory predicts maximum hydrostatic pressure at the bulk of the deforming media and negligible pressure at the edges, hence the bleeding at the ply edges may be driven by the reconfiguration of fibres.

Locking configuration appears to occur when all the fibres are in aligned contact. Simple geometrical considerations allow for the estimation of critical shear angle and through-thickness strain in this condition. For the initially square alignment:

\[ \tan \frac{\phi_1}{2} = 2k \quad \varepsilon_1 = \ln(2\sqrt{k}) \]  \hspace{1cm} (6)

where \( k = \frac{v_0}{\pi} \), \( \phi_1 = \frac{\pi}{2} - \gamma_1 \), \( \gamma_1 \) is the shear angle at the locking configuration, and \( \varepsilon_1 \) is the local logarithmic through-thickness strain in the locking configurations. For the initial fibre volume \( (v_0) \) of 40-50%, \( \gamma_1 \) is in the range of 61.4°±54.7° and \( \varepsilon_1 \) is 33.7±22.6% correspondingly. Combining Equations 2.3 with 6 allows for the estimation of the locking onset for various constraints. Table 1 shows the locking strains for zero friction thick, and no-slip thick or thin samples. It is interesting to note the substantial difference in the locking onset between zero-friction thick and no-slip thin results.

Table 1. Calculated locking strain (\( \varepsilon_h^l \) (%)) for considered samples from the experimental programme.

<table>
<thead>
<tr>
<th>( v_0 ), %</th>
<th>0.4</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero-friction. Thick</td>
<td>-33.7</td>
<td>-22.6</td>
</tr>
<tr>
<td>No-slip. Thick</td>
<td>-9.5</td>
<td>-8.5</td>
</tr>
<tr>
<td>No-slip. Thin</td>
<td>-0.6</td>
<td>-0.5</td>
</tr>
</tbody>
</table>

These estimates are of a qualitative nature only and should not be considered actual predictions – due to the fact that the obtained values depend on an uncertain initial fibre volume fraction, and the orientation and packing configuration of fibre grid. However, no matter what fibre configuration is considered it shows the same feature: a dramatic difference of \( \varepsilon_h^l \) for various constraints and ply thicknesses. Note that thin laminates will reach shear locking much earlier than in thicker ones. It is expected that upon locking the material behaviour will drastically change due to friction dominated responses, elastic deformation of fibres, or bleeding.

In any of these cases the transverse widening of plies will be slowed down or even totally stopped. Experiments on thick laminates show that transverse deformations for bleeding materials of various viscosities do not exceed \( \ln(1.4) = 33.6\% \); whereas for thin laminates widening is negligible. The estimates shown in Table 1 of zero-friction thick samples versus no-slip thin samples fundamentally agree with these observations.

Effective viscosity

To understand the mechanical aspects of the fibre interaction, micro-scale mechanics can be employed. Hjellming and Walker [23] have developed an analytical solution for squeeze flow of a Newtonian matrix between closing fibres at high fibre volume fractions. Their approximate solution, obtained by asymptotic expansion, can be written in terms of true-stress - log-strain as follows:

\[ \sigma_\mu = \tilde{\eta} \frac{\exp(2\varepsilon_\mu)}{(\exp(\varepsilon_\mu) - 2\sqrt{k})^{3/2}} \dot{\varepsilon}_\mu \]  \hspace{1cm} (7)

where \( \tilde{\eta} = 6\eta_\mu \omega k^{-3/4} \), \( \eta_\mu \) is the resin viscosity, \( \dot{\varepsilon}_\mu \) is the strain rate of fibre closure, \( \varepsilon_\mu \) is the contraction of inter-fibre space, and \( \sigma_\mu \) is the force acting perpendicular to the closing fibres normalised by the true area of the unit cell cross-section drawn along the fibres and perpendicular to the force action. Consider again the incompressible shear of the fibre grid (Figure 6). It results in the extension of one (positive) grid diagonal and the contraction of another one (negative). The contraction of the negative diagonal will force the resin out of the inter-fibre space, generating the force acting perpendicular to the positive diagonal. Expressing the rate of diagonal contraction and stress through the shear-rate/shear stress, and neglecting other stress factors, gives an estimation of the effective viscosity:

\[ \eta_{\text{eff}} = \frac{\tau}{\dot{\gamma}} = 2\sigma_\mu \dot{\varepsilon}_\mu = \frac{2\tilde{\eta}}{\exp(\varepsilon_\mu) - 2\sqrt{k}} \frac{\exp(2\varepsilon_\mu)}{(\exp(\varepsilon_\mu) - 2\sqrt{k})^{3/2}} \]  \hspace{1cm} (8)

