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# Experimental characterization of the tensile behavior of a polypropylene/glass 3D-fabric: from the yarn to the fabric

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## Abstract

This paper investigates the tensile behavior of commingled polypropylene/glass yarns at different testing speed. A protocol to perform yarn tensile tests is defined and tests are carried out on yarns before and after weaving (yarns extracted from the fabric) in order to characterize the weaving damage. A protocol is also defined to perform tensile tests on 3D-fabrics. The tensile behavior of a 3D-fabric made of commingled yarns is investigated and results are compared with yarn tensile tests.

**Keywords:** tensile tests, commingled yarns, weaving damage, 3D fabric, testing speed, 3D Light-trans

## 1. Introduction

Experimental characterization of the mechanical properties of a woven composite reinforcement is an important issue to the better understanding of its behaviors during the forming processes. It also provides data for numerical simulations that will allow predicting the feasibility of a part and improving the manufacturing processes. This study considers a 3D-fabric woven with commingled yarns. Commingled yarns have been developed in the past decades in order to take benefit of the advantages of textile reinforced thermoplastic composites where no impregnation process is needed. The thermoplastic is mixed by commingling processes with the reinforcement fibers in the yarns that can then be used to produce highly drapeable fabrics. The final part is obtained by a thermoforming process, the flow length of thermoplastic after melting being drastically reduced by the use of commingled yarns, offering the possibility of a low-cost and rapid manufacturing of complex shaped composites [1, 2].

3D textile composites have been developed because they exhibit, thanks to the use of z-binder for the through-thickness reinforcement, better delamination properties, impact and fatigue resistance than conventional composites [3, 4]. In the literature, few results can be found concerning tensile tests on 3D fabrics. In [5], the tensile strength of 3D-fabrics made with glass and with different weaving architecture is investigated, but there are not known results for 3D-fabrics made of commingled yarns.

In this paper, tensile behavior of 3D fabric and commingled yarns used for its manufacturing is investigated. For each material, experimental protocol based on standards and those used for 2D fabrics and classical yarns is developed and validated. Then, tensile tests at different crosshead speeds of commingled yarns are carried out in order to highlight the strain rate effect on its behavior. In order to characterize the weaving effect on the yarns behavior, and then 3D-fabric, yarns were extracted from the fabric and tested. These tests results are compared with those of yarns before weaving and with the 3D-fabric.

## 2. Description of the materials

### a. Commingled yarns

Different technologies have been developed for the production of commingled yarns, influencing the structure and behavior of the obtained yarns [7, 8]. In this study, yarns commingled with an air nozzle are used. The input materials are similar to those used by Torun and al. [6]. According to the manufacturer, yarns were commingled using a pressure of 4 bars. The input materials are: 300 tex E-glass fiber yarn over-delivered at 2% and 3\*32 tex yarns of PP over-delivered at 4.5%. The obtained yarn is approximately 410 tex (glass fiber volume fraction of 52 %). The yarn structure is highly influenced by the commingling processes with the presence of nips and opened sections along the length of the yarns (Figure 1). A description of such yarns and the commingling process effect on the yarn architecture can be found in [7].

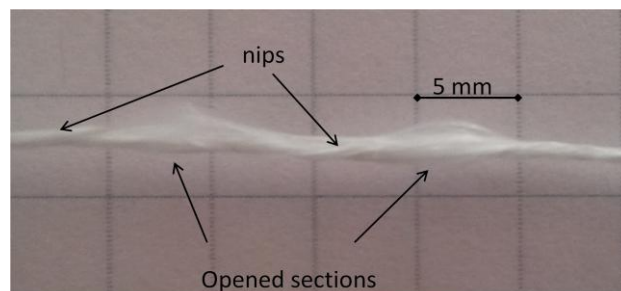


Figure 1: structure of a commingled yarn

### b. Fabric

The weaving architecture of the 3D fabric used in this study is described on Figure 2a. Figure 2.b displays the visual aspect of the fabric. The fabric consists of straight yarns in the warp and weft directions for the in-plane stiffness and of z-binder in the warp direction for the through thickness reinforcement. In the weft direction (black yarns), the fabric is made of 5 layers of commingled yarns. There are 240 weft yarns/10 cm. In the warp direction there are 3 groups of yarns: straight commingled yarns in blue (4 layers and 200 yarns/10 cm), commingled binding yarns in red (200 yarns/10 cm), and 32 tex polypropylene binding yarns in green (100/10cm). The fabric thickness is approximately 4mm, and the fabric weight is close to 2700g/m<sup>2</sup>.

