A NEW EXPERIMENTAL SETUP TO CHARACTERIZE THE DYNAMIC MECHANICAL BEHAVIOR OF BALLISTIC YARNS

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ABSTRACT

In order to improve our knowledge about the dynamic behavior of composite materials used in ballistic protection, it is necessary to characterize first the mechanical behavior of single ballistic yarns, part of these fibrous structures, which will help to predict their impact behavior.

To respond to this yarn characterization, we have developed a new device, the Tensile Impact Test of Yarn (TITY), in order to test yarns under dynamic uniaxial tension and determine their mechanical behaviors in the longitudinal direction. During the test, we measure the displacement of the flying mass when it applies a longitudinal tension on the yarn which undergoes a strain up to its rupture.

After data treatment, we obtain the evolution of the velocity of the flying mass versus time which depends on the mechanical behavior of the yarn (evolution of the stress vs. strain, ultimate stress and strain).Thanks to an analytical approach proposed to model these two phases, we could estimate the longitudinal Young modulus of the yarn under dynamic loading. These results also provide us information about the specific energy absorbed by the yarn and what could be failure mechanisms of yarns under a dynamic tension. This knowledge about dynamic behavior of yarns would then be considered for improving future numerical models.

1 INTRODUCTION

Composite materials with fibrous reinforcement are widely present in ballistic protection and offer both high protection level and lightweight to armored structures. However, these materials could potentially still be improved with a better understanding of the influence of the composite material properties on ballistic performances. During an impact, the mechanical behavior of the composite material is mainly controlled by the dynamic mechanical behavior of its components (matrix and reinforcement). For ballistic protection materials, the fibrous reinforcement can be a woven, a unidirectional or a nonwoven structure, itself composed of a multitude of yarns intertwined, or layered in the case of a unidirectional structure. Among several inner parameters like the number of filaments, the linear density or the nature of the fiber, the mechanical behavior of these complex structures depends on the mechanical behavior of these single yarns. Few studies have been done on the characterization of ballistic yarn mechanical behavior in dynamic load at the three scales: the filament scale [1, 2], the yarn scale [3, 4] and the fabric scale [5, 6]. Thus, characterizing the mechanical behavior of single ballistic yarns can widely help to predict the impact behavior of these fibrous structures.

In this paper, a method for testing aramid yarns in dynamic uniaxial tension using a new experimental device is presented. Then, a description of the measurement device associated is done with the different curves obtained after data treatments. In a third part, we discuss about the experimental results obtained.

2 EXPERIMENTAL TESTS

2.1 The Tensile Impact Test for Yarn (TITY) device

To respond to this yarn characterization, we have developed a new device, the Tensile Impact Test for Yarn (TITY), in order to test yarns under dynamic uniaxial tension and determine their mechanical behaviors in the longitudinal direction. The TITY device consists of three main parts: the support, the projectile and the yarn sample which is maintained by its two ends to the support and the projectile (Figure 1).

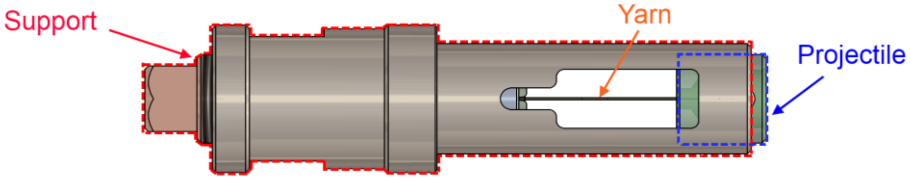

Figure 1. TITY device

A gas gun is used to propel the TITY device at an initial velocity $v_{initial}$ from 20 to 40 m/s. Aramid yarns (Twaron 336Tex) are tested and two different sample lengths are used (5 mm and 20 mm) to reach initial strain rates within the range from 1000 to 4000 s^{-1}. So, the whole device (support, yarn and projectile) is propelled at a velocity $v_{initial}$ through the gas gun up to its muzzle where the support is suddenly stopped caused by a cross-section diminution. The working mass keeps its initial velocity $v_{initial}$ and applies a dynamic uniaxial tension on the yarn sample (Figure 2).

