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INFLUENCE OF STRAIN RATE ON THE BEHAVIOR OF NATURAL FIBER REINFORCED THERMOPLASTIC COMPOSITES, EXPERIMENTAL AND NUMERICAL APPROACHES

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Abstract

These studies aim to explore the behavior of natural fiber-reinforced thermoplastic matrix composites by examining their response to strain rate during traction, focusing particularly on the longitudinal elastic modulus variation in 0° composites and in plane shear elastic modulus for the ±45° laminates. Utilizing bamboo, flax, and basalt fibers as unidirectional reinforcements and Arkema's semi-crystalline polyamide-11 and ELIUM amorphous resin as matrices, experiments are conducted to characterize the materials. Static and dynamic tensile tests are performed using advanced equipment. Numerous explicit numerical simulations are iterated to match experimental data. Results reveal that composites with 0° plies show limited sensitivity to strain rates below 100 s⁻¹, with bamboo and flax composites exhibiting little change in Young's modulus, while basalt-reinforced composites exhibit a slight increase. However, composites with ±45° stacking display heightened sensitivity, primarily influenced by the resin. This comprehensive investigation provides insights into the complex behavior of these composites under different loading conditions, guiding their optimization and application.

1. Introduction

The Reducing weight in the field of aeronautical transportation is a major concern for modern industry, a decrease in mass immediately translates into reduced fuel consumption and emissions of polluting gases. Composite materials are strong enablers in achieving this goal by replacing some common metal alloys. However, the vast majority of materials used in aerospace composite production stem from the petrochemical industry, whether for reinforcements or matrices. The desire to no longer depend on rapidly depleting resources has become a significant motivator for the development and utilization of bio-sourced materials. Plant fibers are, therefore, promising substitutes for fiberglass or carbon fibers, not only due to their lower production costs but also because of their lower densities and good mechanical performance. For composites reinforced with long fibers, the use of high-performance, bio-sourced thermoplastic matrices allows for end-of-life recycling, presenting an environmentally advantageous aspect. Initially intended for non-structural applications, the use of these materials for semi-structural or even structural purposes can only be considered if their ability to withstand various stresses such as shocks or impacts is confirmed.

2. Materials and methods

2.1. Selected fibers and polymers

Composite materials with bamboo were manufactured using bamboo strips supplied by COBRATEX, a French company based near Toulouse, in the form of unidirectional layers with a grammage of 150 g/m² per ply. The theoretical width of the strips, as well as their thickness, are respectively 5 mm and 0.3 mm. The Flax reinforcements were sourced from Terre de Lin, located in Normandy. The Flax fibers, marketed as UD210, are presented as unidirectional with a grammage of 210 g/m² and 6 yarns/cm. FILAVA™, our source of basalt, comes in the form of a unidirectional fabric weighing 360 g/m². Enriched with various mineral additives, the basalt fibers are carefully processed to enhance and ensure their original mechanical, thermal, and chemical properties. These basalt fibers are supplied by the Belgian company ISOMATEX, headquartered in Gembloux. The two thermoplastic polymers are sourced from ARKEMA. The first, ELIUM 188 XO, is an amorphous acrylic thermoplastic, comparable to PMMA, implemented using a room temperature infusion process for composite plate fabrication. The second polymer is a semi-crystalline thermoplastic, Polyamide 11 (PA11), provided in the form of films with thicknesses ranging from 40 to 100 microns in different deliveries. This polymer will be utilized in the thermocompression process and is referenced as RILSAN FMNO. Special attention will be given during the fabrication of the flax and bamboo-based composites using this thermocompression method, with meticulous control over temperature and pressure parameters to prevent degradation of the mechanical properties of these plant fibers due to their sensitivity to high temperatures. Our aim for the composite plates is to achieve a fiber volume fraction of approximately 50%.