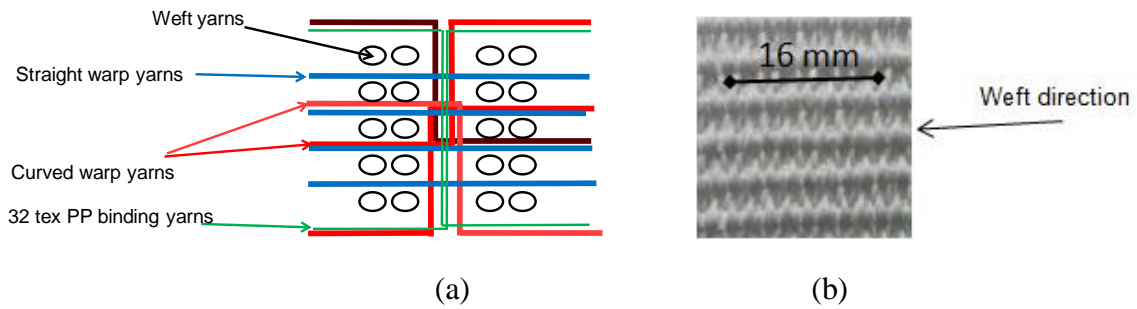


Figure 2: weaving structure (a) and visual aspect (b) of the fabric

### 3. Yarn tensile tests

A protocol was defined to perform tensile test on yarns with a standard tensile testing machine. Yarns are fixed between thin aluminum plates with glue (Figure 3). A uniform pressure is applied on the plates during at least 24 hours (time of drying). The aluminum tabs are directly fixated in the machine jaws for the testing. Tests were realized using a gauge length of 200 mm; preload of 5mN/tex and three different testing speeds of 2, 20 and 200 mm/min. The gauge length of 200 mm was chosen so that the results of yarns tensile tests can be compared with the results of the fabric tensile tests which were also performed with this length. The speed of 200 mm/min corresponds to the specimen extension of 100% per minute recommended by ISO 2062 [11]. It was also chosen to perform the test with the speed of 2mm/min (quasi-static loading) better corresponding to the speed involved during the fabric shaping. 20 mm/min was chosen as an intermediary speed. At least 10 tests were performed in each testing configuration.

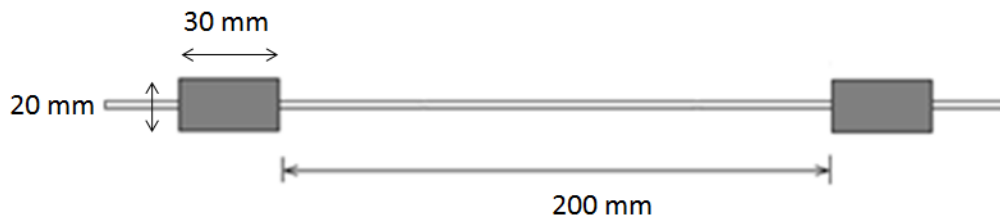


Figure 3: Schematic illustration and dimensions of a test specimen

First tests were performed with yarns from the bobbin (yarns obtained after the commingling process), with the 3 testing speeds. Figure 4 shows an example of results obtained with the speed of 20 mm/min. At the beginning of the loading, a non linear behavior corresponding to the realignment of fibers along the yarn direction is observed. After this first phase, a linear behavior is obtained. Small but brutal decreases of force can be observed on some curves during this linear phase, corresponding to the opening of some unstable nips [7]. This linear part is followed by a brutal break of the glass fiber. After the breaking of the glass fiber the load is taken up by the PP [9], with a breaking elongation ranging from 8 to more than 40% (Figure 5). Due to the particular structure of the yarns, there is a quite important dispersion from one test to the other. This can be attributed to the particular structure of the commingled

yarns where the number and types of nips/opened sections along the yarn length can vary from one sample to the other which leads to some differences in their tensile behavior.