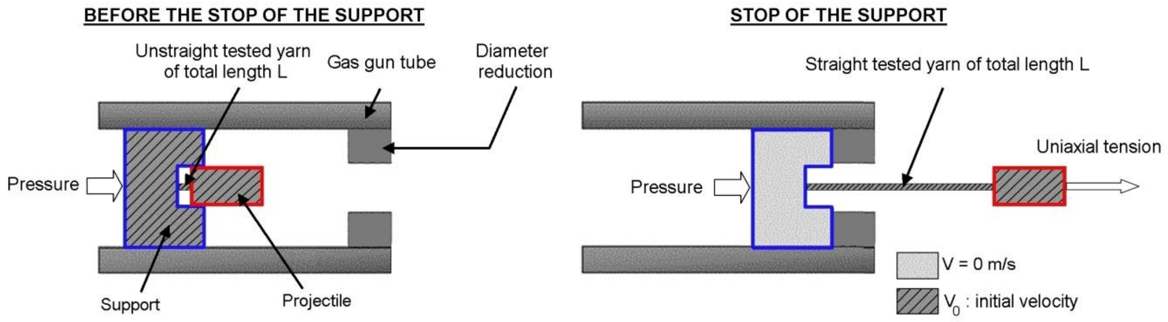

Figure 2. Principle of the TITY device.

Criteria had to be taken into account in order to realize tensile tests in good conditions:

- Firstly, the yarn has to be maintained straight along the TITY device in order to apply a longitudinal tension with the projectile without transversal component.

- Secondly, any slide of the yarn inside the support or the projectile has to occur during tensile tests. It results in an energy absorption provided by the projectile to the yarn. The yarn rupture and the data obtained are thus misrepresented.

- Moreover, the rupture of the yarn has to occur in the effective length, between the edge of the support and the edge of the projectile.

- At least, the projectile weight has to be adapted to the tested yarn. The energy provided by the projectile to the yarn has to be superior to the rupture energy of the yarn but it also doesn't have to be so important in order to observe elongation and rupture phenomena of the yarn.

2.2 The laser measurement device

During the test, we measure the light intensity variation of a homogeneous laser beam with a photo detector. This variation is due to the motion of the projectile in front of the homogeneous laser beam when it applies a longitudinal tension on the yarn which undergoes an elongation up to its rupture. From this light intensity variation, the photo detector provides us a voltage variation versus time.

In order to define a relationship between the coverage of the laser line and the position of the projectile, a second discontinuous laser line with five markers is superposed to the homogeneous laser beam (Figure 3).

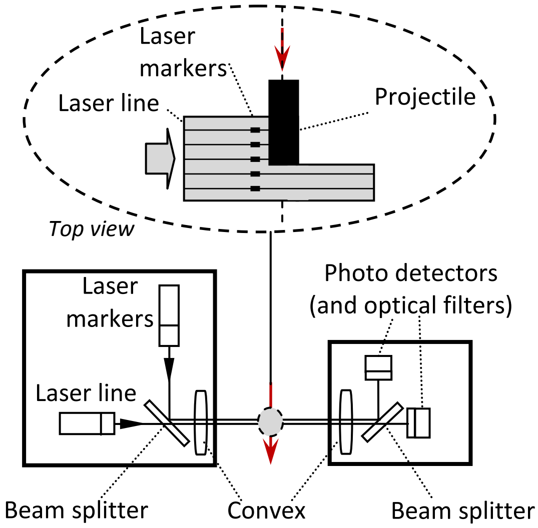

Figure 3. Sketch of the double laser device.

During the passage of the projectile in front of the homogeneous laser beam, we can identify several phases among which four ones interest us. The first phase corresponds to a constant displacement of the projectile at a velocity $v_{initial}$, the second phase to the strain of the yarn, the third phase to a gradual rupture of the yarn and a fourth phase to a constant displacement of the projectile at a velocity $v_{residual}$ (Figure 4). The times t_1, t_2 and t_3 are identified with the use of an ultra high speed camera during tests.