2.2. Experimental Setup

Initially, composite laminates at 0° or ±45° angles were subjected to testing at low velocities using static and quasi-static procedures at ambient temperature. Conducted at speeds of 2 mm/min for static assessments and around 300 mm/min for quasi-static evaluations, these tests provided a robust basis for our composite evaluation. The strain rates achieved ranged from 2 10⁻⁴ s⁻¹ for static tests to 2 10⁻² s⁻¹ for quasi-static loadings. This baseline became crucial for quantifying, in following dynamic tests, the impact of strain rate on the composites. These tests were conducted on an electromechanical testing machine, with a maximum load capacity of 100 kN. Strain measurements on the specimens were performed using a virtual extensometer approach, with each specimen marked with specific landmarks for tracking using a camera. The distance between the landmarks, set at 50 mm, corresponded to the L0 of the extensometer. The procedures used to characterize the 0° and 45° ply composites were aligned with established standards, namely EN2561 and AITM 1-0002, respectively.

Two dynamic testing machines, located at the Clement Ader Institute (ICA) laboratory in Toulouse, were utilized for the dynamic characterization of all our composites. These two dynamic characterization devices belong to the drop tower family. The first one, the "New Dynamic Tensile Test Device", now designated by its abbreviation NDTTD, represents an ongoing innovation being developed at the ICA laboratory. Designed as part of our doctoral research, it also benefits from collaboration with Rallo et al. [1], who also use this device for dynamic characterization of composite and metallic materials. The structure, depicted in figure 1, comprises the following elements:

- {1} Structure
- {2} Ball joint
- {3} Kistler 120 kN cell force
- {4} Multi part upper jaws
- {5} Characterization specimen
- {6} Multi part lower jaws
- {7} Pin
- {8} Impactor (200 Kg)
- {9} Bar
- {10} Bar stopper (impact area)

An impactor {8}, weighing 200 kg, is released from a height of 0.8 m to generate theoretical strain rates of approximately 80 s^{-1} . The impactor slides along the bar {9} until it strikes the stopper {10}, thereby creating a tensile wave that travels back up the bar {9}. The upper part of the bar is secured using a pin {7} to a self-clamping jaw system composed of multiple parts {6}, in which the specimen to be characterized {5} is installed. The tensile wave is transmitted to the specimen, then to a self-clamping jaw system {4}, identical to the one fixed on the top of the bar. This upper jaw is connected to a 120 kN Kistler force sensor {3}. The sensor is linked to the frame {1} via a ball joint {2}, thus avoiding the introduction of non-axial components to the sensor, which could damage it. Strains are obtained through optical tracking by a high-speed camera, analyzed by the DICe software (Digital Image Correlation Engine). The camera typically operates at a calibrated acquisition frequency of 50,000 images per second, as does the force acquisition frequency, for easier processing of experimental signals, at 50 kHz.

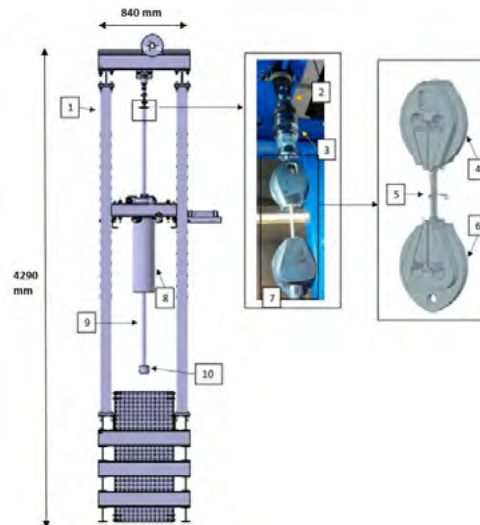


Figure 1. Representation of the 'New Dynamic Tensile Test Device'.

