

High Strain Rate Mechanical Characterization of Carbon Fiber Reinforced Polymer Composites Using Digital Image Correlations

Louise A. Powell, William E. Luecke, and Matthias Merzkirch
National Institute of Standards and Technology

Katherine Avery
Ford Motor Company

Tim Foecke
National Institute of Standards and Technology

ABSTRACT

The introduction of carbon fiber reinforced polymer (CFRP) composites to structural components in lightweight automotive structures necessitates an assessment to evaluate that their crashworthiness dynamic response provides similar or higher levels of safety compared to conventional metallic structures. In order to develop, integrate and implement predictive computational models for CFRP composites that link the materials design, molding process and final performance requirements to enable optimal design and manufacturing vehicle systems for this study, the dynamic mechanical response of unidirectional (UD) and 2x2 twill weave CFRP composites was characterized at deformation rates applicable to crashworthiness performance. Non-standardized specimen geometries were tested on a standard uniaxial frame and an intermediate-to-high speed dynamic testing frame, equipped with high speed cameras for 3D digital image correlation (DIC). Specimen cross-sections, according to each fiber orientation tested, were consistent across strain rates to ensure results were comparable. Tensile strength and modulus were experimentally investigated over a wide range of strain rates (0.0001 to 200 s⁻¹). DIC was used to estimate strain profiles on composites surfaces, and the modulus was calculated from those strain measurements. Experimental results demonstrated an increase in the tensile strength of UD CFRP composites in the longitudinal (0°) and transverse (90°) direction with increasing strain rates. In contrast, the tensile strength of 2x2 woven composites and the tensile modulus of the UD material were insensitive to increasing strain rates. Comparison of failure modes provided insights on how loading rates influenced failure mechanisms.

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INTRODUCTION

For the last few decades, carbon fiber reinforced polymer (CFRP) composites have been implemented in the production of components and structures in aerospace and automotive applications [1,2] due to their high strengths capability. Several manufacturers have also substituted metal parts with composites because they can be formed into complex shapes that, for metallic parts, would require machining to create joints. Pre-formed composite components are lightweight and strong and reduce the number of heavy fasteners and joints. Hence, composite materials are helping to drive an industry-wide trend of fewer components, which can contribute towards weight reduction and fuel efficiency increase while being easy to handle, design, shape, and repair.

In the automotive industry, the incorporation of advanced, lightweight materials into vehicle structural components has a mission to save money, energy and reduce emissions.

The design process of automotive structures relies extensively on component level testing to validate the overall component crash performance. However, these tests may not provide sufficient information essential to the development of smarter and more robust modeling tools that link deformation behavior to material characteristics, which are crucial to the design process.

It is necessary for designers to understand the dynamic mechanical characteristics over a broad range of strain rates at a fundamental level in the design process. These characteristics are usually produced from material coupon level testing [3]. Due to the lack of existing standards at high strain rate testing procedures, obtaining accurate dynamic experimental data, suitable for material modeling predictive tools, represents a challenge for current testing methods [3].

Research studies on the effect of strain rates on the mechanical response of CFRP composites have not been fully investigated. Limited amount of data was obtained on the tensile behavior of fiber

composites at high strain rates using the expanding ring technique [5, 6]. Techniques used to determine mechanical properties under tensile impact loading of unidirectional (UD) carbon/epoxy and graphite/epoxy composites were investigated [7]; the dynamic stress-strain curves for UD carbon/epoxy and woven fabric glass/epoxy composites were also examined. Tensile tests to determine high tensile strength at various strain rates (crosshead speeds) were conducted [8]. The effect of strain rates via crosshead speeds on tensile strength and Weibull modulus of T1000GB PAN-based carbon fibers epoxy-impregnated bundle composites was evaluated. Nevertheless, the mechanical response of CFRP composites under low and high-speed loading is not entirely understood. In order for tests to generate the required data for building material models and to accelerate new product development, it is necessary to use predictive tools combined with experiments, and integrate them into the full product development cycle. As part of this process, quasi-static and dynamic mechanical characterization of CFRP composites material is currently underway. The strain rate sensitivity of UD CFRP composites in the longitudinal (0°) and transverse (90°) directions as well as 2x2 twill weave composites at strain rates ranging between 0.0001 to 200 s^{-1} is being characterized in uniaxial tension tests using digital image correlation (DIC). DIC is a non-contact quantitative full-field method to measure 2D and 3D shapes, and it is capable of quantitative measurement of surface strains during deformation [9]; it is used on the intermediate-to-high speed dynamic testing frame for longitudinal, transverse, and woven strain measurements. A mechanical extensometer is used on specimens tested at lower loading rates on a standard uniaxial testing frame for strain measurements. A specific strain rate of 0.01 s^{-1} ties both testing machines to the same loading rate condition. Also, specimen cross-sections, according to each fiber orientation tested, are consistent across loading rates for comparison purposes. The strain results are used for chord modulus and Poisson's ratio [10] calculations necessary to develop, integrate and implement predictive computational models for CFRPs composites linking the materials design, molding process and final performance requirements for optimal design and manufacturing of CFRP automotive systems. Preliminary results of the stress-strain relationship as well as measured strengths and chord modulus versus a wide range of strain rates are presented in this paper. Comparison of failure modes at different loading rates is also investigated to determine how loading rates influence specimen failure mechanisms.

