STRAIN RATE EFFECTS ON THE MECHANICAL BEHAVIOR OF CARBON-THERMOPLASTIC MATRIX WOVEN COMPOSITES

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Abstract

Carbone long fiber thermoplastic laminates are considered for structural parts design of an automotive frame. Knowledge of the crashworthiness and dynamic behavior of this material is essential for the structure design. The proposed contribution concerns the application of an optimized approach dedicated to the experimental characterization of the overall dynamic mechanical behavior of a Twill woven carbon-polyamide laminate. The methodology aims to report the strain rate effect on the material response with an attempt to isolate the inherent inertial disturbances in the specimen attributed to the test system. The procedure, already developed in previous work, is applied to a tensile test performed until the specimen total failure for 3 specific relative orientations of fiber: 0°, 90° and ± 45°. The tests are carried out for a strain rate range from the quasi-static (10^{-4} s^{-1}) up to 300 s^{-1}. The behavior of the material appears to be strain rate sensitive especially for the ±45° fiber orientation. The strain rate effect is attributed to both the viscous behavior of the PA6-6 matrix and visco-damage effects.

1. Introduction

The growing interest of the transport industry for using composites to improve performance, especially thermoplastic matrix reinforced with continuous fibers, substantially meets the standard requirements in terms of reducing pollution by lightweighting and recyclability of materials. However, the use of such composites in the design of structural applications submitted to severe loads as shock, crash or fatigue is not completely controlled [1, 2]. Moreover, unlike thermosets and largely due to their viscous behavior, thermoplastics are more sensitive to several factors including the temperature, relative humidity and the applied strain rate during tests [3, 4]. The current mechanical behavior models do not sufficiently integrate the physical aspects governing the material degradation. Mechanical behavior modelling must include the initial anisotropy due to the microstructure and its evolution caused by the damage phenomena. In fact, the damage threshold and kinetics are highly dependent of the composite loading conditions. Analysis of the damaged mechanical behavior of thermoplastic composites reinforced with continuous fibers under high and moderate strain rates requires theoretical tools and specific experimental approaches to quantify the strain rate effects.

In line with previous work [5, 6, 7], this study contributes to the development of an experimental characterization method applied to woven carbon fabric reinforced composite. The proposed methodology concerns a numerical approach coupled with an experimental strategy. This approach led to a robust dynamic characterization, at both macroscopic and microscopic scales, of the dynamic behavior of continuous and discontinuous fibers composite materials [6]. In this study the experimental approach has been achieved at different strain rates over a range from $2x10^{-4}$ s^{-1} to $3x10^{2}$ s^{-1} on a woven carbon reinforced polyamide 66. The high-speed tensile tests are performed using a servo-hydraulic machine. The main objective is to optimize the rapid tensile tests achievement to quantify non-linear behavior like plasticity, damage evolution, strain rate sensitivity and main effects on the overall mechanical behavior.

2. Experimental methodology

2.1Material and Representative Elementary Volume (R.E.V) description

The material is examined for the use in structural applications such as components of automotive structures. The composite consists of polyamide 6-6 matrix reinforced by Twill 2x2 woven carbon fiber obtained by thermo-compression molding. The PA66-CF48 composite laminate is made from 10 layers with a total carbon fiber volume ratio of 48%. The carbon fabric is equilibrated in the warp and weft directions involving two perpendicular orientations with theoretically identical properties. Indeed, the tensile tests are performed in three configurations distinguished by the reinforcement orientation (0°, 90° and ±45°). The tested specimens are cut from plates by machining or water jet cutting process. During the test, the machine environment is at ambient temperature and constant relative humidity.
Figure 1 shows a schematic representation of the fabric texture and repetitive elementary patterns following configurations orientation 0°/90° (a) and ±45° (b). These patterns are used to define, in accordance with the Representative Elementary Volume (REV), the minimum useful width and length of the tensile specimen. Indeed, the useful central zone of the specimen (test volume where the deformations are measured) should be large enough to be representative of the material behavior. Consequently, the upper surface (Figure 1) of the central zone to be tested must be 8x8 mm for the configuration 0°/90° and 12x12 mm for the ±45°.