This setup has been utilized to characterize our composites with the highest stiffness and ultimate strengths, leveraging the capabilities of the 120 kN sensor within its preferred measurement range, specifically, composites fabricated with 8 plies oriented at 0° . As there is no standard for dynamic characterization tests on such devices, the shapes and dimensions of the specimens have been specifically developed for this setup and our various experimental campaigns. Details on the specimen dimensions are represented in figure 2. Specimens with a width of 8 mm and 10 mm in the central region were used to characterize our flax and basalt fiber-based composites, while specimens with a wider width of 12 mm were employed for characterizing bamboo strip-based composites. Due to the 5 mm width of the bamboo strips, a wider width was chosen to ensure consistency and reproducibility of measurements. The specimens adopt a specific shape to induce failures in the central region.

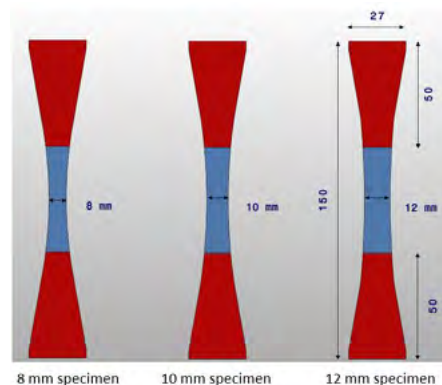


Figure 2. Dimensions of the dynamic characterization specimens for 0° composites on the NDTTD.

A second dynamic characterization setup, developed during the work of Aubry et al [2], was also used for the dynamic characterization of composites. The dual-frame dynamic setup was dedicated to rapid dynamic tests involving specimens with rupture forces much lower than those characterized on the NDTD device. Additionally, this setup allows the use of specimens with much wider widths, which is crucial for characterizing specimens of composites consisting of $\pm 45^\circ$ drapes. Illustrated in figure 3, this system was designed using a dual-frame mechanism placed under a falling weight and consists of the following elements:

- {1} Falling mass guide rail
- {2} Falling weight
- {3} Mobile frame
- {4} Fixed frame
- {5} Lower jaw
- {6} Specimen to be characterized
- {7} Upper jaw
- {8} Force sensor
- {9} High-speed camera

The top of the test specimen {6} is linked to a fixed frame {4} through the upper jaw {7}. In contrast, the base of the specimen is connected to a mobile frame {3} with a lower jaw {5}, which can slide relative to the fixed frame. A falling weight {2} is released from an adjustable height to control the impact velocity. Guided along a rail {1}, the weight precisely impacts the top of the mobile frame, thus inducing a tensile force on the specimen. The mobile frame, made from pultruded unidirectional carbon and aluminum, aims to minimize preloading of the specimen before the test. A force sensor {8} is positioned between the fixed frame and the specimen to measure the force during the test, closest to the specimen. The machine offers the option to use three different capacity sensors, 5, 10, and 50 kN, allowing for testing of specimens with rupture forces ranging from less than 1 kN to over 10 kN. The displacements of the specimen and the mobile frame are tracked by image correlation using a high-speed camera {9}. The dimensions and masses associated with this setup are significantly smaller compared to the NDTD device, and the masses of the free-falling objects are also lower, allowing for a choice between masses of 2, 4, or 8 kg to generate impacts of varying energies. The composite characterization specimens employed here are identical to the AITM 1-0002 samples used for static and quasi-static tests. However, they are cut to half the length, measuring 115 mm, with a width of 25 mm, and equipped with 40 mm long glass fiber tabs.

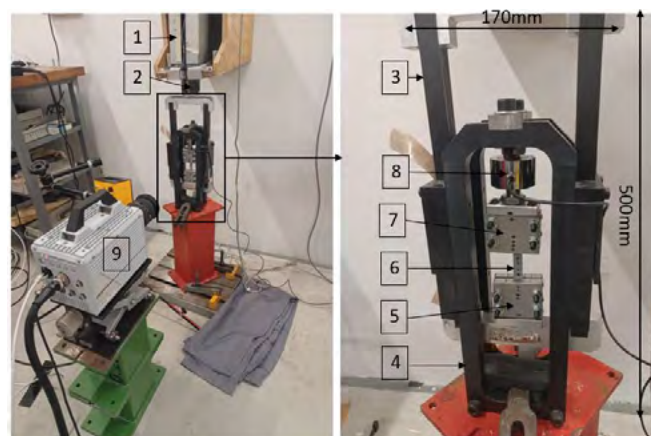


Figure 3. Presentation of the Dual-Frame Dynamic Setup.

