Mechanical properties of 2D and 3D braided-reinforced thin walled composite cylinders

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Abstract

A 3D braiding machine has been designed in order to produce high performance composites. In a first part, we sum up the process parameters that allow the construction of a unit-cell of the reinforcement. Based on this representative elementary element, a simple model is developed for the prediction of the stiffness properties of the braided composite. In order to compare the performances of 2D and 3D braiding configuration, simulations of the effect of the braiding angle on compliance terms are first carried out. In a second part, an experimental comparison is made on the responses of 2D and 3D braided carbon/PA12 composite cylinders under low velocity impact loading. Two levels of impact energy are considered (7 and 11 J). Compression-after-impact and vibration tests are carried out so as to show the less sensitivity of the 3D reinforcement to impacts.

I Introduction

Composite materials find numerous applications in the fields of aeronautic and aerospace from about forty years. These materials have been chosen for their specific high stiffness and strength. The adaptation of existing techniques and the improvement of new processes in the textile industry have conduced to the occurring of new composite structures presenting very interesting geometry and physical performances. Even if textile preforms used as composite reinforcement are still bi-directional in most cases and required manual cutting, stitching and handling in mould, the potentiality of three-dimensionally textile-reinforced structures is admitted. The interest of 3D technique is to provide a lighter and more adapted reinforcement because the fibre can be placed directly along the
load direction. The 3D architecture also allows obtaining a continuous reinforcement through the thickness of the composite piece that leads to the limitation of the delamination phenomena. Moreover, some techniques permit to obtain near-net-shape preforms and then to decrease the cost of the composite. In order to be used as industrial processes, these techniques must satisfy several criteria and especially the compatibility with large production cadences.

The multi-layer interlock braiding technique complies with this criterion. This technique and the parameters that govern the process are presented in section 2. In section 3, we will model the 3D reinforcement geometry as a function of the process parameters. From these data, we will present a mechanical prediction model for the 3D braided composites. In the last section, we will make the validation of our models and will propose a comparison of the performances of 2D and 3D braided reinforcements and especially toward impacts.

2 Interlock layer-to-layer braiding

To form a multi-layer braid, several separate layers have to be serially superimposed. The problem of these multi-layer braids is the sensitivity to delamination. 3D braiding overcomes this problem by introducing yarns of materials that extend transversely through the layers during the process.

2.1 The machine

The multipath braiding machine developed at IFTH (Institut Français du Textile et de l’Habillement) can produce five-layer interlock braids (Fig.1a). This prototype has five crowns of 64 counter-rotating four-slot horn gears. There are ten different circulation tracks. 320 axial yarns at a maximum could be introduced from the center of each horn gear. The interconnectivity of the three dimensional braid is realized by using systems of intermeshing and counter-rotating horn gears, similar to those found on a conventional braiding machine. Here, each cylinder of horn gears is intermeshed not only with its adjacent neighbor but also with those producing an adjacent layer of braid. The colored lines (Fig.1b) represent the path of the braiding carriers as they progress from layer to adjacent layer. A moving mandrel allows the handling of large and heavy core structures for the formation of braids with complex shapes. The braiding angle ranges from ±15° to ±80°. Further details can be found in [1].

2.2 Process parameters

After these few details concerning the braiding machine, it is advisable to enumerate the different parameters that govern the braiding process. The aim is to understand their influence on the final geometry of the braided preform and to explicit their relationship. The process parameters involve a direct adjustment on the machine or follow from the choice of a part of the braiding machine. There are the rotation speed of the horn-gear \( \omega_{\text{hg}} \) (0 – 120 round/min), the speed \( V_m \) and the diameter \( D_m \) of the mandrel (Fig.2).
The primary braiding parameters present direct relationships with the geometry of the braided preform. There are the rotation speed of the carriers \( \omega_c \) (for our machine configuration, a complete bed plate turn is done in \( \omega_c=\omega_{bg}/32 \)), the braiding period \( p \) (\( p=32.V_m/\omega_{bg} \)) and the visible braiding angle \( \theta \) (eqn (1))

\[
\tan \theta = \frac{\pi D_m}{p} = \frac{\pi D_m \cdot \omega_{bg}}{32.V_m} \tag{1}
\]