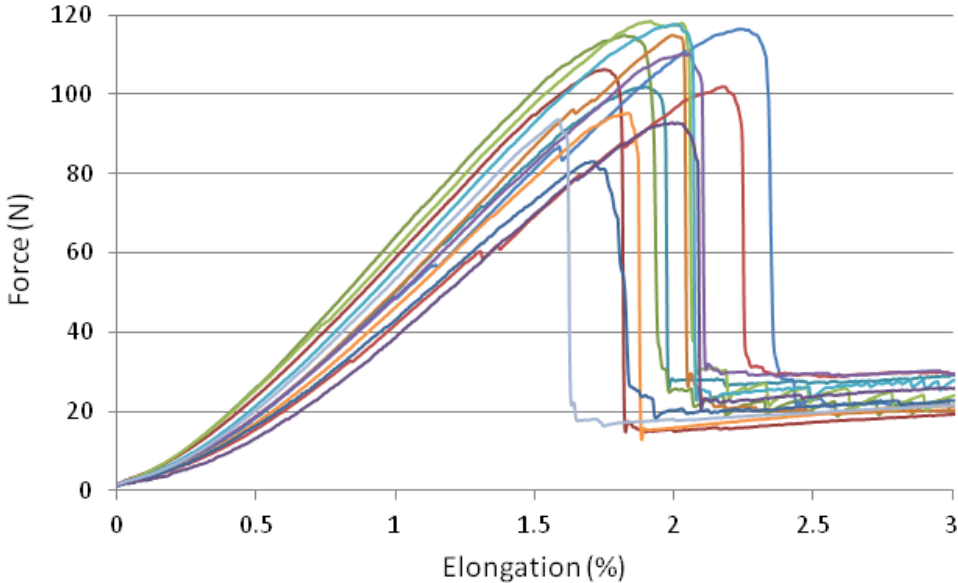


Figure 4: First part of the commingled yarns tensile behavior at testing speed of 20mm/min

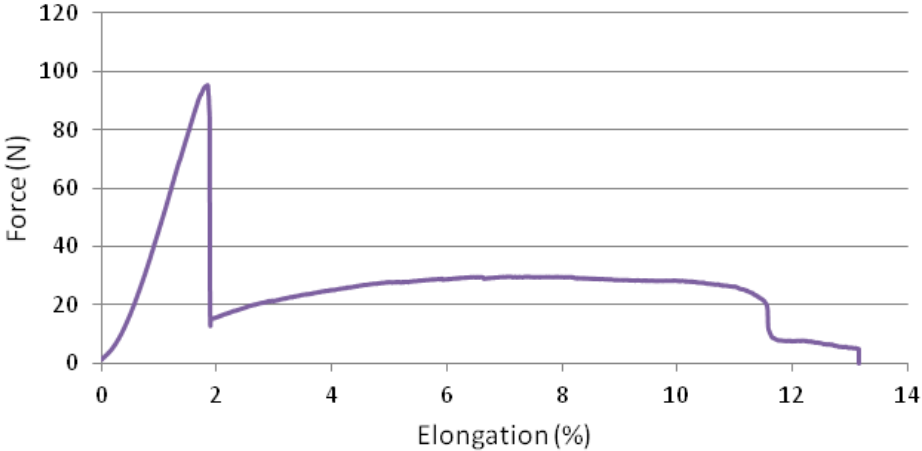


Figure 5: Full force-elongation curve at 20mm/min showing the behavior of polypropylene

On figure 6 are presented the mechanical parameters obtained for the yarns extracted from the bobbin for the speeds of 2, 20 and 200mm/min. There is a strong dependence of the breaking strength and elongation at break of the yarns with the testing speed. With the 200 mm/min speed, the breaking strength is 70% greater than with the 2 mm/min speed (Figure 6.a). The Young modulus of the yarns is close to 30 GPa and doesn't have a strong dependence with the speed (Figure 6.b).