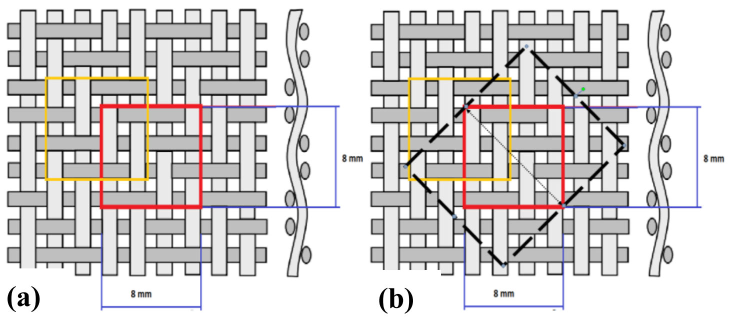

Figure 1. Elementary patterns, (a) orientations configurations 0°/90° and (b) ± 45°, for tensile test specimen minimum width and length definition, in line with REV.

2.2 Optimization of the tensile test specimen for high-speed characterization system

When characterizing dynamic behavior, it is primordial to dissociate the structure effects, mainly due to the natural frequency of the system and the grips and fixtures inertial effects, from the material intrinsic phenomena [6, 8]. An effective method for minimizing the disturbances related to structure effects is to optimize the specimen shape and dimensions in order to generate mechanical impedance breaking. This crucial step requires a first testing phase at tensile strain rates to be investigated. Thus, in order to minimize disruption measurement during dynamic tests (transient dynamics stage related to inertia and shock); a spatio-temporal stress analysis is performed by numerical computations using ABAQUS finite element explicit code. We consider in this analysis only the elastic stage of the material behavior. The boundary conditions, specified in Figure 2, are imposed in terms of displacement-rate at one extremity of the specimen, so the rise-time to reach imposed speed is defined from preliminary tests [6].

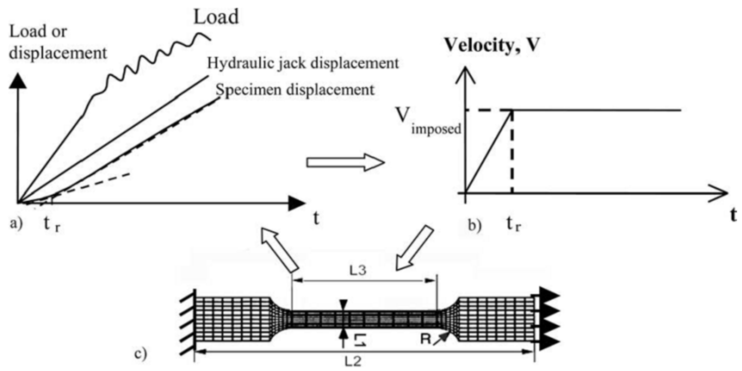

Figure 2. Specimen optimization stages coupling experimental tests and FE simulations. (a) Experimental data. (b) Boundary conditions. (c) FE computations for optimizing the dumbbell-shaped specimen geometry [6].