The secondary parameters correspond to technological parameters that are very useful for the manufacturer. There are the position of the braiding point \( h \) (representing the distance between the bed plate and the convergence point of the yarns), the angle of lay-up on the mandrel \( \gamma(t) \) (eqn (2)), the radial \( \rho(t) \) and the angular positions \( \alpha(t) \) of a carrier (if \( \alpha_0 \) is the initial position of the carrier, \( \alpha(t) \) is done by \( \alpha(t) = \alpha_0 \pm \omega_{bg}.t/32 \) depending on the circulation direction).

\[
\tan \gamma(t) = \frac{\rho(t) - \frac{D_m}{2}}{h} \tag{2}
\]

Figures 1 : (a) front view of the braiding machine – (b) detail of the bed plate.

Figure 2 : Representation of some braiding parameters.
3 Definition of the geometrical model

In order to estimate the mechanical properties of the braided composites, we develop a simple geometrical model. So as to describe the spatial path of the yarns within the unit cell of braid, we need to know the braiding angle and the functions giving the yarns undulations. These functions are based on the motion equations of the carriers on the braiding bed plate. Compared to the center of the mandrel, the yarns undulate according to the equation (eqn (3)):

\[ \rho_y(t) = (a + b \sin(3\pi \tau_t)) \cdot r_y + \frac{D_m}{2} \]

(3)

where a and b are coefficients depending on the circulation track followed by the carrier and \( t \) varying from 0 to \( 2/\omega_{bg} \).

A complex expression of this equation could be given as a function of the process parameters \( \omega_{bg} \), \( D_m \) and \( p \).

The magnitude of the undulation (function of a and b) depends on the circulation track and of the braiding configuration. Without axial yarns, these coefficients take the values summed up in the table 1.

<table>
<thead>
<tr>
<th>Track n°</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>2</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>9</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>b</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

The braid unit cell reconstituted from these path equations is shown below.

Figure 3. Representation of the unit cell for a braiding without axial yarns.
4 Mechanical modeling

The modeling of the mechanical properties depends on the orientation of the reinforcement and on the volume of fibers. The previous geometrical description provides the essential data to this modeling. The database includes the coordinate of the yarn center within the unit cell and the local and directional fiber volume ratios. The estimations done on the preform will be extended to the case of the composite neglecting by that the consolidation phase.

4.1 Different material scales

The figure 4 shows the different paths of the reinforcing yarns within a braided composite and the material scales involved in our analysis. At a first analysis scale, the composite is considered as a mixture of yarns and matrix. At a second scale, a yarn is regarded as an assembly of unidirectional segments with individual orientations. At the lower scale, the yarn segments are considered as the mixture of matrix and fiber with the local volume ratio denoted by $K_f$. This volume ratio corresponds to the packing factor of the fiber within a single yarn; it is considered to be the same for all yarn segments. The global fiber volume ratio, denoted by $V_f$, is different from $K_f$. It is determined by the ratio between the total volume of fiber within a unit cell and the whole volume of the unit cell.

![Figure 4: Different analysis scale for the braided composite.](image)

- (a) yarn paths, (b) a yarn regarded as a assembly of unidirectional segments, (c) this segment is constituted by matrix and fiber.

4.2 Prediction of stiffness properties

The properties of the fibers + matrix mixture along the yarn segment direction are first determined according the microscopic law given by Chamis [2]. In order to take into account that $V_f \neq K_f$, the yarn + matrix mixture is considered as two laminates of yarn-type and matrix-type layers. Considering that the transverse properties must be the same along 2 and 3, the stiffness characteristics of the yarn + matrix mixture will be finally considered as the combination of two thick laminates (figures 5b and 5c). The laminates properties are determined according to the average stress and strain theorems and by considering conditions of displacement and stress continuity between the layers (Sun [3]).

The stiffness properties of a yarn (assembly of yarn segments) and those of the composite (assembly of yarns) are calculated by using iso-strain and iso-
stress models. These simple models are of current application in the literature. They provide the bounding of the stiffness properties.

By choosing an accurate strength criterion for each constituent at the different material scales, it is possible to extend the model to the prediction of yarn segments or resin failure. The damaged entity is then eliminated from the unit-cell and a new elastic study is carried on. Finally, the failure behavior of the braided composite, or at least its bounding (according either to the iso-strain or the iso-stress method), can be predicted.

