EVALUATION OF THE STRAIN RATE DEPENDENT BEHAVIOR OF A CFRP USING TWO DIFFERENT HOPKINSON BARS

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Abstract

In many studies the strain rate sensitivity of a CFRP material is investigated thoroughly in only one layup and loading direction, which brings about challenges in the comparison of the results due to the large layup- and loading mode-dependence of the material behavior. To address this challenge, in this study we characterize one CFRP material comprehensively in different rate dependent configurations. We demonstrate the feasibility of the Hopkinson Bar technique in the high strain rate testing of CFRP materials. We also highlight the importance of carefully designing and analyzing the experiments for each layup separately. That is, we show how notably different material behavior and therefore notably different test requirements are obtained for the nominally same composite material by simply changing the layup. Two different Hopkinson Bar Set-ups were used; a Direct Impact Hopkinson Pressure Bar (DIHPB) for the characterization of the compressive response of the UD material perpendicular to the fiber direction and a Split Hopkinson Tension Bar (SHTB) for the characterization of the tensile response of three different layups: UD material perpendicular to the fiber direction, a ±45-laminate, and a quasi-isotropic layup. For each studied layup, the specimen geometry, mounting concept and testing approach were individually adapted. As a result, it was possible to comprehensively evaluate the high rate response of the CFRP composite at a strain rate of 200 s^{-1} with a high quality of results.

1. Introduction

The drive to lighter structures has highlighted the promise of fiber reinforced composites. At the same time, an increasing number of engineering applications must rely upon material characterization at high strain rates in order to consider impact and crash in design. It is established that the mechanical behavior of fiber reinforced composites is dependent on the strain rate during loading. The deformation regimes at high strain rates such as those observable in automobile crash and aircraft bird strike are well suited to experimental characterization using the Hopkinson Bar technique [1]. In this class of methods both the mechanical boundary conditions as well as load measurement data are obtained from elastic stress wave propagation in long slender bars placed in contact with the specimen. Compared to high speed servo-hydraulic or electric testing machines, the overall test setup geometry in the Hopkinson Bar method is simple and straightforward to describe analytically. Furthermore, the use of long slender bars as load cells allows for high-precision measurements of transient loads without the challenges often encountered with traditional load cells, such as distortion of the signal due to the vibration of the structure or the load cell itself.

Typically in the published literature the strain rate sensitivity of a CFRP material is investigated thoroughly in only one layup and loading direction. However, it is well known from quasi-static tests that the mechanical response of the composite is strongly dependent on the layup and loading mode due to the various micro-mechanisms of deformation and damage, which can be activated during the loading. It is also know that the strain rate dependence of these materials depends on the layup and loading mode. This fact should be taken into account in the analysis of the material behavior. In this report we present the results of a comprehensive experimental study on the strain rate sensitivity of several different layups and loading directions of a single CFRP composite. Our purpose in this contribution is not only to report the test results for different layups, but also to demonstrate with practical examples the importance of carefully designing and analyzing the experiments to account for the unique features of each layup.

2. Experimental Set-Up

In the experimental campaign the target testing strain rate was 200 s^{-1}. Two different Hopkinson Bar Set-ups were used: a Split Hopkinson Tension Bar (SHTB) and a Direct Impact Hopkinson Pressure Bar (DIHPB). The DIHPB was used to characterize the strain rate dependence of the UD material perpendicular to the fiber direction in compressive loading. In the SHTB three different tests were performed: a tension test of the UD material perpendicular to the fiber direction, a tension test of a ±45-laminate to characterize the strain rate dependent shear behavior, and a tension test of the quasi-isotropic layup.

The high strain rate characterization with the Hopkinson Bar Technique followed the general methods established in the field (see for example [2]). Figure 1 illustrates schematically the Hopkinson bar configurations used in this project. The compression tests were carried out in the direct impact configuration, that is, the striker impacted directly the specimen, whereas the tensile tests were done in the split-configuration, that is, the specimen was attached between the input and the output bars. In this case the loading pulse was generated by the impact of the striker on the flange at the free end of the input bar. The force acting on the specimen was determined in both configurations based on the high speed oscilloscope recording of the elastic stress wave imparted on the output bar (measured with strain gauges attached on the bar).