2.2.1 *The dumbbell specimen geometry for high-speed loading*

The dumbbell-shaped specimen is used in numerous studies [3, 5, 6, 7, 9, 10] and recommended by the standards [ISO 527-1: 2012, ISO 527-2, ISO 8256: 2004 ISO 18872: 2007] for reinforced discontinuous, short, long fibers or woven fabric composites. It is considered for different material class and studies regarding composites high-speeds tensile testing. Numerical computation by finite element explicit method [11] allows estimation of the stresses spatio-temporal evolution in the specimen. The goal is to optimize the geometry to ensure across the specimen central zone, on the one hand uniformity of stress field and on the other hand a constant strain rate [6]. These conditions are obtained through the introduction of a damping joint experimentally optimized and also through the mechanical impedance breaking directly consequent of relatively sudden variations in sections of the dumbbell-shaped specimen. The mechanical wave produced during acceleration and during the impact can be damped. The criterion to be achieved is that the imposed strain rate must be constant and constraints homogeneous in the useful zone while it is still in the stage of elastic material behavior. From the feedback, it is necessary to observe at least 10 transitions of the mechanical shock wave-front along the central zone of the specimen. Our different indications for the proposed adequate achievement of the experimental methodology agree with the standard SAE J2749 Nov2008. The optimum geometric parameters L1, L2, L3 and R shown in Figure 2 define the specimen dimensions to use in the tensile tests until rupture. These geometric parameters must enable to attenuate the amplitude of the dynamic shock waves due to rapid testing device and the inertia effects of the gripping system [6].

2.2.2 *Tensile test specimen geometry optimization by numerical computation*

The optimized geometry is defined for the two configurations by width L1= 8 mm and length L2= 30 mm for 0°/90°, respectively L1= 12 mm and L2= 22 mm for ±45°. The composite thickness is of constant value of 2 mm. The laminate woven carbon ultimate stress determined experimentally for the quasi-static loading test is of the order of 900 MPa for 0°/90° orientations and 250 MPa for ±45° orientation. Due to the material symmetry across the specimen thickness, we opted for a 2D computation [11]. The mesh size of 1 mm is chosen, and the element is of the type CPS4R (shell element with reduced integration plane stresses). The strain rate is applied to the specimen extremities at 3 m/s corresponding to a rise time of about $3x10^{-5}$ s. The following figure 3 shows the spatio-temporal profile of the longitudinal stress σ_{11}

carried on the nodes along the central line of the test specimen for the composite oriented at 0°/90°. The simulation is performed for different successive time increments from the test beginning until stabilization to a value of 0.29x10^{-4} s (Front wave at the test beginning) and becomes relatively homogeneous until the end of the test.

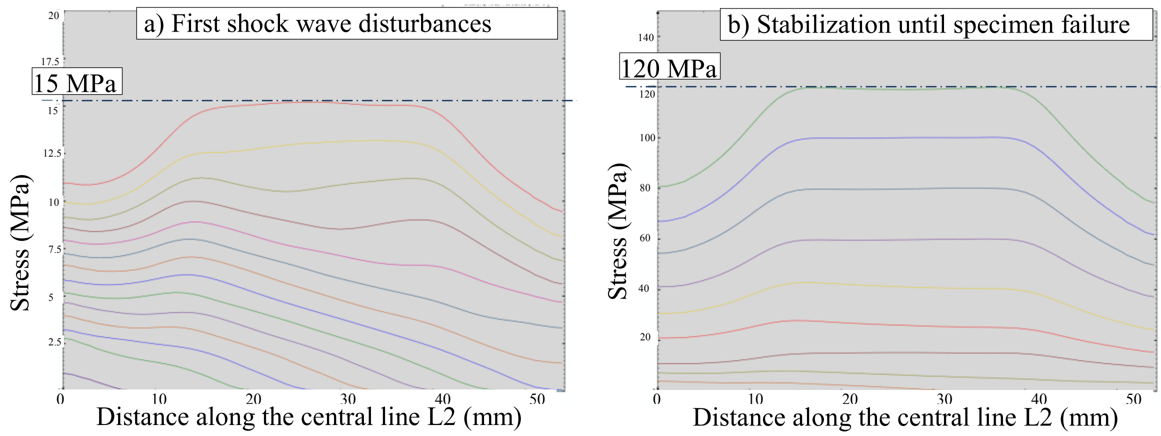

Figure 3. Spatio-temporal profile of the longitudinal stress (σ_{11}) calculated along the central line of the composite specimen at 0°/90° vs. time.