![Diagram of yarn and matrix mixture](image)

Figure 5: The yarn + matrix mixture is considered as the combination of two laminates (5b) et (5c).

5 Characterization of the 3D braided composites – Comparison with 2D braided composites

Our first objective is to experimentally determine the mechanical properties of a braided composite and to compare them with the values predicted by our model. The mechanical tests will be conducted on plate specimens. In a second step, the objective is to compare some performances of the 3D reinforced composites with those of 2D reinforced composites presenting equivalent braiding characteristics (same period, same angle of braiding but no interlacing of the layers through the thickness). Here, we concentrate ourselves on the effect of an impact. The impact generating inter-laminar cracks, we will compare its effect on the 3D and 2D reinforcement. Vibration and compression-after-impact tests will be carried out on thin walled carbon / polyamide 12 composite cylinders.

5.1 Tested specimens

The braided plate specimens tested are made of hybrid carbon / PA12 yarns ($K$: 54%). The hybrid yarn contains commingled reinforcement and matrix fibers and is spun by a PA12 film. The characteristics of the reinforcement and the matrix fibers are summed up in the table 2 (f: fiber, m: matrix). The consolidation of the braided composite is done in a heated mold. Two braided composites have been tested. They present two different braiding angles at $\pm 45^\circ$ and $\pm 30^\circ$. The experimental values of the compliance terms are presented in the table 3.

5.2 Simulation and comparison of 2D and 3D braided composites

The different compliance (or stiffness) matrix terms being experimentally identified, we can assess the validity of our mechanical model. For the two braided angles ($30^\circ$ and $45^\circ$), we estimate some of the mechanical characteristics...
according to the iso-strain and iso-stress approaches. We complete a parametrical study (figures 6 and 7) by the estimation of their variation for an angle $\theta$ ranging from 10 to 80°.

The first parametrical study concerns the variation of the first compliance term $1/E_L$ as a function of $\theta$. We first remark that the iso-strain approach (averaging of stiffness) provides a rather good prediction of this term. The experimental values for 30 and 45° are quite in good agreement with the modeled values. The maximum discrepancy is about 17% for the angle of 30°. On the contrary, the use of the iso-stress approach (averaging of compliance) provides an over-estimation of $1/E_L$. Although we need to confirm this with other composite systems, it seems that this second approach should be avoided for our braided composite. Finally, concerning the whole estimated curve, we notice an increase of $1/E_L$ as a function of the braiding angle and that 2D braided composites seem to present a more important stiffness of about 10%.

The second parametrical study considers the effect of the angle on the shear compliance term $1/G_{LT}$. Once again, we remark the better estimation of the experimental values provided by the iso-strain approach. We also notice that no actual symmetry is observed around 45° contrary to the case of a unidirectional composite. The yarn crimping through the thickness can explain this. The shear stiffness of the 2D braided composites seem here lower than the 3D composites.

Table 2: Characteristics of the reinforcement constituents.

<table>
<thead>
<tr>
<th>Carbon</th>
<th>PA12</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_r$ (GPa)</td>
<td>240</td>
</tr>
<tr>
<td>$E_t$ (GPa)</td>
<td>16</td>
</tr>
<tr>
<td>$G_{tt}$ (GPa)</td>
<td>52</td>
</tr>
<tr>
<td>$G_{tt}$ (GPa)</td>
<td>1.30</td>
</tr>
<tr>
<td>$v_{ft}$</td>
<td>0.30</td>
</tr>
<tr>
<td>$v_{fr}$</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 3: Experimental values of the compliance terms.