2.3. Numerical simulations

Our work presented here significantly relies on numerical methods, particularly the use of finite element method with explicit integration scheme, aiming to develop a material law describing the behavior of

composite materials combining natural fibers and thermoplastic resins under rapid dynamic loading, as well as to enhance the understanding and interpretation of dynamic tests. Indeed, dynamic tests on drop towers often make it challenging to extract the behavior laws of the tested materials [3]. To overcome this difficulty, the use of explicit numerical simulations with inverse identification method is necessary [4, 5, 6, 7, 8]. This method involves numerically reproducing the test means to virtually recreate the phenomena observed during the experiments. We are referring to the creation of digital twins, a numerical representation faithful to real physical phenomena. However, it is essential to calibrate and validate this numerical approach using known materials, both in terms of behavior laws types and associated characteristic values.

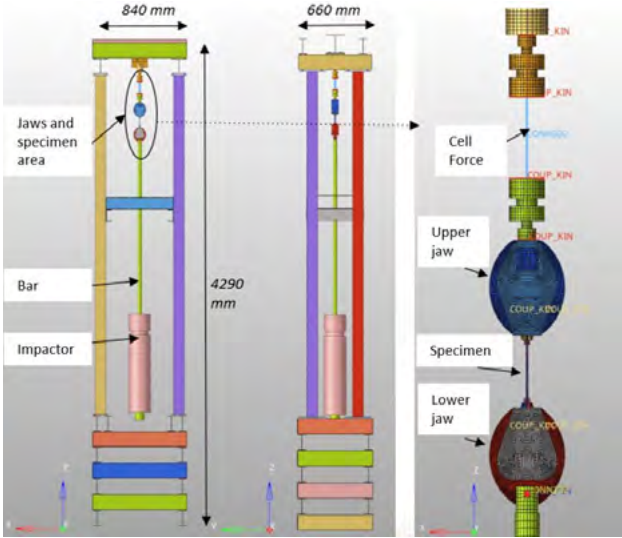


Figure 4. NDTTD Abaqus Explicit model.

Therefore, an experimental validation campaign was conducted on specimens with a width of 10mm and a thickness of 3mm taken from a 2024T4 aluminum plate, material already characterized in static. The Abaqus explicit model of the NDTTD, depicted in Figure 4, produced satisfactory correlations, as demonstrated by Figures 5a and 5b, both in terms of the temporal curves of the force sensor and the strain gauge curve from a test on an aluminum AL2024T4 specimen with a measured strain rate of 122 s^{-1} . The same experimental and numerical approach also validated the modeling of the double-frame setup using identical material law for the aluminium.

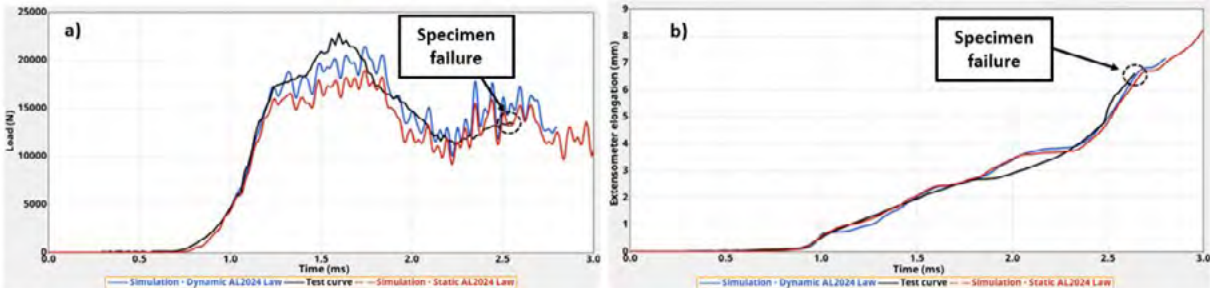


Figure 5. Numerical simulation and dynamic tests temporal curves comparison for AL2024T4, (a) Force sensor, (b) Virtual extensometer ($L_0=20\text{mm}$).