It is noted that the shock wave front is stabilized relatively quickly to a stress level of about 50 MPa. Thereafter, the curves show a homogeneous increase of the stress along the central zone. The test is then performed, macroscopically, under conditions equivalent to those of a quasi-static test conditions. Moreover, the longitudinal strain rate $\dot{\varepsilon}_{11}$ evolution versus time was computed and is quickly stabilized during the elastic stage of the material behavior. The same results and observations are obtained for the composite specimen geometry oriented at 0°/90° and ±45°. Thus, the geometry adopted in terms of shape and dimensions enable to perform high-speed tensile tests.

2.3 Mechanical testing protocol for strain measurement

The investigated range of high-speed reaches a longitudinal strain rate of 300 s^{-1}. This level corresponds largely to the strain rates undergone by materials within the scope of the investigated shock cases (for low impact car to crash at 64 Km/h). The adapted testing system used in the current study is a servo-hydraulic tensile machine Schenck Hydropuls VHS 50/20. It is provided with a gripping device that ensures a sufficient and constant clamping of the composite specimen. The piezoelectric force sensor used ensures acquisition of dynamic forces to a level of 50 KN. The strain measurement in the specimen central zone is performed by strain gauges or from a high speed video carried out with a Photron camera.

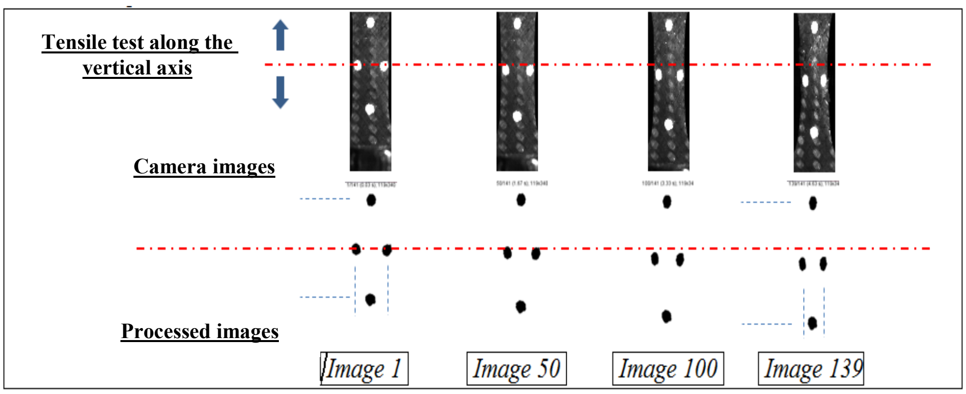

Figure 4. Acquisition and processing of digital images for the strain measurement.

The last method is based on a first marking made on the specimen central zone surface. This surface filmed using a high-speed camera shows the material deformation revealed by successive image processing [12]. The relative displacements of the geometric centers of the markings (Figure 4) are used to determine the longitudinal and transversal strains.
In order to assess the dynamic tests quality obtained through the optimization procedure described above [6], the graphs in Figure 5 show examples of measurement results of the longitudinal and transverse strains performed on optimized specimens for composite ±45° and the shear strain that results. The shear strain rate is determined directly on curves of Figure 5 and reaches values close to 800 s^{-1}.

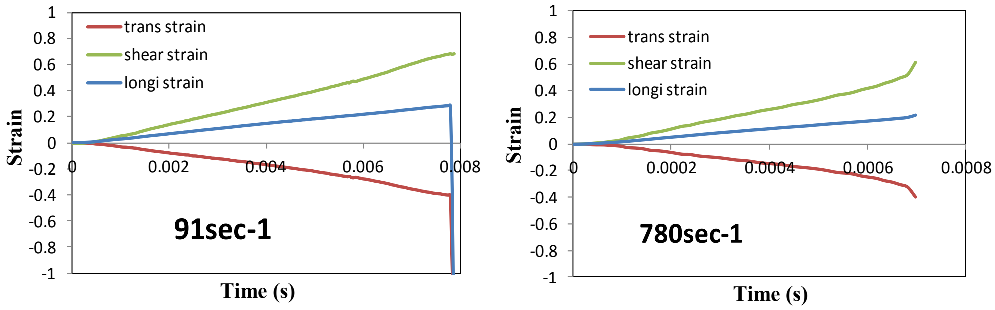

Figure 5. Strain measurement obtained by Image processing for two high-speed tests on the composite at ± 45°.

