EFFECT OF THE TAPE/SUBSTRATE ORIENTATION ON THE TAPE DEFORMATION DURING AUTOMATED TAPE PLACEMENT.

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1 Introduction

Thermoplastic composites offer new possibilities for the aeronautical industry. Large structures of the order of several meters can be processed rapidly without the need for a cure cycle. The ability to melt the matrix and ensure fast and local consolidation gives new perspectives for forming processes.

This paper focuses on a thermoplastic matrix composite forming process: the automated tape placement (ATP). The ATP process is a complex forming method involving transient heating and cooling, material flow, consolidation and bonding [8,9]. The ATP uses robotic equipments to sequentially deposit pre-impregnated tape segments (prepreg) onto a mould. The composite laminate is gradually manufactured by the deposition of multiple plies formed by the prepreg segments which are placed side by side with the appropriate orientation. The ATP process can become really attractive to a composite manufacturer when combined with the in-situ possibilities offered by thermoplastic based materials. Since thermoplastics are already fully polymerized, they harden when they cool down from the melt phase, and do not require a post-processing cure step in an autoclave. The final quality of a composite laminate could thus be obtained directly on site, via local application of heat and pressure, as the material is deposited on the part. The expensive autoclave step can, in theory, be avoided if sufficient heat and pressure are applied during the ATP layup process to adequately consolidate the laminate.

In order to ensure a good final part quality, it is necessary to establish the optimal process parameters (velocity, heating power, pressure) for the deposing head. This can be done by simulating the leading physical phenomena occurring in the process.

Many authors have focused on heat transfer and its effects on the quality of flat plates [8,9,10], but few have investigated the squeeze behaviour of the pre-impregnated material. This aspect, although often neglected for in-situ ATP processing, is of prime importance for laminate integrity; placement induced defects, such as gaps between adjacent passes and material overlaps, are highly affected by the tape spreading [4,11]. Therefore, in order to improve the design of placement paths, there is an actual need for understanding the material deformation behaviour under the compaction roller.

The objective consists in determining how the prepreg material responds to the application of the compaction forces (Figure 1). A static approach where the tape is squeezed in an instrumented hot press is first used. A model is developed to predict the tape spreading depending on the closing force and the tape to substrate orientation. The missing parameters are obtained using simple to perform static compression tests.

Then the model is extended to the continuous process case involving a moving compaction roller. A fitting parameter is determined with a single in-situ experiment. The model then fully predicts the transverse tape deformations during tape placement process for a wide range of roller force and tape to substrate orientation. It can be used as a guideline to optimize deposition paths and reduce laps and gaps in tape placement.
2 Experimental methods

2.1 Approach

ATP is a complex and dynamic process where some of the important processing parameters are interrelated. In order to isolate the squeeze flow phenomenon responsible for the tape transverse deformation, a “static approach” was adopted [1]. The compression of a carbon/peek composite tape deposited on a composite substrate was studied experimentally using a hot press configuration.

The focus of the analysis was placed on the effects of two processing parameters: the compaction force applied on the tape section and the angle difference between the tape and the substrate orientations (forming an angle $\alpha$). These two parameters were found to be the most influent on the squeeze flow [1].

Beside the static approach, an experimental campaign was performed on the real in-situ consolidation process using an actual ATP deposition head. The aim was to verify if the understanding of the phenomena at the static level can be extended to the dynamic process.

2.2 Material

The material used throughout this study is APC-2/IM7 from Cytec Industries. This pre-impregnated material consists of unidirectional carbon fibres impregnated in a polyether ether ketone (PEEK) matrix. The manufacturer recommends to process the material with temperatures between 370 °C and 400 °C. The material is provided as continuous rolls of material slit to the desired width. The dimensions of the pre-impregnated tape used were approximately 6.2 mm wide and 0.20 mm thick.

2.3 Static compression

2.3.1 Compaction fixture

An experimental compaction fixture was specially designed in order to overcome the limitations of some typical characterisation instruments, namely the high temperatures and consolidation forces required for PEEK processing.