Finally, as the Abaqus Explicit solver lacks a built-in law to account for intralaminar shear pseudo-plasticity or strain rate dependency, we developed a custom VUMAT law in FORTRAN, implemented via a subroutine, to closely match experimental observations. This VUMAT is an orthotropic viscoelastic-damage model in the longitudinal and transverse directions, while it's an elastoviscoplastic-damage model with nonlinear isotropic hardening for in-plane shear, formulated within the framework of irreversible thermodynamics.

3. Results

3.1. Composites with 0° plies

Two series of iterations were conducted on the 0° composites tested on the NDTTD. The first series of reference simulations involved the use of a material card defined as linear elastic orthotropic, along with a HASHIN failure criterion based on maximum stress, aimed at providing simple estimates of Young's modulus and rupture stress. The second series of iterations utilized the VUMAT with strain rate sensitivity parameters and a rupture criterion based on energy restitution levels. An example of results regarding iterations on the modulus of elasticity in the fiber direction of the composite flax/ELIUM, which led to the identification of a value of 12 000 MPa, is presented in Figure 6, enabling a convincing reproduction of the experimental curves. The same methodology was employed to identify the evolution of mechanical parameters of the composites with 0° plies, and results are summarized in Table 1.

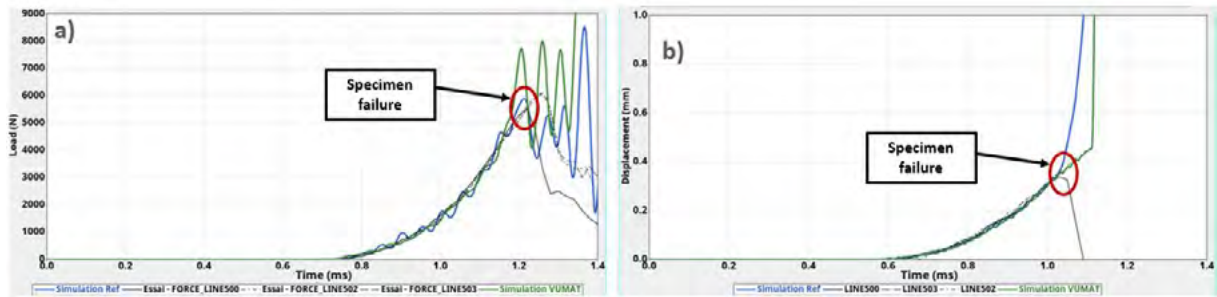


Figure 6. Numerical simulation and dynamic tests temporal curves comparison for a flax/ELIUM composite [0°]₈, (a) Force sensor, (b) Virtual extensometer ($L_0=20\text{mm}$).

Tests characterizing mechanical properties have shown a plateau or even a slight decrease in longitudinal elasticity modulus for plant fiber-reinforced composites with the PA11 matrix, and a minor increase for those with the ELIUM resin. Notably, there's a slight increase in modulus between static and quasi-static solicitations before observing a drop in properties during solicitations exceeding 10^{-4} s^{-1} , indicating a distinct mechanical behavior of these composites under faster solicitations. However, it's worth noting that the significant variability in the properties of natural fibers used in our study should prompt some caution regarding this observation. Nonetheless, it appears evident that the plant fiber composites studied here seem to be minimally or not sensitive to strain rate. Basalt fiber-reinforced composites have exhibited a more pronounced sensitivity to strain rate, with respective increases of 14% and 24% with ELIUM and PA11 resins.