It is remarkable that all these results are direct measurements obtained without smoothing. This confirms the effectiveness of the optimization process carried out previously, on the one hand, a constant strain rate and, on the other hand, a uniform strain in the specimen central zone with very limited interference [5, 6, 7].

2.3.1 *Composite mechanical properties under quasi-static loading*

Tensile tests under quasi-static loading (2 mm/min) were performed on test specimens according to the considered directions: 0°, 90° and ±45°. As indicated in Figure 6, we did not observe any volume effect on curves obtained in quasi-static between optimized dumbbell-shaped specimen and a rectangular one (250mm*25mm) whose geometry is that recommended by the standard [ISO 14129: 1998]. This result shows that the Representative Volume Element (RVE) selected is suitable for the characterization and analysis of the carbon fabric composite mechanical behavior.

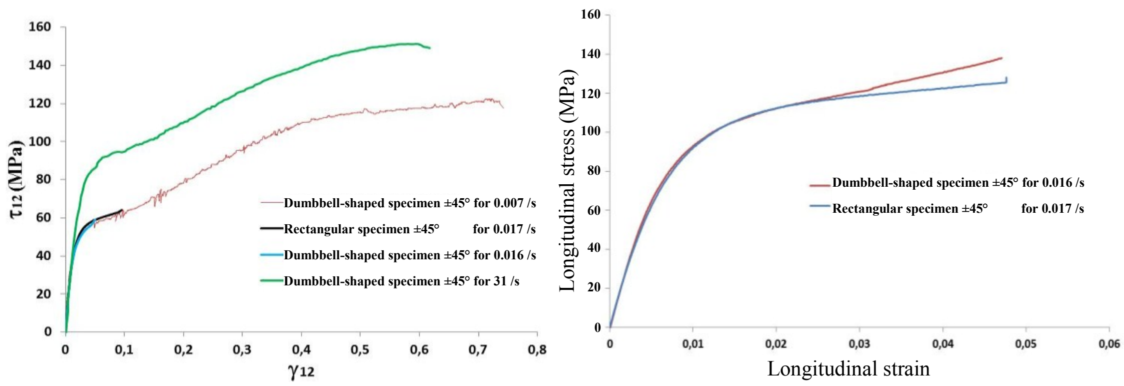

Figure 6. Inplane shear behavior of the composite oriented at ±45°.

Note that for two specimens on the figure 6 the measurement is performed on an Instron 5884 tensile test machine using strain gauges and extensometer with maximum strain capacity are limited respectively to 5% and 10%. The other two specimens at 0.0017 s^{-1} and 31s^{-1}, the strain is determined by analyzing the images recorded by the Photron high-speed camera during tensile tests on a Schenck Hydropuls VHS 50/20 machine.

Below, the results observed on tensile tests at 0°, 90° and ±45° in quasi-static loading (Table 1).

Property	E_{11} (GPa)	E_{22} (GPa)	G_{12} (GPa)	ν_{12}	σ_{11max} (MPa)	σ_{22max} (MPa)	σ_{12max} (MPa)
Value	64	64	4,1	0,06	850	900	245

Table 1. Summary of the mechanical properties for the woven fabric composite in quasi-static.