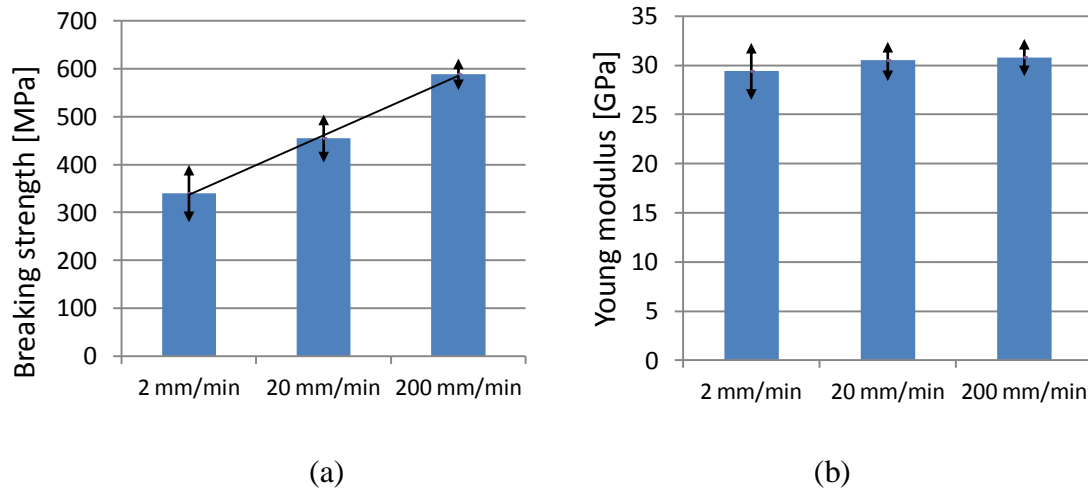


Figure 6: breaking strength (a) and Young modulus (b) of the commingled yarns as a function of testing speed

An important point that must be considered is that during the fabric weaving process, the yarns can be damaged. In order to highlight and quantify the damage on the commingled yarns during the 3D-fabric weaving, yarns were extracted from the fabric and separated in 3 groups: weft yarns, warp yarns 1 (straight warp), warp yarns 2 (binding warp). Yarns extracted from the fabric were only tested with the speed of 2 mm/min and the results were compared with the results of yarns from the bobbin.

The results can be compared with those obtained by Lee and al. [10], where the damage caused to glass yarns in 3D weaving is investigated. Tensile tests performed on the warp yarns of a 3D-fabric after the different weaving stages have shown that the stiffness remains unchanged but that the tensile strength of glass yarns can be reduced of up to 30%. The damage is mainly attributed to the abrasion between the yarns and the machine components. In our case, as described in 2.a., the structure of the commingled yarns is different compared with classical yarns, it is therefore interesting to compare the weaving damage on those yarns with the results of Lee. It can be seen (Figure 7 & Table 1) that there is a decrease in the breaking strength for all the yarns extracted from the fabric. For the warp yarn, the decrease is of 15 % for the binding yarns and of 22 % for the straight yarns and their stiffness is not modified. In [10], no results are presented for the weft yarns, but our results show that the weft yarns are the most damaged, with a decrease of 28 % in the breaking strength and also a reduction in stiffness (-17%). This damage might occur during the weft insertion stage, when the rapier passes across the fabric at high speed or during the beating, when the reed pushes the weft yarns.

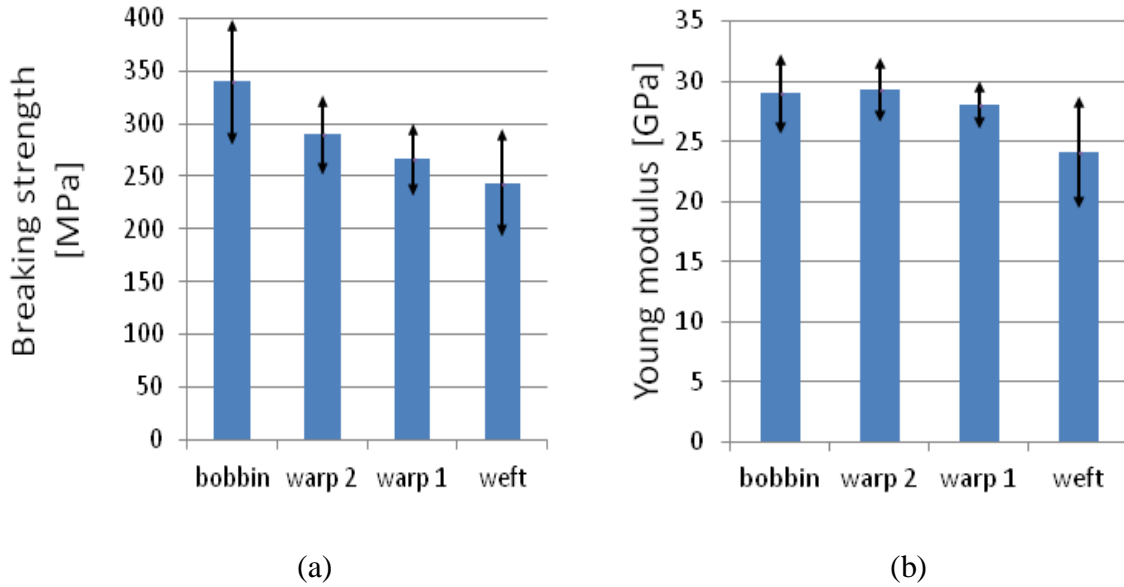


Figure 7: Breaking strength (a) and Young modulus (b) of the commingled yarns extracted from the fabric