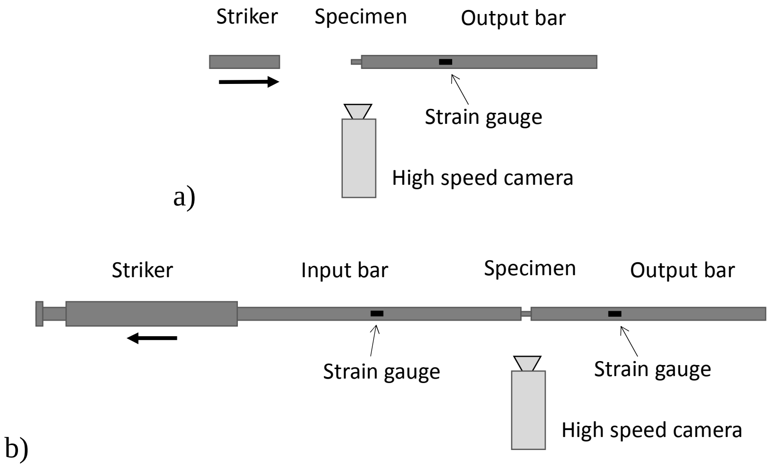


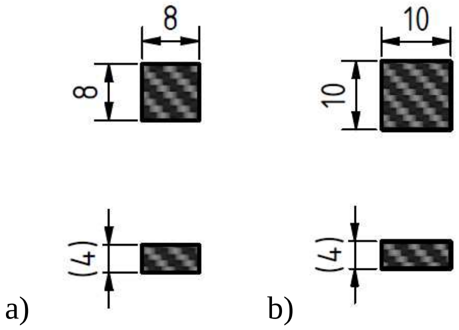
Figure 1. Schematic illustration of the Hopkinson Bar configurations used in this research: a) direct impact configuration for compression and b) split configuration for tension.

The specimens for the high strain rate testing were prepared from CFRP plates by means of CNC-machining. The specimen geometries used in the measurements are presented by Figures 2 to 4. As shown by Figure 2, in the compression tests end-loaded specimens were used similarly to Koerber and Camanho [3] with the exception that no extra support fixtures were used to stabilize the specimen. This was made possible in the current study by the relatively large laminate thickness (4 mm) and the loading direction (perpendicular to the fibers), which both reduced the risk of buckling during the loading. For the tensile tests rectangular specimens shown in Figure 3 were used. The rectangular specimens were chosen, as this is the standard for quasi-static testing for fiber reinforced composites.

This specimen type has also been shown suitable for different CFRPs and layups in previous studies [4,5].

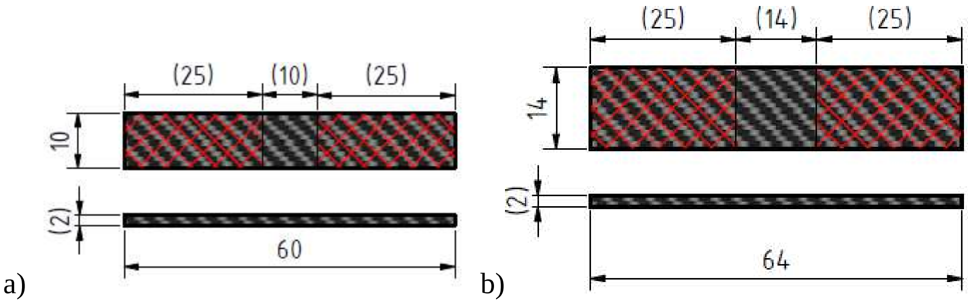
For the quasi-isotropic laminate initial quasi-static and high strain rate tests were carried out with the constant width specimen geometries shown by Figure 3, which has previously been successfully used for other quasi-isotropic CFRP materials [5]. In the current study it was, however, noticed that due to the high strength of the quasi-isotropic laminate, the constant width specimen geometry depicted by Figure 3 was not usable due to the insufficient shear strength of the adhesive joint between the specimen and the mounting. Therefore, for the testing of this laminate the dog-bone geometries depicted by Figure 4 were implemented. For CFRP materials the dog-bone specimen is not ideal, since fibers are cut and failure will be most likely initiated in the shoulder between the gauge and grip sections. Despite this drawback, dog-bone specimens are often used in the testing of CFRP with the SHTB method [6-9].

