1. Introduction

Transverse behaviors of unidirectional materials such as fibers have been studied for a long time, either from a theoretical or an experimental way. However those studies are majoritarily focused on monofilaments; too few of these investigated on tows' transverse behavior, even less concerning tows used in composite materials. Several studies developed analytic models describing transverse compression behavior of fibers assemblies. One of the earliest work was the study of Van Wyk’s, in 1946. He proposes an analytic model for the compression of randomly oriented wool fibers; without favoured directions contrary to the tows. Trying to respond to this limitation, Komori and Makishima expanded Van Wyk’s ideas by derivating the equation and calculating the number of contacts within the randomly oriented fibers assembly. However, experimental and theoretical studies available in the literature do not reflect the impact that some geometrical and mechanical characteristics might have on tows’ transversal behavior. The first objective of this study is the understanding of the shift between the fiber’s behavior and the wick’s behavior composed of N twisted and tensioned fibers. The goal of this study is to determine the transverse behaviors of carbon tows used for the composite materials reinforcement. Thus, the second part of this work aims the characterizing of the interaction between several carbon parallel tows. The numerous results were then implemented in an industrial code; they improved significantly the numerical predictions. These results will be published later.

2. Transverse behavior of standard PA monofilaments

2.1 Experimental device

We developed an experimental device (Fig. 1 and 2) to compress in their radial direction large diameter filaments, or tows of glass or carbon fibers [5, 6]. A unit with four steel columns, consisting of three perfectly parallel plates is the essential element of this assembly. The lower plate is fixed to the motionless frame of the tensile testing machine (MTS 20/M). The intermediate plate is connected to the moving crosshead of the tensile testing machine via a ball joint (ball bearing) and is actuated by it. This plate is guided in translation by means of ball bearings fixed on the four guiding columns. The last top plate is screwed and fixed on the four columns. The vertical movement of the crosshead is used to transversally compress linear textile samples. Indeed, when the crosshead moves upwardly, it is to translate the intermediate plate like the traction frame.

Figure 2 shows the details of the transversal fiber compression. The sample (part number 6) is compressed between two glass parts (5 and 8). The upper one, conically shaped, is fitted in the upper plate (4) of the device. The bottom one is a plate, placed on another aluminium part. The opening filled by the armoured glass cone has been designed to observe, using a camera, the evolution of the contact surface throughout the test. We chose to compress our tows between two glass plates having undergone an anti-reflective coating to eliminate measurement errors due to the light reflections. It also allows observing the deformation of the samples during testing, thru an optical system and a camera.
Two LVDT displacement transducers (HBM), with a measuring range of ± 1mm, in direct contact with the glass plate, measure the relative displacements between the two compression plates regardless of the effects of the driveline’s backlashes. The average value of the two displacements will be used to process our results.

A force sensor U3 (HBM) showing a capacity of 0 to 2KN (or 0 to 0.5kN depending on the sample type), placed directly under the fiber to be tested, measures the compressive force applied on the sample. The optical system always views the lower base center of the cone glass. Yarns are fixed to the center of the glass plate (Fig. 2).

2.2 Materials

In the full study, the influence of several parameters during the transversal compression was studied: the effect of the initial twist in the tow, the effect of its initial tension, and the influence of the number of monofilaments. Table 1 is a summary of the different studied conditions; for each condition, we have a varying parameter and we keep all of the others constant. This paper is just dedicated to the effect of the twist; the effect of tension was published in [7].

The studied standard materials are composed of PA 6-6 monofilaments, with a diameter of 230 or 400 micrometers. We also vary the parameters such as the density of filaments (range from 40 to 230 filaments per tow), the initial twist (from 6.67 r/m to 40 r/m, see Fig 3) and also the initial tension (1N or 2N).

2.3 Experimental results on standard materials (PA)

We present here the flattening of the tow subjected to different twists. The varying parameter is the tow’s initial twist. The tow is composed of 40 monofilaments (diameter of 400 μm each). Figure 5 shows the evolution of \( \eta_1 \): thickness divided by the initial thickness depending on the applied compression load (\( \eta_2 \) widths respectively).

\[
\eta_1 = \frac{d1(F)}{d0} \\
\eta_2 = \frac{d2(F)}{d20}
\]

With \( d1(F) \): thickness of the yarns according to the applied force
\( d0 \): initial thickness of the yarn.
\( d2(F) \): widths of yarns according to the applied force
\( d20 \): initial widths of the yarns

The analysis of the curves highlights a typical transverse filaments subsidence behavior. Plateaus, with the dimensions of the diameter of the fibers, appear on the compression curve [6]. These “granular” phenomena are also observed during the simulation and allow us to characterize scale changes, from the microscopic structure to the macroscopic one. [7]

The general shape of the curves in figure 5 shows that the twist does not have strong influence on the overall transverse behavior of the standard tows. However, we note that a strong twist (inducing more internal compaction) tends to "smooth" the experimental curves. On the other hand, we also noted that by increasing the number of fibers, the "plateaus” tend to decrease or even disappear. It should be noted that the coefficient of friction (seen as governed by a Coulomb friction law in the numerical modelling) seems to be a major barrier to understand the subsidence phenomena. Numerical simulations in parallel with the experimental work showed their major importance. [8]

3. Transverse behaviors of carbon tows

For the realization of complex composite structures, Snecma uses multilayer 3D textures. New mechanical parts are developed; they are produced by injection of epoxy resin on 3D-woven carbon fiber reinforcement. These fabrics have significant technological new interests, in particular their impact behavior.