Table 1: Comparison of the breaking elongation, breaking strength and Young modulus of the damaged and undamaged yarns

	Number of tests	Difference in % with the values obtained for yarns from the bobbin		
		Breaking elongation	Breaking strength	Young Modulus
Warp 2	14	-16 %	-15 %	+ 1 %
Warp 1	19	-17 %	-22 %	- 3 %
Weft	40	-11 %	-28 %	- 17 %

#### 4. Fabric tensile tests

##### a. testing protocol

A protocol was developed for the fabric tensile tests, the fabric was tested in both weft and warp directions. The difficulty is to ensure a good fixation of the fabric despite its important thickness. First tests were performed fixating directly the fabric in the machine clamps, resulting in the premature breaking of the samples near the clamps. Good results have been obtained by impregnating with resin the fixation part of the fabric and directly gluing aluminum tabs on those parts. Like for the yarn tensile tests, after 24 hours of drying, the specimen can be tested, directly fixating the aluminum tabs in the machine clamps. With this protocol the breaking occurs in the middle of the samples. Since important loading forces are reached, we cannot rely on the displacement given by the machine. The elongation of the fabric during the test is measured by an optical acquisition using a marker tracking method and the software Deftac [12]. Two unwoven zones on the edges of the specimen help to prevent the unweaving of the zone of interest itself. The dimensions of the zone of interest are of 33 (80 yarns in the weft direction) by 200 mm. See Figure 9 for a schematic illustration.

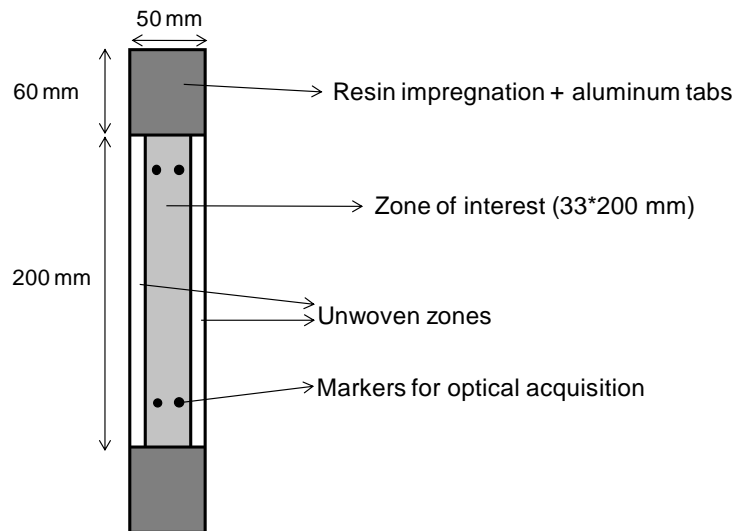


Figure 9: Schematic illustration and dimensions of a test specimen

### b. Results and comparison with yarn tensile tests

In the weft direction, where we have just straight yarns, we should expect a similar behavior between the weft yarns extracted from the fabric and the fabric itself. As specified in section 3. Comparison between the fabric and the yarns tensile behavior can be done given the fact that the testing conditions are the same for the yarns and for the fabric (gauge length of 200mm and testing speed of 2 mm/min). In the warp direction, comparing the results with yarn tensile tests is more difficult since in this direction we have both straight and curved yarns, but we can suppose that during the beginning of the loading we should obtain the behavior of the straight warp yarns since they will be the first one to take the load.

Figure 10 compares the behavior of the fabric in the weft direction, the average behavior of yarns from the bobbin and of weft yarns extracted from the fabric. We can see that the behavior of the fabric is close to the average behavior of yarns unwoven from the fabric. For the fabric, at the beginning of the loading there is a more important non linear phase compared to the yarn behavior, this can be explained by the fact yarns are not strictly straight in the fabric. Once the yarns are straight and when their behavior is linear, we obtain the same modulus for the fabric and for the yarn tensile tests. The maximum strength per yarn obtained for the fabric is between 10 and 15% lower compared to the one obtained for the yarns extracted from the fabric. A possible explanation is that there could be interactions between the yarns during the tensile tests, leading to their premature breaking.