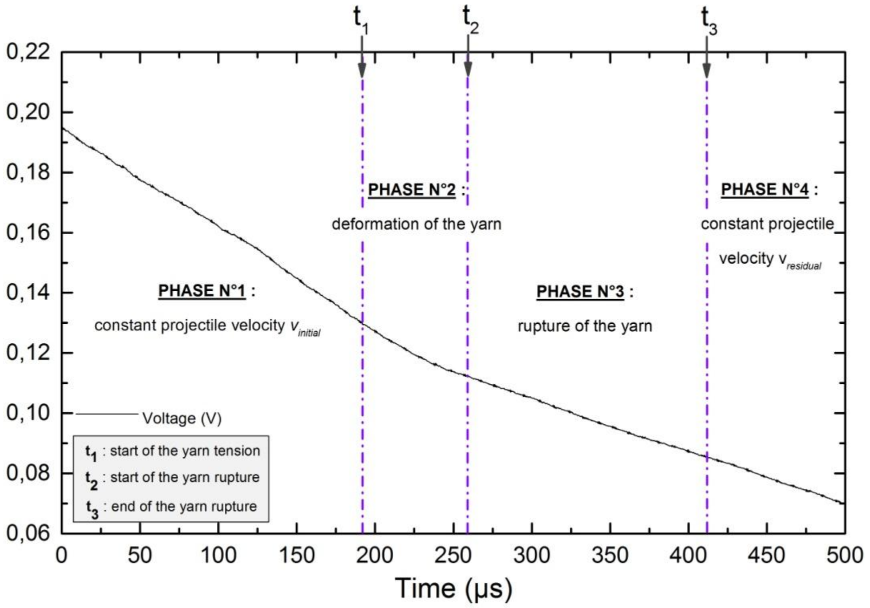

Figure 4. Test on aramid yarn (Twaron 336Tex) on 2 cm at $v_{initial}$ = 20 m/s:
Identification of the four phases on the voltage curve.

In order to obtain the projectile displacement from the voltage, a calibration of the laser measurement device is necessary. Then, adapted mathematical data treatments of the projectile displacement provide us the projectile velocity (Figure 5).

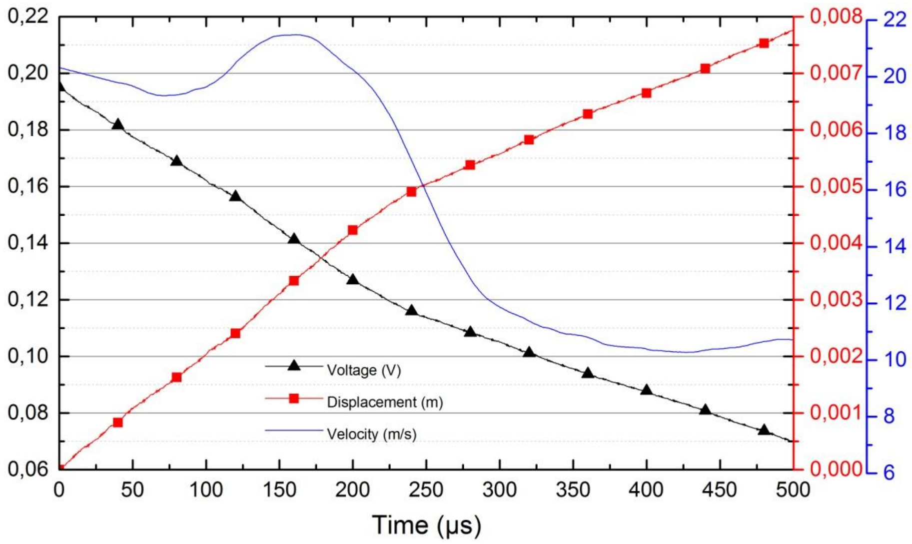

Figure 5. Test performed on aramid yarn (Twaron 336Tex) of 2 cm at $v_{initial} = 20$ m/s: black (triangular shape) left scale: Voltage-time curve, red (square shape) first right scale: projectile displacement-time curve and blue second right scale: projectile velocity-time curve.

2.3 Validation of the laser measurement device

In order to validate our laser measurement device, we realized a campaign of tests with both our device and a Photon Doppler Velocimeter (PDV). The PDV device can provide us directly a measurement of the velocity by measuring the difference of frequency between the incident (f_0) and the reflected lasers light (f_d) (Figure 6).

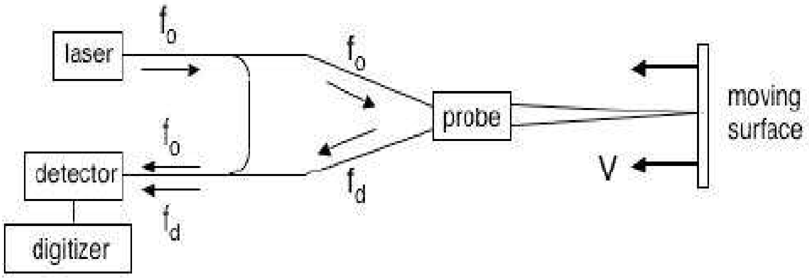

Figure 6. Principle of the PDV device.

A set of 16 tests have been performed on yarn samples (Twaron _ 336Tex) of 2 cm length at $v_{initial}$ = 31 m/s. For each test the PDV device curve and our laser device curve are superimposed, principally during the phases of the yarn strain (phase n°2) and the yarn rupture (phase n°3) what allows validating our new experimental device and the laser measurement device (Figure 7).