3.1 Experimentation and materials

Snecma uses WiseTex software [9] to calculate the mechanical properties of carbon fiber composites. This tool is based on the tow properties (geometry, transverse compression behavior, bending), in order to model the fabric structure. The knowing of the geometry and behavior of the tows is therefore essential to obtain reliable models. This needs to develop compression tests to characterize the properties of carbon tows. For confidentiality reasons, we do not further describe the tested tows.
3.2 Experimental results on single tow

Carbon tows, with three initial twists, 5, 10 and 20 r/m were tested in the setup shown in the first part of this paper. The experimental curves (figure 6), after being processed, averaged and smoothed show the same general shape as the PA standard materials ones. Of course, the plateaus will not appear on the carbon curves because of the very small fiber diameter size as well as the accuracy of our measurements. The influence of the twist is similar to those observed through PA monofilament results. The more the twist increases, the higher is compaction and the less the fibers have space to slide and rearrange. The tests were carried out on unique tows but also on several parallel tows placed on the compression plates, we divided then the experimental data by the number of tows. We found that the tows of carbon fiber show a different behavior in compression as they are free or placed side by side. A second series of tests has been performed to characterize the influence of neighbouring tows in the radial flattening of the final 3D woven structure.

3.3 Multi tows tests

In order to perform tests on parallel tows on which it is possible to set the initial tensions and twists, it was necessary to design a new device that could be adapted on the previous transverse compression machine. The device is built up with standard items plus some dedicated manufactured parts. The base of the machine is the same as for a unique tow: three parallel steel plates, middle one is mobile and guided by four columns (see paragraph 1). Two subsystems, the first one for tow twisting and the second one for tows tensioning, are fixed on two parallel faces of the moving plate (Fig. 7).

The torsion system consists of two rows of gears, which intermesh such that the 5 upper sprockets rotate in the same direction. Each tow is clamped in a gear (in the top row); a crank permits to apply the same twisting to each tows (see Fig. 7 and 8). The tension system is on the other side of the tows. It is composed of two parts, the first one is fixed on the movable plate and the other one is equipped with five dynamometers. Their rotation is blocked in order to block the twist of the tows. Each tow is fixed on a dynamometer, and then pulled. The spacing between the individual tows can be controlled by the rotation of two combs; one is fixed on the twisting system side and the other one on the tension system side. These two combs are synchronized in rotation through a belt/pulley system located at their bases. The gap setting is done thanks a precision angle vernier associated with one of the pulleys.

The tests were conducted on three identical parallel tows, separated by different spacings (from 2.12 to 2.40, or 3.18 mm). We observed the limits in the widening of the central tow according to the initial distances between adjacent tows.

After processing the experimental results through MATLAB, curves of the same type as those obtained in Figure 6 are obtained and showed in Figure 9. Note that the routines were originally designed to handle data on the flattening of a single tow; we therefore assumed that the compressive load is evenly distributed on three tows. Then, each tow is loaded under the third of the total applied load.

Several curves displaying \( \eta_1 = (d_1 (F) / d_{10}) \) are established as in the previous paragraphs (Fig.6). The general shape tracks well the standard materials, but it is clear that taking into account the interaction between the tows is not negligible. When the distance between tows increases, the behavior of the central tow tends to the behavior of a single tow, since nothing blocks its widening on both sides.

For small spacings (e.g. 2.12 mm), the tows have very small space to deform laterally (less than 3% of final extension), compression is in fact more complicated than just unidirectional because of the lateral confinement created by the neighbouring tows. Upon compression of tows positioned side by side, an asymptote appears on the curve showing a limited evolution of the width according to the applied force. This asymptote corresponds to the initial gap between the fibers, filled with their own distortions. Moreover, the final thickness of the tows remains slightly larger compared to those observed in a single tow test. Additional curves for \( \eta_1 \) and \( \eta_2 \) (not presented in this paper) are obtained on other tow structures, where the density of fibers changes, they are then used to characterize the compression behavior of the tows in the Snecma simulation tools’.
4. Conclusion

These experimental results have been implemented in the Wisetex code and have validated the simulation results characterizing the structure of wovens (image analysis on sliced material or microtomography); and so confronted the results of mechanical tests with the calculations. These behavioral identifications have improved the geometry models generated by WiseTex, and thus the prediction of the mechanical properties of the composite.

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References


Fig. 1 Experimental device: transverse compression of fibers and tows [5]

1. Mounting brackets for sensors
2. Spacers for sensors alignment
3. Displacement sensors (LVDT)
4. Top plate
5. Glass cone
6. Monofilament or tow
7. Attaching the sample
8. Glass plate
9. Aluminium plate
10. Force sensor
11. Intermediate plate

Fig. 2 Details of compression zone [5]

Fig. 3 Pictures of standard PA tows [7]
Fig. 4 Fiber compression

Fig. 5 Evolution of the ratio instantaneous thickness/initial thickness versus compression force

Fig. 6 Evolutions of relative thickness $\eta_1$ and width $\eta_2$ for carbon tows with varying twists

Fig. 7 Additional device for test compression on parallel tows
Fig. 7 Schematic diagram of the transverse compression device

Fig. 8 Evolutions of relative thickness $\eta_1$ and width $\eta_2$ for carbon tows with different spacings
Fig. 9 Evolutions of relative thickness $\eta_1$ and width $\eta_2$ for carbon tows with different spacings