After machining, each specimen was visually inspected for acceptable surface quality and the dimensions of the gauge area were measured with a digital micrometer. After that, the mounting areas of the tensile specimens (indicated by red lines in Figures 3 and 4) were lightly ground with sandpaper and subsequently washed with isopropanol. The specimens used in the high strain rate tests were additionally cleaned with a SmartPlasma 30 (plasma technology GmbH, Germany) plasma system (5 minute treatment with O2-plasma).



a) b)

Figure 2. The specimen geometries used in the high strain rate compression testing of the UD 90° material: a) 8 mm x 8 mm and b) 10 mm x 10 mm.



a) b)

Figure 3. The specimen geometries used in the tensile testing of the UD 90° and +/- 45° materials as well as in the preliminary tests of the quasi-isotropic laminate: a) 10 mm x 10 mm and b) 14 mm x 14 mm. The red lines indicate the areas of the specimen used for the mounting. It should be noted that specimens with longer mounting sections (50 mm instead of 25 mm) were used in the preliminary quasi-static tests.

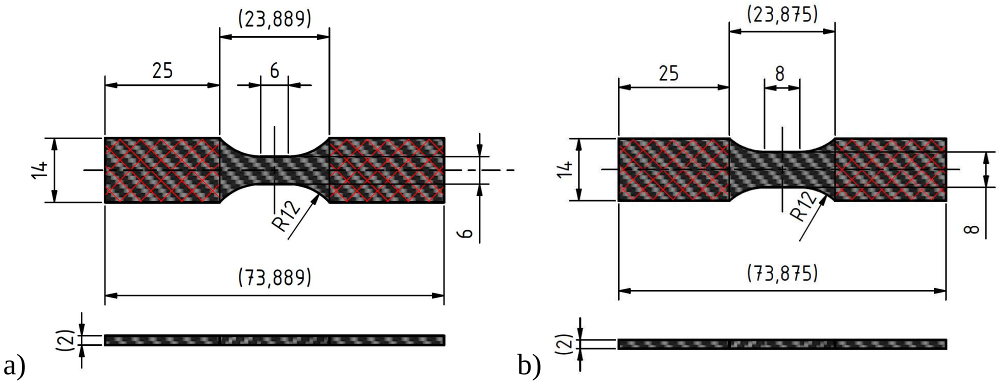


Figure 4. The dog-bone specimen geometries used for the tensile testing of the quasi-isotropic laminate: a) DB 6 mm x 6 mm (R12) and b) DB 8 mm x 8 mm (R12).

For comparison, quasi-static experiments were carried out with an Instron 8801 servo-hydraulic materials testing machine using the same specimen dimensions as for the high-rate tests. The specimen was mounted into the machine by hydraulic grips, as illustrated in Figure 5c. The force acting on the specimen was measured through a 50 kN load cell (class 0.5) and, as explained below, the specimen deformation was measured with the Digital Image Correlation (DIC) technique. The force and the deformation signals were numerically synchronized so that the force values were interpolated to match the deformation measurement time steps. During the tests a constant displacement rate on the actuator was maintained. The displacement rates were selected so that comparable strain rates were obtained with different specimen geometries.

In both quasi-static and high strain rate testing specimen deformation was measured with 2-dimensional Digital Image Correlation (DIC) method. The speckle patterns for the measurements were obtained by applying thin layers of black and white water soluble spray paint. Figure 5d shows an example of the speckle pattern laid on a high strain rate tensile specimen. The cameras were set so that the whole specimen gauge section could be monitored during the experiment. The strain values and stress-strain curves presented in the following are, when not otherwise stated, obtained by averaging the measured deformation over the specimen gauge area.

For the specimens used in quasi-static testing 1 mm thick glass-fiber end-tabs were bonded to the mounting surfaces with UHU Endfest two-component epoxy. The specimens used in the high strain rate tensile testing were bonded into steel mountings by using a Scotch Weld DP490 two-component high strength epoxy, as illustrated by Figure 5a. In this case, a two hour curing treatment at +65 °C was applied to the specimens after the gluing. As will be discussed later, for selected specimens of the +/- 45° laminate additional high strain rate tests were carried out with the mechanical clamps shown by Figure 5b. In general, when not otherwise stated, the high strain rate tensile test results shown in this paper are from tests carried out with adhesively bonded specimens.