Equation 8 shows that the effective viscosity depends not only on the fibre volume fraction but
also on the degree of deformation. Thus when fibres approach the locking configuration the viscosity becomes singular.

For thin plies in the no-slip condition, after locking starts the shear locked zones occupy the corners of the flowing media. The central zone of material is shear free because of flow symmetry. Due to the singular increase in viscosity, the locking rapidly progresses towards the midline of the sample and blocks further flow. For thick samples with a zero-friction constraint the situation is inherently different. Locking starts in the bulk of the sample and progresses outwards towards the edges. As locking progresses resin bleeds out along the fibres, releasing pressure in the sample bulk. This results in the decay of transverse expansion as can be seen in isolated plies in CP samples.

Phenomenological approximation of material behaviour

Due to the observed complex dependency of viscosity on strain, an analytical solution for squeeze flow is out of reach even for Newtonian fluids. Robust modelling of the material hardening is beyond the scope of this current paper and so will not be discussed here. Instead, based on structural considerations, an approximation of the effective material response is suggested. To enable this it is assumed that geometrical locking occurs almost instantaneously over the sample thickness.

Following the proposals of Kelly [15] (about the multiplicative superposition of elastic and viscous material responses), the apparent viscosity is presented as the product of strain rate \( \eta_s (\dot{\varepsilon}_h) \) and strain dependent terms. The latter is decomposed onto the fibre-scale term - the effective viscosity \( \eta_{ef} (\varepsilon) \) (8), and the ply scale term - the apparent viscosity of transverse flow \( \eta_a (\varepsilon_h) \):

\[
\frac{\sigma}{\dot{\varepsilon}_h} = \eta_M = \eta_{ef} (\varepsilon) \eta_a (\varepsilon_h) \eta_s (\dot{\varepsilon}_h)
\]

Figure 7 shows that for a given temperature \( \eta_s (\dot{\varepsilon}_h) \), calculated for different steps of ramp-dwell loading, constitute a single strain-rate function. For the simple assumptions used to process the data the agreement between the viscosity profiles at different steps is satisfactory. The obtained curves follow a power law dependency and represent the material shear thinning properties of the considered medium. Combined with the strain dependent functions, they can reasonably describe the material behaviour up to the moment of locking onset. Upon fibre locking and consequent bleeding, the material behaviour changes and different relationships are needed to address the problem. This behaviour needs to be explored using a structural model showing the progression of fibre locking and pressure redistribution associated with this process.

![Figure 7. Strain-rate dependent constituent of the viscosity. The curves are based on the measurements of blocked UD plies processed as \( \frac{\sigma}{\eta_{ef} (\varepsilon_h) \eta_a (\varepsilon_h) \dot{\varepsilon}_h} \).](image)

Conclusions

The investigations of this paper show that a new formulation of the prepreg material model in compaction is needed. For example, even prior to bleeding the modern prepreg material can show important features which are hardly covered by standard squeezing flow models.

One of the key experimentally observed phenomena is the compaction limit. Its nature is different from what is known for low viscosity prepregs. The rate-independent constituent of the material response is not necessarily elastic in nature. As the experimental results suggest, it can be efficiently described by a strain-dependent viscosity model. Simple micro-mechanical considerations give a basis for the geometrical interpretation of this dependency, and as a result, sensible thresholds for the widening of...
samples with various thicknesses and tool constraints can be obtained.

The compaction limit determines the onset of bleeding, and so a step change in material behaviour at various scales. This process is complex and more needs to be done to understand its mechanics. Preliminary results have indicated that modelling of inter-fibre channel reconfigurations may be a promising approach in which to proceed with.

References

Transitional behaviour of prepregs in automatic fibre deposition processes