Strain, stress and shear intralaminar modulus (Equation 1) are determined from the results obtained on the composite longitudinal and transverse directions [13, 14, 15, ISO 14129:1998].

$$\boldsymbol{\tau_{12}} = \frac{\sigma_{longitudinal}}{2} \;\; ; \;\; \boldsymbol{\gamma_{12}} = 2 * \varepsilon_{12} = (\varepsilon_{longitudinal} - \varepsilon_{transversal}) \;\; ; \;\; \boldsymbol{G_{12}} = \frac{\sigma_{longitudinal}}{2*(\varepsilon_{longitudinal} - \varepsilon_{transversal})} \quad (1)$$

2.3.2 *Strain rate effect on the mechanical behavior*

The tensile test results on the composite oriented at 0°/90° indicate that increasing the strain rate has no significant effect on the elastic behavior of the composite (Figure 7). Indeed, the Young's modulus observed at 0° and 90° with value of 70 GPa remains stable. However, the overall behavior is marked by evolution of the ultimate strain and stress as shown by the curves of Figure 7. The overall trend for the ultimate properties evolves with the strain rate increase.

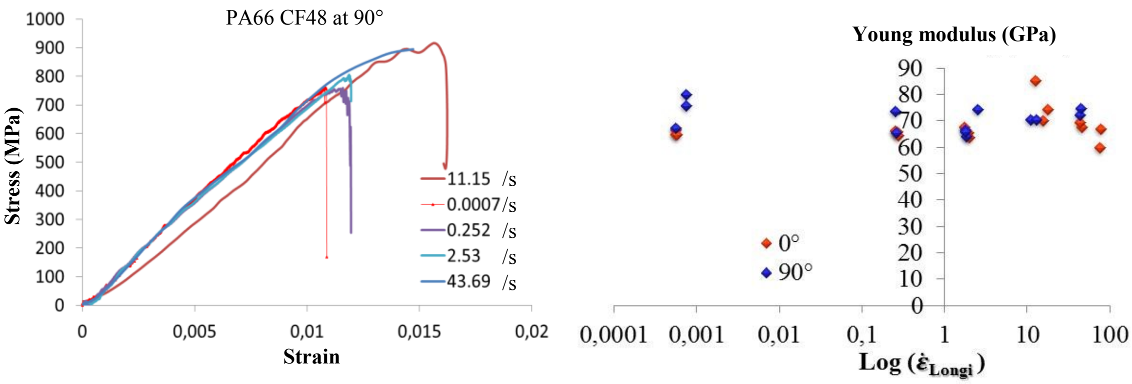

Figure 7. Evolution of the composite behavior at 0°/90° vs. Strain rate.

Moreover, the evolution observed in the behavior of the composite oriented at ±45° versus the strain rate is very significant on the threshold and ultimate stress levels and in terms of apparent longitudinal modulus in loading direction (Figure 8). The ultimate strain reaches a level of about 30% and decreases slightly with the increase of the imposed strain rate.

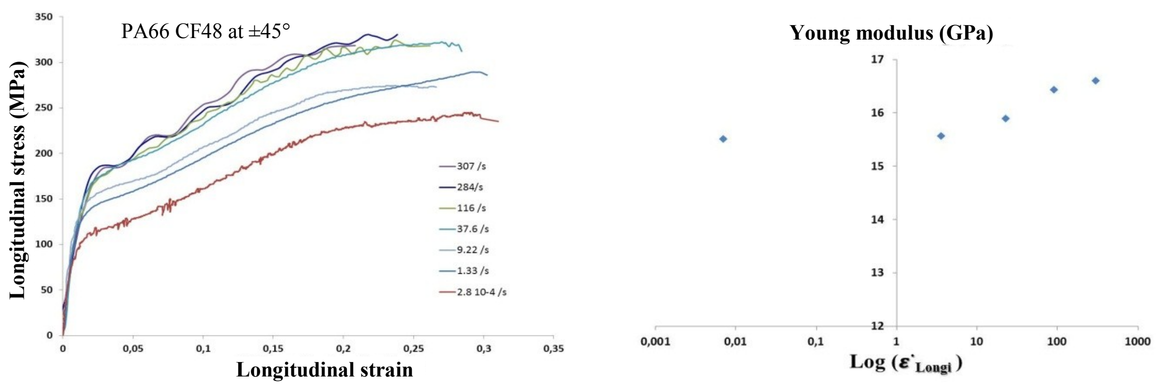

Figure 8. Evolution of the composite behavior at ±45° vs. strain rate.