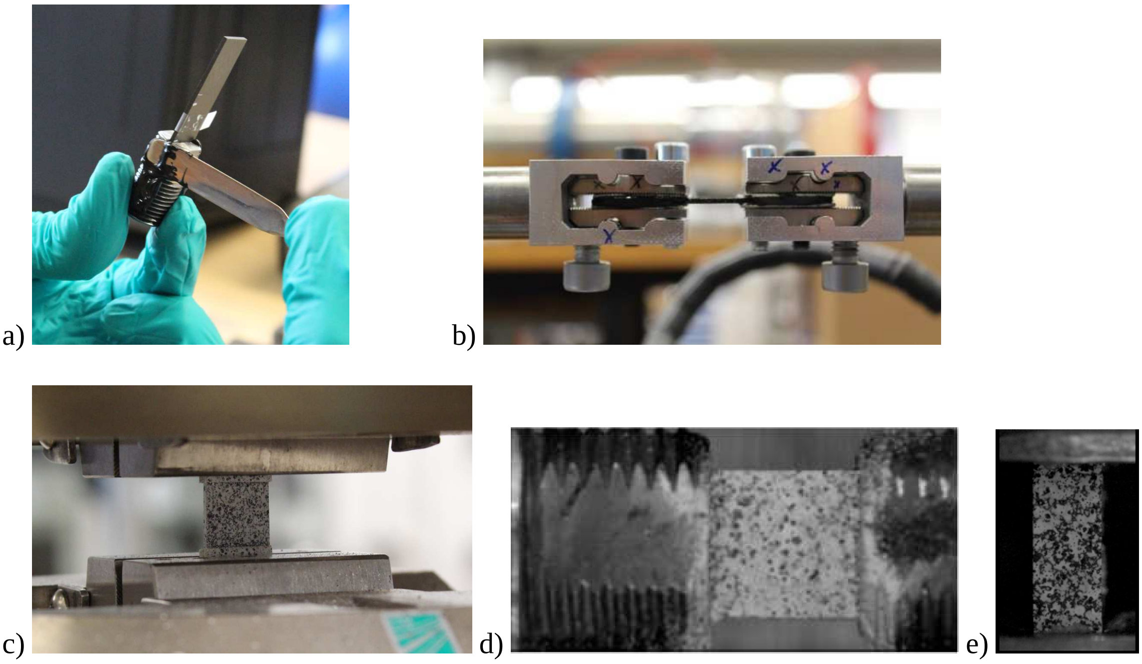


Figure 5. Illustration of the attachment of the high strain rate tensile specimen into the steel mounting with a two-component high-strength epoxy, b) mechanical specimen mountings used in selected high strain rate tests of the +/- 45° laminate, c) quasi-static specimen attached in between the hydraulic grips of the universal materials testing machine, as well as d) and e) high strain rate tensile and compression specimens as seen by the high speed camera, respectively.

3. Results

Figure 6 (left) presents the measured compressive stress-strain curves for the UD 90° configuration for both quasi-static and high strain rate tests. The respective strain rate histories are shown by Figure 6 (right). The measured material response was very similar between the two geometries. However, the larger (10 mm x 10 mm) geometry was found better in terms of the measurement accuracy of the DIC method and therefore the final tests were carried out with this geometry.

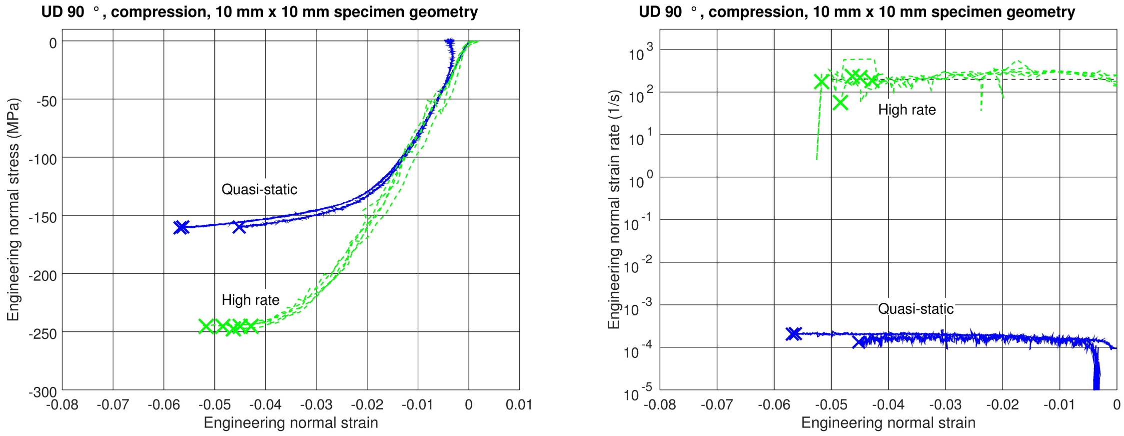


Figure 6. Measured engineering normal stress-strain curves (left) and measured strain rate histories (right) in compression for the UD 90° material configuration.