The designed fixture, presented in Figure 2, is a miniaturized heated press. The consolidation force is applied with an 8 cm diameter compressed air piston (1), and is controlled by the air pressure in the system. The compaction fixture is capable of applying compaction forces up to 2200 N. The applied force is measured using a 4.5 kN S-type load cell (2) from Omega. Self-alignment of the platens is ensured by a ball joint rod end (3). The test section (4) consist of two flat 50 by 50 mm steel plates which were polished and coated with release agent to help to collect the sample after testing. The compaction plates are fixed to two copper blocks (5) that are independently heated via two 500 W cartridge heaters. The platens’ temperature is monitored and controlled by a DSS-15 auto-tuning PID controller from DME.

2.3.2 Procedure

The compaction samples were placed at different angles $\alpha$ over larger 35 x 35 mm substrates made of the same unidirectional APC-2/IM7 material (see Figure 3). The setup was heated to processing temperature (385°C), and closing forces were applied for 300s as determined in a previous study [1,5]. The platens were then cooled to collect the samples.

The test parameters were chosen according to a full factorial test matrix constructed with three different closing forces and three different substrate/tape angles, as shown in Table 1.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Pressure (MPa)</th>
<th>Orientation (°)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0</td>
<td>0.57</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>45</td>
<td>0.65</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>90</td>
<td>0.95</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>0</td>
<td>0.75</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>45</td>
<td>0.71</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>90</td>
<td>1.52</td>
</tr>
<tr>
<td>7</td>
<td>30</td>
<td>0</td>
<td>0.69</td>
</tr>
<tr>
<td>8</td>
<td>30</td>
<td>45</td>
<td>0.86</td>
</tr>
<tr>
<td>9</td>
<td>30</td>
<td>90</td>
<td>1.35</td>
</tr>
</tbody>
</table>
2.3.3 Analysis

A microscopy approach was adopted because no conventional measuring techniques (ruler, vernier caliper, etc.) were adequate to precisely determine the final geometry of the samples that were fused to the substrates. The samples were prepared for optical microscopy; they were cut in half in a direction perpendicular to the fibre, embedded in epoxy, and polished. The samples were observed under a 50X magnification, which was sufficient to allow the identification of the two different composite layers. Multi-image scans (M.I.S.) of each of the processed tape and substrate combinations were taken and assembled to obtain images where the entire cross-sections of the samples were visible.

The micrographs were then analyzed to precisely measure the tapes’ width after compression. The final widths of the deformed tapes were measured from the multi-image scans using an image processing software (ImageJ).

The strain $\varepsilon$ is then defined as:

$$\varepsilon = \frac{L_f - L_i}{L_i}$$ (1)

where $L_f$ is the measured final width and $L_i$ the initial width of the tape.

2.4 In-Situ continuous experiments

A series of experimental tests was performed using the ATP head in order to provide a comparison basis. The ATP experiments performed were based on a Taguchi test matrix combining three different orientations, compaction forces, and placement speeds. The specific details concerning the different processing parameter combinations are provided in Table 2. Note that the compaction force is specified in terms of kg to reflect how the parameter is programmed in the user interface.

The tests were performed on the automated tape placement machine of Aerospace Manufacturing Technology Center (AMTC) of the National Research Council of Canada [5]. The machine is an overhead gantry and spindle robot system manufactured by Automated Dynamics. It possesses 6 axes of motion that can be used in a 4m x 2m x 1m working envelope. The thermoplastic placement head can deposit a single 6.35mm (0.25") tape that is heated with a nitrogen gas torch. The experiments were conducted using the flat table configuration. The APC-2/IM7 composite tape was deposited directly on a substrate cut from 300 mm wide rolls of the same material. Figure 4 shows the deposition process for one of the 45° Taguchi test entries.

The ATP deformation samples were collected towards the end of the substrate in order to ensure that the analysis would be performed on laminate sections processed under steady state conditions. The deformation samples were cut and analyzed following the procedure presented in Section 2.3.3. The average strain results for the 9 Taguchi test entries are also given in Table 2.