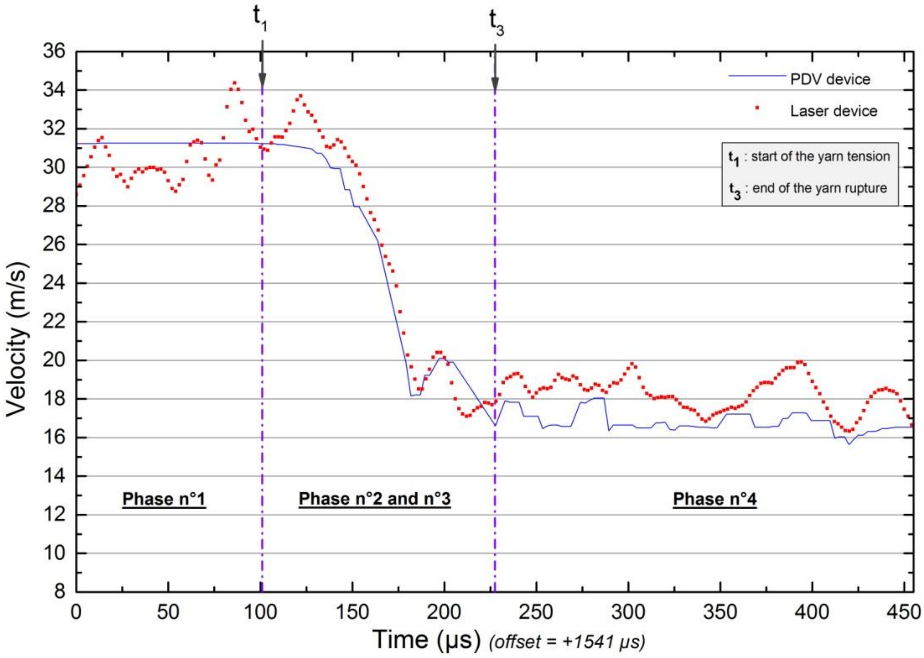

Figure 7. Validation of the laser measurement device with the PDV device.

3 RESULTS

A set of ten tests with the TITY device has been performed on aramid yarn (Twaron _ 336Tex) of 2 cm length at $v_{initial}$ = 20 m/s. We can evaluate the initial strain rate at 1000 s^{-1}. The projectile velocity variation is obtained from the voltage measured thanks to the calibration and the adapted mathematical data treatments. We can identify the four phases including those with the deformation and the rupture of the yarn (Figure 8).

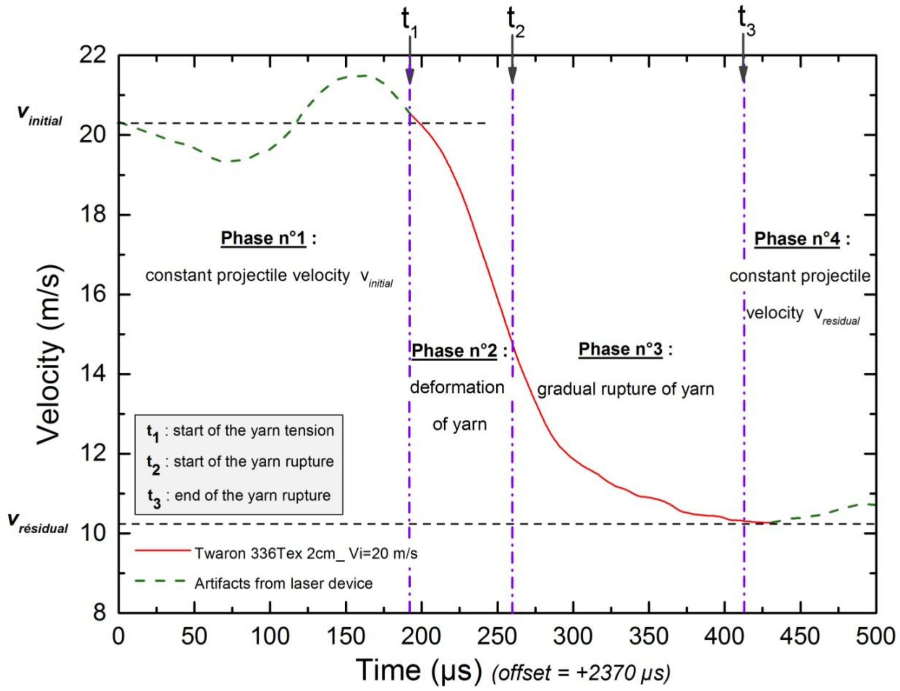

Figure 8. Identification of the four phases on the projectile velocity-time curve for tests performed on aramid yarn (Twaron 336Tex) of 2 cm length.