In Figure 9, the modulus and the ultimate shear strain seem insensitive to strain rate as opposed to the threshold and ultimate stress which have a high dependence. Over 100 s^{-1} the behavior seems to be stable and less affected by the strain rate effect, where the asymptotic trend as overall appearance.

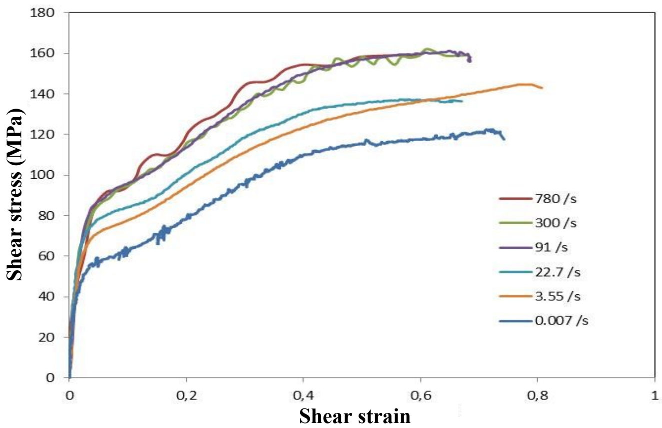

Figure 9. Inplane shear behavior evolution vs. strain rate.

The shear strain threshold growth by increasing the strain rate. This reflects the sensitivity of the matrix behavior in the end of the elastic stage to the strain rate loading: Plasticity initially thereafter damage by cracking to the final breaking. Furthermore, it was already verified that the considered RVE reflects correctly the composite material behavior. Finally, the results are reproducible and minimally disturbed by the inertial and shock effects.

3. Conclusion

After an initial step of dynamic tensile tests optimization conducted successfully, this first analysis of the mechanical behavior of thermoplastic composites reinforced with woven carbon long fibers allowed highlighting the strain rate loading effect through the following results:
Firstly, a small effect across the main orientations, 0° and 90° still marked by a slight evolution of the ultimate strain and stress. The Young's modulus seems insensitive to strain rate.
Secondly, a very marked effect on the longitudinal shear behavior observed through the test results performed on the ±45° orientation and characterized by a strong increase in threshold and ultimate stress levels. However, the Young's modulus is not affected significantly by the strain rate effect.
These results allow us to conclude that the viscous effects related to the matrix behavior and damage remains relatively limited when the tests are carried out in the fibers direction. As against, in the case of a longitudinal shear in plane the strain rate affects, on the one hand the plasticity threshold regarding the matrix behavior and other parts, on the thresholds and the kinetics of damage which appears as the dominant phenomenon (visco-damage already observed in other materials [16]). The material final rupture came after a strain of the order of 30% in longitudinal (70% shear) orientations at ±45° against 1.8% following those at 0° and 90°. To better understand the origin of the strain rate effect, it would be necessary to develop the method of interrupted tensile tests coupled with SEM observations. The goal would be to propose an experimental multi-scale analysis to choose the best way to modeling the mechanical behavior of materials and structures in carbon - thermoplastic composites. Finally, different sources may be at the origin of the observed high speed effects. They generally result in the following physical mechanisms: (a) visco-damaged viscoplastic behavior of the thermoplastic matrix, (b) Visco-damage of the fiber-matrix interface and (c) Development of

micro-ductile zones at closeness of fiber-matrix interfaces more or less developed depending on the strain rate.
Hence the need of experimental data produced by qualitative and quantitative analysis describing the damage mechanisms evolution under high-speed loading. This study will extended to both macroscopic and microscopic scales during loading [5]. The approach applied to different strain rates, will identify the mechanical behavior and subsequently propose a predictive law of the composite damaged dynamic behavior.

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