Table 2. Taguchi test matrix and final strain for in-situ experiments.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Force (kg)</th>
<th>Speed (mm/s)</th>
<th>Orientation (°)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>16.5</td>
<td>0</td>
<td>0.15</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>33.5</td>
<td>45</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>50.0</td>
<td>90</td>
<td>0.17</td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>16.5</td>
<td>45</td>
<td>0.22</td>
</tr>
<tr>
<td>5</td>
<td>25</td>
<td>33.5</td>
<td>90</td>
<td>0.36</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>50.0</td>
<td>0</td>
<td>0.29</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>16.5</td>
<td>90</td>
<td>0.23</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>33.5</td>
<td>0</td>
<td>0.48</td>
</tr>
<tr>
<td>9</td>
<td>40</td>
<td>50.0</td>
<td>45</td>
<td>0.44</td>
</tr>
</tbody>
</table>

3 Modelling

3.1 Geometry

As schematized in Figure 3, the molten tape is squeezed between the substrate and the upper platen as the space between the two parallel plates is reduced. Because of the fibres constraining the flow in the longitudinal direction, a deformation purely transverse to the fibres is considered, and a two dimensional plain strain assumption is pertained (see Figure 5). For the current application, the composite tape is treated as a homogeneous viscous material [2,3,4,7,10]; the carbon fibre reinforcement, having a much smaller diameter than the tape thickness,
flows with the matrix as if it was in suspension in the highly viscous molten PEEK. For transverse
deformations, as discussed in these papers, an
equivalent material viscosity $\eta$ can be attributed to
this combination of molten PEEK and carbon fibres.

### 3.2 Static study

#### 3.2.1 Lubrication assumptions

The problem geometry is illustrated in Figure 5
where the APC-2/1M7 tape material is represented
between two rigid compaction plates of infinite
dimensions. The tape sample has a width of $2L$, a
height $h$, and possesses a unit length (depth). The
origin is taken in the centre of the tape, the $x$
direction is along the width direction and $y$ is normal
to the platen. A closing force $F$ (per unit length
basis) is applied on the top plate.

Following the lubrication assumption discussed in
[2], a one-dimensional approach was used based on
the fact that the width of the sample is much larger
than its height.

$$ L \gg h \quad (2) $$

As a result, the pressure expression is modelled as a
sole function of the $x$-position:

$$ P = P(x) \quad (3) $$

and the material deformation speed is much higher
in the $x$-direction than it is the $y$-direction:

$$ v_x \gg v_y \quad (4) $$

the changes in the $y$-direction take place much more
rapidly than the changes occurring in the $x$-direction:

$$ \frac{d}{dy} \gg \frac{d}{dx} \quad (5) $$

#### 3.2.2 Squeeze flow

Due to the high viscosity of the molten composite,
the Reynolds number has a value well under unity,
and the gravity over viscosity terms can be
neglected. The equilibrium equation then reduces to:

$$ (\eta \; v_y)_{,y} = P_x \quad (6) $$

where $v$ is the material velocity and $P$ the pressure.
The conventional Einstein notation is used for
spatial derivation.

The material is considered as incompressible.
Considering a control volume between $y \in [-h/2,h/2]$
and $x \in [0,L]$, one obtains:

$$ \int_{-h/2}^{h/2} v_x \; dy = -x \frac{dh}{dt} \quad (7) $$

Finally the sum of the pressure along the platen
being equals to the closing force $F$, one gets

$$ \int_0^L P \; dx = \frac{F}{2} \quad (8) $$

Similar squeeze flow modelling under lubrication
assumption has been proposed in the past [2,3,4].

#### 3.2.3 Boundary conditions

The boundary between the upper platen and the tape
sample is assumed to have a non slip behaviour:

$$ v_x = 0, \quad v_y = \frac{dh}{dt} \quad (9) $$

The interface between the tape sample and the
substrate being of interest for this study, an original
slip behaviour is proposed. As in [3], a velocity $v_y$
with a partial slip proportional to the shear stress
$\eta \frac{\partial v_x}{\partial y}$ is assumed:

$$ v_x = \frac{\eta}{f} \frac{\partial v_x}{\partial y}, \quad v_y = \frac{\partial h}{\partial t} \quad (10) $$

where $f$ is a friction coefficient that depends on the
tape to substrate orientation $\alpha$. In the case of parallel
deposition ($\alpha=0^\circ$), nesting of the fibres will result in
a high friction coefficient whereas in the case of an
orthogonal deposition ($\alpha=90^\circ$), the fibres will slide
more easily. An empirical relation of the form:

$$ f(\alpha) = A + B(1-\sin(\alpha)\hat{\alpha}) \quad (11) $$

was assumed, where $A$ and $B$ are to be determined
experimentally.