Figure 7 present the tensile tests results for the UD 90° material configuration. Quasi-static tests and preliminary high strain rate tests were carried out on both tensile geometries (10 mm x 10 mm and 14 mm x 14 mm). Based on the quasi-static tests, the larger geometry (14 mm x 14 mm) shows better reproducibility of the failure strength and therefore this geometry was selected for the high strain rate test series. However, as expected [10], even with this geometry considerably large scatter in the test results was observed, when compared with the other tested material configurations. The origin of this scatter could not be related to any macroscopic material defect or any other factor in the test procedure.

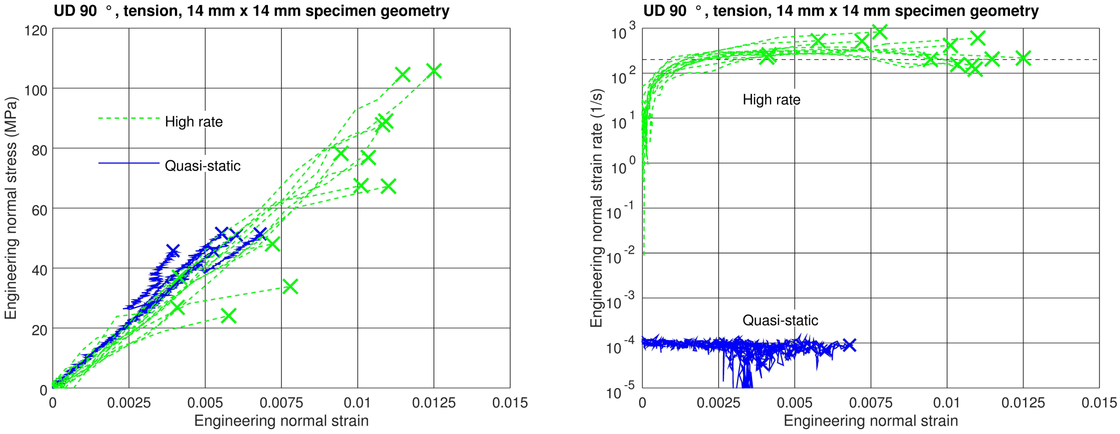


Figure 7. Measured stress-strain curves (left) and measured strain rate histories (right) in tension for the UD 90° material configuration.

For the +/- 45° laminate, quasi-static tests were carried out for both high strain rate geometries (10 mm x 10 mm and 14 mm x 14 mm presented in Figure 3) as well for a geometry recommended by the ASTM D3039 [11] standard. The standard-geometry has dimensions of 25 mm x 150 mm (total length 250 mm). For the standard geometry, deformation analysis with the DIC method was carried out on an area of 25 mm by 25 mm at the center of the specimen. Based on the quasi-static experiments, the material response measured with the 14 mm x 14 mm geometry agrees well with the results obtained with the standard geometry (25 mm x 150 mm). Furthermore, similar strain rate effect was observed in the initial high rate tests carried out with the two high strain rate geometries. Therefore, further high-rate testing was carried out with the 14 mm x 14 mm geometry.

The ASTM D3518 [12] standard recommends that the tensile test of a +/- 45° laminate is terminated or the data is truncated when the shear strain reaches 5 % (= normal strain 2.5%) due to the large amount of fiber rotation taking place at higher strains. However, in the context of this research it was considered justified to measure the material response until failure even when the above mentioned strain limit is exceeded. In the initial high rate tests it was observed that the adhesive joint between the specimen and the mounting fails after approximately 7.5 % normal strain probably due to the excessive lateral deformation of the specimen. As a solution to this challenge mechanical specimen mounting fixtures depicted by Figure 5b were implemented for the high strain rate tests of this laminate. This method allows for the high-rate testing of the laminate until failure, but at the same time introduces additional mass and interfaces to the stress wave path thus decreasing the quality of the measured load signal [4]. This is evidenced by the oscillations seen at the beginning of the measured stress strain curves (see Figure 8).

For the above mentioned reasons two approaches were adopted for this material; one series of tests carried out with the adhesively mounted specimens for accurate characterization of the low strain response and a second series with the mechanical mounting to obtain the material response until failure. It is recommended that the mechanical response of the mechanically mounted specimens below 5% normal strain (with reference to Figure 8) is excluded from the analysis.