Table 1. Longitudinal elastic modulus E_1 (Mpa) of composites (0°) from static to dynamic conditions.

Composites	Static	Quasi Static	Dynamic	Factor Static to Dynamic
Bamboo/ELIUM	9680	10941	10000	1.03
Bamboo/PA11	12467	No data	12000	0.96
Flax/ELIUM	10798	12703	12000	1.11
Flax/PA11	16507	17663	16000	0.97
Basalt/ELIUM	32996	34782	37500	1.14
Basalt/PA11	28124	32601	35000	1.24

3.2. Composites with ±45° plies

The sensitivity study of composites consisting of ±45° plies has revealed significant modifications in the mechanical properties of these composites, including an increase in the elasticity module G_{12} , the yield strength, and plastic flow stresses. The characteristic values regarding the evolution of the G_{12} module and the yield strength σ_{y12} are compiled in Table 2. Overall, there is a slightly more pronounced sensitivity to the increase in elastic properties of composites with the ELIUM resin. In our work with

this resin, we observed a greater variation in the elastic module during dynamic loading, whereas the PA11 polymer showed less variation in the elastic part but exhibited a more pronounced increase in the plastic part of its behavior curve, as reflected in the slightly more pronounced sensitivity to the increase in the yield strength for composites with PA11 polymer. These observations are evident in our $\pm 45^\circ$ composites, except for the flax/ELIUM composite, where its G_{12} module remains stable, contrary to its yield strength, which is significantly increased. Additionally, we observe the limited evolution of flax-based composites in terms of the elasticity module evolution, a trend previously noted with the same composite but with 0° plies.

Table 2. In plane shear mechanical properties of composites ($\pm 45^\circ$) from static to dynamic conditions.

Composites	G_{12} (Mpa)				σ_{12}^y (Mpa)			
	Static	Quasi Static	Dyn.	Factor Static to Dyn.	Static	Quasi Static	Dyn.	Factor Static to Dyn.
Bamboo/ELIUM	1989	2441	4400	2.21	5.9	6.9	8.8	1.49
Bamboo/PA11	1396	1703	2500	1.79	10.8	15.7	17.0	1.57
Flax/ELIUM	2075	2075	2100	1.01	9.2	13.0	30.6	3.32
Flax/PA11	1915	1915	1850	0.97	12.8	15.7	25.4	1.98
Basalt/ELIUM	3659	4670	4500	1.23	11.7	13.6	17.5	1.49
Basalt/PA11	2191	2579	2490	1.14	7.0	10.5	17.3	2.47

3. Conclusions

The exploration of strain rate effects on natural fiber-reinforced thermoplastic composites has produced valuable observations into their mechanical behavior under varying loading conditions, from static to dynamic solicitations. Through a combination of experimental tests and explicit numerical simulations, this study explores the response of these composites to dynamic loading, focusing on longitudinal and shear modulus variations in 0° and $\pm 45^\circ$ laminates, respectively.

The findings underscore the limited sensitivity of composites with 0° plies to strain rates below 100 s^{-1} , with bamboo and flax exhibiting minimal changes in Young's modulus, while basalt-reinforced composites show a slight increase. In contrast, composites with $\pm 45^\circ$ stacking demonstrate heightened sensitivity, primarily influenced by the resin type.

The comprehensive investigation provides essential understanding crucial into the complex behavior of these composites, offering guidance for their optimization and application, particularly in industries like aeronautical transportation, where weight reduction and sustainable materials are crucial for reducing fuel consumption and emissions. By comprehensively understanding how these materials respond to different loading conditions, including variations in strain rate, designers and engineers can better benefit from their properties to develop innovative and environmentally friendly solutions. This detailed insight into the behavior of natural fiber-reinforced thermoplastic composites exposed to various strain rates provides a foundation for optimizing their performance and expanding their application potential in various industries, thus contributing to both economic and ecological sustainability.

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