Finally, the edge of the tape is left free such that at
$x=\pm L$:

$$ P = 0 \quad (12) $$

#### 3.2.4 Analytical simplification

Integrating equation (6) twice along the $y$ coordinate
gives

$$ \eta \; v_y = P_x y^2/2 + G(x) y + H(x) \quad (13) $$

where the integration constants $G$ and $H$ are
obtained using the boundary conditions (9) and (10):


\[ G(x) = P_x \frac{h}{2(1+hf/\eta)} \]  \hspace{1cm} (14)

\[ H(x) = -P_x \frac{h^2}{4\eta} \left( \frac{1}{2} + \frac{1}{2(1+hf/\eta)} \right) \]  \hspace{1cm} (15)

Replacing the expression of \( v_s \) given in equation (13) in the incompressibility equation (7), one gets

\[ P_x = \frac{dh}{dt} \frac{2\eta}{h^2} x \]  \hspace{1cm} (16)

where for the sake of clarity we defined:

\[ \gamma(h) = \frac{1}{6} + \frac{1}{2(1+hf/\eta)} \]  \hspace{1cm} (17)

Integrating (16) with respect to \( x \) and using the boundary condition (12), one gets the pressure distribution along \( x \):

\[ P = \frac{dh}{dt} \frac{\eta}{h^3} (x^2 - l^2) \]  \hspace{1cm} (18)

It can be replaced in the force balance equation (8) and gives, after integration:

\[ \frac{dh}{dt} = -\frac{3FH^3}{4\eta L^3} \left( \frac{1}{6} + \frac{1}{2(1+hf/\eta)} \right) \]  \hspace{1cm} (19)

The tape height \( h \) is found to follow an ordinary differential equation.

### 3.2.5 Implementation

For a tape to substrate orientation \( \alpha \), equation (11) gives the friction coefficient. Then, given the closing force \( F \), the tape geometry \( (L, h) \), and the viscosity \( \eta \), the right hand side of the ODE (19) can be computed. Given the initial conditions \( L(t=0) \) and \( h(t=0) \), one can therefore compute the evolution of the platen gap by solving numerically the ODE (19). A fourth order Runge Kutta scheme was used in MATLAB (\textit{ode45} function).

### 3.3 Extension to continuous process

In order to extend the above-mentioned approach to the continuous process, the differences between the squeeze flow model and the actual dynamic ATP process needed to be addressed. The first step was to convert the industrial ATP processing parameters into equivalent laboratory scale static squeeze flow parameters. The continuous aspect of the compaction process was reduced to a simpler compaction problem by assuming that the roller is applying a force on an area that corresponds to its roller imprint. Using Fujifilm Prescale\textsuperscript{\textregistered} pressure sensitive paper, static roller imprints such as the one shown in Figure 6 were obtained by applying a closing force directly on the paper. The measured contact length versus compaction force is reported on Table 3. In order to recreate the dynamic aspect of the ATP process, the applied compaction force was assumed to be imposed uniformly on the compacted area for short periods of time.

<table>
<thead>
<tr>
<th>Force (kg)</th>
<th>Contact length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.27</td>
</tr>
<tr>
<td>20</td>
<td>1.37</td>
</tr>
<tr>
<td>30</td>
<td>1.53</td>
</tr>
<tr>
<td>40</td>
<td>1.75</td>
</tr>
</tbody>
</table>

In the industrial ATP process, the load distributions are dynamic and a very high pressure might be reached locally under the roller. This induces lamination effects and increases the flow. Moreover, the material’s temperature is highly non-homogeneous due to the localized heating torch. Since both of these phenomena act towards amplifying the material deformations, and due to the added complexity of accurately predicting them, a simplified approach was opted for. A correction factor \( C \) was introduced as a multiplication factor acting on the compaction force \( F \) in Equation (19):

\[ \frac{dh}{dt} = -\frac{3FH^3}{4\eta L^3} \left( \frac{1}{6} + \frac{1}{2(1+hf/\eta)} \right) \]  \hspace{1cm} (20)

\( C \) is expected to be greater than 1.