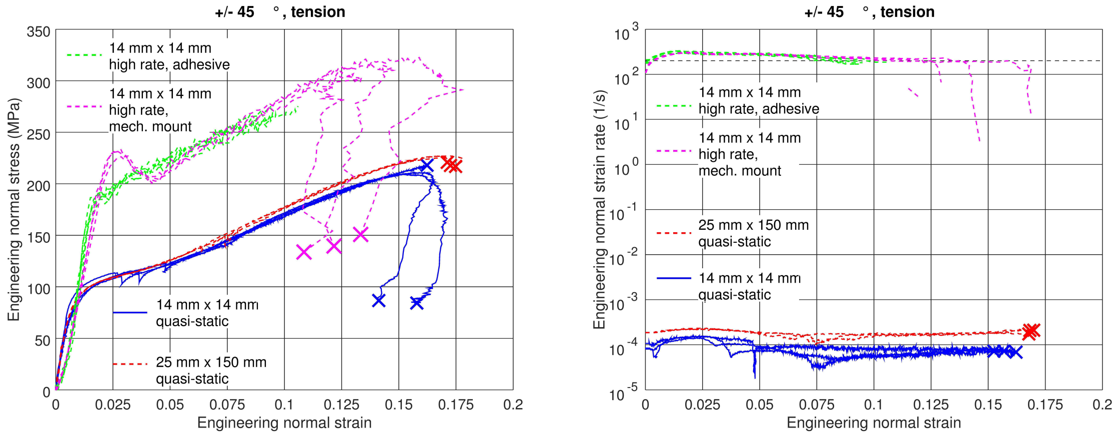


Figure 8. Measured stress-strain curves (left) and measured strain rate histories (right) in tension for +/- 45° laminate.

For the quasi-isotropic laminate, high strain rate tests were successfully carried out with both of the dog-bone geometries. Quasi-static tests were carried out with both dog-bone and constant width geometries to evaluate the representability of the results. Based on the quasi-static tests, the 8 mm x 8 mm (R12) dog-bone geometry shows material response similar to the constant width geometries and therefore this geometry was selected for the final tests. The results are shown in Figure 9.

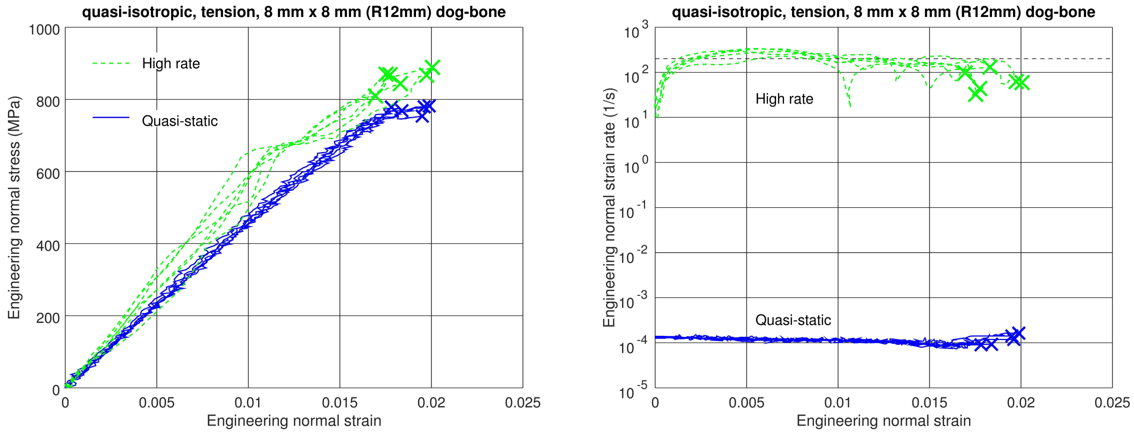


Figure 9. Measured stress-strain curves (left) and measured strain rate histories (right) in tension for the quasi-isotropic laminate.

4. Conclusions

With the results of this experimental campaign we demonstrate that the Hopkinson Bar technique is well suitable for characterization of CFRP at crash relevant loading rates of 200 s^{-1}. The study also shows that depending on the layup and loading direction there is a significant influence of the loading rate on the results.

We highlight the importance of carefully designing and analyzing the experiments for each layup separately. The composite layup influences not only the mechanical response of the material, but also the test procedure itself. That is, the specimen geometry, type of specimen mounting and test parameters (such as required load and loading duration) have to be adapted to the requirements of each tested layup. As evidenced by the results of this study, when these aspects are taken into account in the procedures, the high rate response of a CFRP material can be thoroughly characterized with the methods described in this paper.

Acknowledgments

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[12] ASTM D3518 Standard Test Method for In-Plane Shear Response of Polymer Matrix Composite Materials by Tensile Test of a +/- 45° Laminate