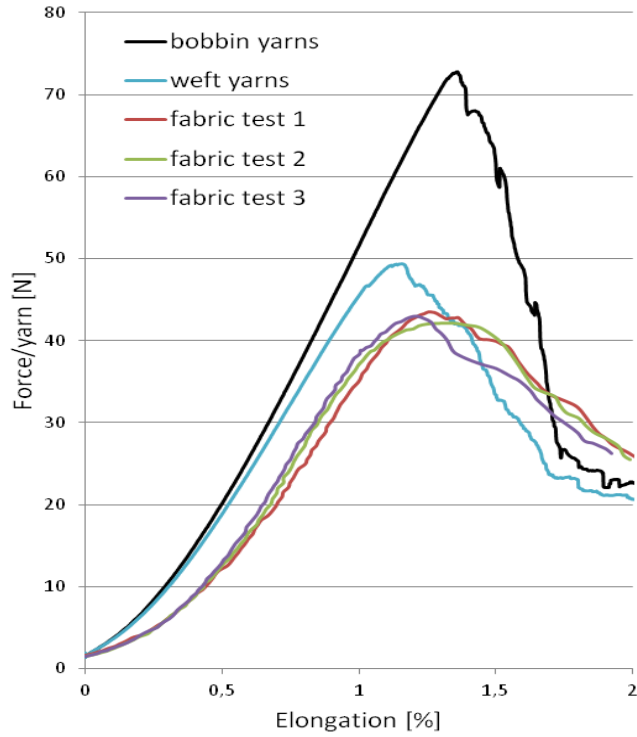


Figure 10: Tensile behavior in the weft direction, testing speed 2mm/min

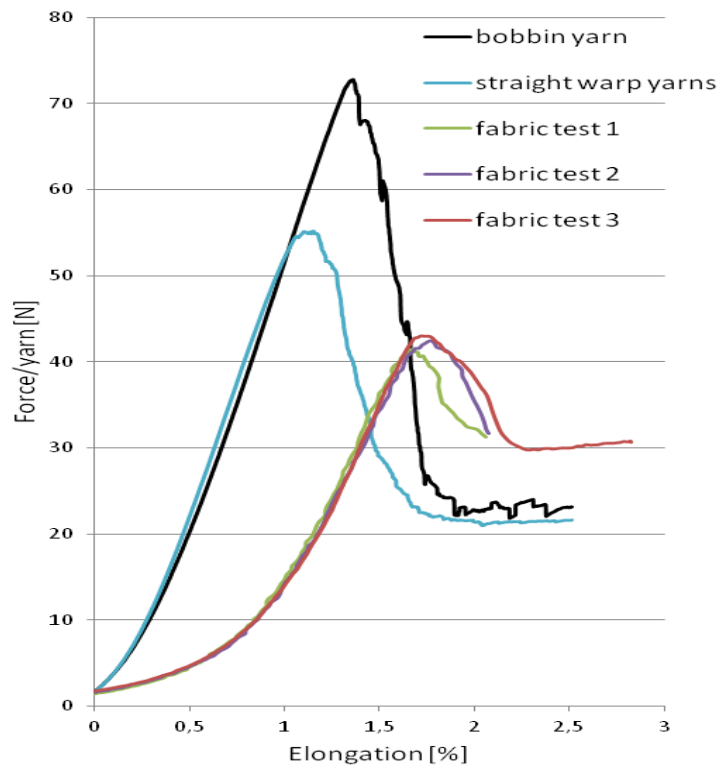


Figure 11: Tensile behavior in the warp direction, testing speed 2mm/min

In the warp direction, Figure 11 shows that the non linear phase at the beginning of the loading for the fabric is more important than in the weft direction. The modulus obtained for the fabric is lower compared to the yarn modulus. Those results can also be explained, like in the weft direction, by the waviness of the yarns in the fabric, but in the warp direction, since the weaving density is approximately twice the weaving density of the weft direction, the influence of the waviness is more important.

## **Acknowledgments**

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## **Conclusion**

A protocol to perform tensile tests on commingled yarns is defined. The tensile behavior of commingled yarns at different speed is investigated. The comparison between tensile tests performed on yarns from the bobbin with yarns extracted from the fabric show the importance of the weaving damage, especially for the weft yarns with an important decrease of the breaking strength (-28%) and Young modulus (-17%). A protocol to perform tensile tests on the 3D fabric is exposed and a good agreement is obtained between the behavior of the yarns and that of the fabric in the weft direction. In the warp direction the behavior of the fabric is less comparable with the before of the yarns since in this direction the weaving density is more important.

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