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>±45°</th>
<th>±30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/E_L$ (MPa⁻¹)</td>
<td>$1,83.10^4$</td>
<td>$6,12.10^3$</td>
</tr>
<tr>
<td>$1/E_T$ (MPa⁻¹)</td>
<td>$1,90.10^4$</td>
<td>$3,21.10^4$</td>
</tr>
<tr>
<td>$1/G_{LT}$ (MPa⁻¹)</td>
<td>$5,24.10^5$</td>
<td>$1,51.10^4$</td>
</tr>
<tr>
<td>$-v_{LT}/E_L$ (MPa⁻¹)</td>
<td>$-1,14.10^4$</td>
<td>$-3,18.10^5$</td>
</tr>
</tbody>
</table>

Figure 6: Estimated variation of $1/E_L$ as a function of $\theta$. 
5.3 Effect of an impact

The ability of high performances composite materials to resist damages induced by impact must be taken into account when designing a composite structure. The internal damages consist in matrix cracks, delamination and failure of fibers conducting to a loss of stiffness and strength. In the following paragraph, we aim at comparing the effect of an impact on 2D and 3D braided composites.

5.3.1 Impacts on thin-walled composite tubes

The impact tests are carried out on tubes presenting respectively a length and a diameter of 100 mm and 50 mm. These tubes will be cut at a length of 69 mm according to the ASTM D5440 standard for the subsequent compression tests. The specimens are placed under a 12.7 mm diameter spherical impactor. They are subjected to two diametrically opposite impacts in order to ensure a certain symmetry and to avoid its instability during the compression tests.

Two levels of impact are considered at 7 and 11 J. The first level initiates a visible damaging at surface of the tubes. The second causes their perforation.

5.3.2 Compression-after-impact tests

The tests are carried out using a Zwich 1475 dynamometer equipped with a 50 kN load cell. The speed test is 2 mm/min.

The table 4 sums up the values of the experimentally measured strength for the undamaged (0 J) or damaged (7 and 11 J) 2D and 3D tubes. For both the damage levels, we notice the loss of strength compared to the undamaged state. At the level of 7 J, we observe that this loss is less important for the 3D configuration; the 3D reinforcement is less sensitive to the impact than the 2D configuration. On the contrary, at the level of 11 J, we remark that this loss is about the same between the 2D and 3D reinforced tubes. Actually, at this impact level, the tubes are punched and then, the tested specimens present reduced areas almost equivalent.
Figure 8: Experimental device for the impact tests

Table 4: Results of CAI tests

<table>
<thead>
<tr>
<th>Braiding</th>
<th>2D</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level impact (J)</td>
<td>0 7 11</td>
<td>0 7 11</td>
</tr>
<tr>
<td>Max. Stress (MPa)</td>
<td>68.5 62.2 52.20</td>
<td>73.47 69.71 52.16</td>
</tr>
<tr>
<td>Loss of strength (%)</td>
<td>-10.1 -31.2</td>
<td>-3.7 -29.8</td>
</tr>
</tbody>
</table>

5.3.3 Vibration tests

Vibration tests are carried out on undamaged and damaged tubes under free-free boundary conditions. An accelerometer is bound to the external surface and located in the middle of the tubes. We consider the first mode of vibration that corresponds to the bending of the tube. The impact response can be given in form of magnitude vs frequency curves (Fig. 9).

Figure 9: Impact response of 2D undamaged and damaged (11 J) tubes.
The table 5 sums up the data collected from the vibration tests. We do not observe any significant results as far as the drop of maximum frequency is concerned. The observation of the damping ratio (at 3 dB) can give us more data about the difference of the impact behavior of the 2D and 3D reinforcements. If we consider that the increase of the damping ratio can be related to the apparition of debonding between layers, we can estimate that the 2D configuration is more sensitive to the impact than the 3D one.

Table 5 : Results of vibration tests

<table>
<thead>
<tr>
<th></th>
<th>Impact level 7 J</th>
<th>Impact level 11 J</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2D</td>
<td>3D</td>
</tr>
<tr>
<td>Variation of maximum frequency</td>
<td>-1.86%</td>
<td>-0.70%</td>
</tr>
<tr>
<td>Variation of the damping ratio</td>
<td>12.0%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

6 Conclusions

A new multipath interlock braiding machine has been presented. It produces 3D braided composites which stiffness properties can be predicted by means of a simple multi-scale modeling. Some elastic characteristics of 2D and 3D braided composites have been compared through simulations. If the 3D braided composites do not necessary present better elastic properties than 2D ones, we show that the 3D configuration permits to be less sensitive to impacts. It has been proved by means of compression and vibration tests after impacts.

Acknowledgements

The authors fully acknowledge the French Ministry of Industry and the Rhône-Alpes Region for their financial supports to this research.

References