The yarn deformation phase is of about 70 µs and is followed by a gradual yarn rupture phase of about 150 µs. This characteristic evolution of the projectile velocity versus time depends on the mechanical properties of the tested yarn. Reproduce the shape of this characteristic curve with an analytical approach will allow us determining the longitudinal mechanical parameters of the yarn in dynamic load.

The laser measurement device lets appear artifacts during the phases of constant velocity but the discontinuous laser light with the five markers allows measuring the initial and residual velocities and visualizing the complete shape of the projectile velocity-time curve during the phases n°1 to n°4.

The residual velocity measured is 10 m/s. With a projectile of 2,6 g mass, the kinetic energy variation ΔEc is equal to 0,390 J. By assuming that the whole yarn volume is a part of the absorption of the energy provided by the projectile, the specific energy absorbed by the yarn E_{abs} is equal to 83,5 MJ/m^3. In order to compare this data between a dynamic load and a quasi-static load, tests have been performed on the same yarn sample at a strain rate of 0,001 s^{-1} (Figure 9).

The specific energy absorbed by the yarn under quasi-static load (0,001 s^{-1}) is equal to 67,5 MJ/m^3. From these two results of the specific energy absorbed by the yarn, we can suppose that the rupture mechanisms in dynamic load are different and need more energy than that in quasi-static load (Figure 9).

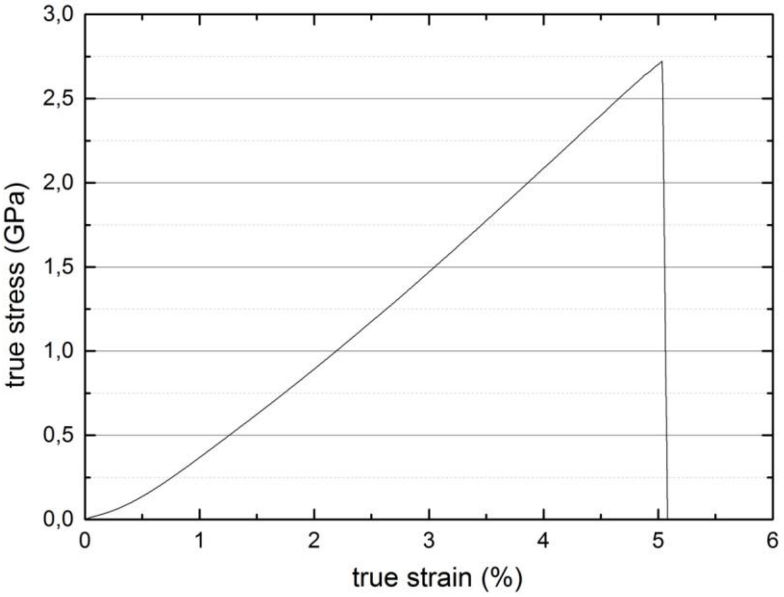

Figure 9. Quasi-static tests performed on aramid yarn (Twaron 338Tex) of 15 cm at 0,001 s^{-1}.

4 CONCLUSION

We have developed a new device to test yarn in dynamic uniaxial tension, the Tensile Impact Test for Yarn (TITY), in function of several criteria in order to respect good test conditions. A measurement device is used to obtain the variation of the projectile displacement thanks to a homogeneous laser light.

After several data treatments, we obtain the evolution of the projectile velocity versus time which depends on the mechanical behavior of the yarn (evolution of the stress vs. strain, ultimate stress and strain). The comparison of our results with ones of a Photon Doppler Velocimeter allows validating this new dynamic uniaxial tension device and the associated laser measurement device. Four phases are defined on the velocity versus time curve. Among them, we identify two important phases which are the yarn elongation and the progressive yarn rupture.

Thanks to an analytical approach proposed to model these two phases, we could estimate the longitudinal Young modulus of the yarn under dynamic loading. These results allow us assuming that the rupture mechanisms in dynamic load are different and need more energy than that in quasi-static load. Thus, this new test on yarns under dynamic loading gives promising results and, with further work, could lead to a better knowledge of ballistic yarns. This knowledge about dynamic behavior of yarns would then be considered for improving future numerical models.

5 REFERENCES

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