### 4 Results

#### 4.1 Parameters

The parameters used in the model are given in Table 3. The dimensions of the tape are based on the average of the measured dimension for each test. The viscosity was fitted in a preliminary study \cite{5} and is in agreement with the literature values \cite{2,6,7}.
Table 3. Parameters used in the simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial tape thickness</td>
<td>$h(t=0)$</td>
</tr>
<tr>
<td>Initial half width</td>
<td>$L(t=0)$</td>
</tr>
<tr>
<td>Viscosity</td>
<td>$\eta$</td>
</tr>
<tr>
<td>Tape length</td>
<td>$l$</td>
</tr>
<tr>
<td>Temperature</td>
<td>$T$</td>
</tr>
</tbody>
</table>

4.2 Determining the friction coefficient

The static experiments allow one to determine the friction coefficient behaviour (11). For each combination of force and tape to substrate orientation defined in the test matrix (Table 1), a half interval inverse method was used. A unique friction coefficient $f$ was fitted such that the model (19) gives the experimental measurements. It corresponds to each dot on Figure 7. Using the empirical equation (11) the following values for $A$ and $B$ were determined with a least square method:

$$A = 10^6 \text{Pa.s.m}^{-1}, \quad B = 15 \times 10^6 \text{Pa.s.m}^{-1} \quad (21)$$

Note that, as expected, the friction factor highly depends on the tape to substrate orientation. Nesting occurs at lower angles giving a factor over 10 times larger than when the fibres are perpendicular.

In the case of a 10 MPa closing pressure, this results in a final strain $\varepsilon$ after 300s that increases from 0.61 for $\alpha=0^\circ$ to 0.93 for $\alpha=90^\circ$. It highlights the high influence of the tape to substrate orientation on the spreading of the tape.

The presented model is now fully predictive: it gives the tape transverse deformation versus time as a function of the closing force and the tape/substrate orientation.

4.2 Extension to continuous process

This section describes the attempt at replicating, using the model presented in Section 3, the experimental results obtained for the samples that were manufactured with the actual in-situ ATP process.

The value for the correction factor was determined by adjusting the parameter such that the semi-slip modelling results would match the deformation results of one of the ATP experiments. The results for the fourth entry in the Taguchi test matrix (16.5 mm/s, 25 kg, and 45°) were used to determine that the roller factor has a value of 500.

The strain results predicted from the modelling are plotted in Figure 8 along with the experimental strains obtained from the actual ATP samples. The comparison between the two sets of data shows a reasonably good fit. The residual sum of squares (RSS) was computed to be 0.1870 which is an average 5% relative error over the 9 cases. This result was obtained using the input of a single experimental point to determine the correction factor; in comparison, a RSS of 0.1718 would have been obtained if all of the experimental data would have been used to determine the optimum correction factor. This indicates that the unique point approach is a viable and efficient way to approximate the correction factor.

5. Conclusion

While depositing a tape on a substrate using an automated tape placement head, the roller applies a compaction force to the prepreg. This results in a squeezing of the tape that is non negligible (strain may reach over 100%). In order to control laps and gaps between adjacent tapes, an accurate prediction of this spreading is needed.

In preliminary work [1], the tape to substrate orientation and the compaction were found to be the most influential parameters on the tape spreading.

In this paper, a static approach is considered where a constant closing force is applied on a tape placed on a substrate. An instrumented hot press was specifically designed for the experimental campaign. A model which accounts for the tape to substrate orientation and the closing force was developed to predict the global strain that the tape is subjected to. Using only nine static tests, the missing parameters were determined.

The model is then extended to the in-situ continuous process with a moving compaction roller. Experiments were conducted over an industrial range of orientation and pressure. Using one point fitting, the model was predictive for all the other experimental measurements within approximately 5% error.
Finally, a predictive model for the in-situ spreading during automated prepreg tape deposition was developed. All the missing parameters were identified using a series of static tests (that are cheap and easy to perform), and one single in-situ experiment.

Acknowledgements

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References


Figure 2: Compaction fixture (left) and detail of the heated platens (right).

Figure 5: Two dimensional squeeze flow problem definition.

Figure 3: Compression setup and representation of the orientations.

Figure 6: Static roller imprint using pressure sensitive film.

Figure 4: In-Situ tests. 45° tape to substrate orientation.

Figure 7: Friction factor versus tape/substrate orientation.
Figure 8: Continuous process. Predicted and measured tape transverse deformation vs. roller force and tape/substrate orientation.