MATERIAL

Carbon fiber reinforcements, due to their small cross-sections, are not directly used in engineering applications. Therefore, they are embedded in matrix materials to form carbon fiber composites [11]. The matrix serves to bind the fibers together, transfer the loads to the fibers, and protect them from damage due to handling and environmental effects.

The matrix material used in this study is a high temperature cure epoxy resin produced by the Dow Chemical company. For the purpose of this study, samples with three types of fibers orientations were produced: carbon fiber reinforced laminate composites with UD fibers in the 0° and 90° directions, as well as carbon fiber reinforced with a 2x2 twill weave laminate composites. The continuous and

woven prepreps are produced by DowAksa (A-42 24K) [12], and the composites laminate sheets were formed by the compression molding technique. In this processing method, epoxy/carbon composites were produced with 12-ply and 50:50 volume percent (vol.%) of fiber/matrix content for the UD material. The 2x2 twill weave laminate has 4-ply with a 50:50 fiber weight ratio in the weft and warp directions. Non-standardized samples for uniaxial tensile testing were prepared from the composite materials. Figures 1a. and 1b. illustrate the UD specimen geometry and nomenclature, and table 1 shows specimen dimensions. Figures 2a. and 2b. illustrate the 2x2 twill weave specimen geometry, and table 2 shows specimen dimensions.

Specimen Surface Preparation

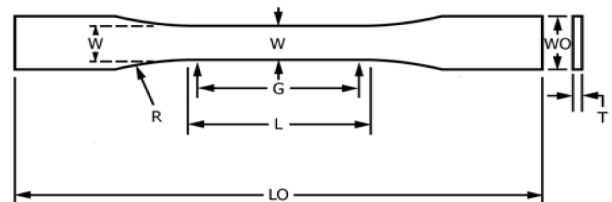
Each specimen in Figures 1a and 2a was cut using abrasive waterjet cutting with fine abrasive of 220 mesh. In order to produce the specimens, the end-tab region of a $250 \text{ mm} \times 250 \text{ mm}$ composite panel (UD or woven) subset was abraded using sand paper of 240 grit. The surface of NEMA grade G11 glass reinforced epoxy plastic laminates (yellow material in Figure 1a.) was also abraded in order to roughen the surface to be bonded as tabbing material. The abraded surfaces were washed thoroughly with water and air-dried. Another stage for the surface preparation of end-tabs consisted in using a file to cut a groove in the G11 and placing a wire spacer to control the bondline thickness. Then, wiping the end-tab areas of the composite panel and the G11 with isopropyl alcohol to get them ready for adhesive bonding was the final stage for the surface preparation.

Adhesive Bonding Process

The choice of adhesive for this study was 3M Scotch-Weld™ Low Odor Acrylic Adhesive DP810 (black) [13]. Curing was conducted in a fume hood at room temperature. The acrylic was dispensed on the G11 and CFRP laminate panels generously. The G11 was then bonded on each side of the CFRP end-tab region and let to cure for 24 hours. The specimens were cut via waterjet the following day.



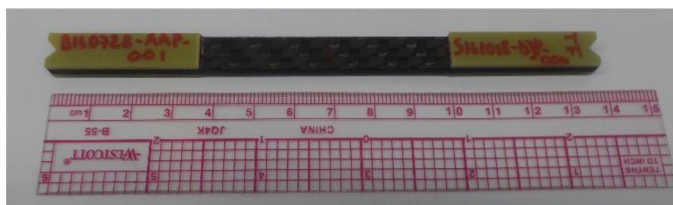
a.



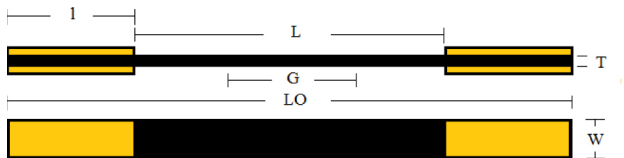
b.

Figure 1. (a) Tensile specimen geometry for unidirectional (UD) material in the 0° and 90° . (b) specimen nomenclature.





a.



b.

Figure 2. (a) Tensile specimen geometry for 2x2 twill woven laminate composites. (b) specimen nomenclature.

Table 1. UD dogbone specimen dimensions.

Specimen fiber orientation	Unidirectional (0° and 90°)
Geometry	Dogbone
LO - Overall length	166 mm
WO - Overall width	9.53 mm
W - Width of narrow section	2.0 mm
T - Thickness of narrow section	2.53 mm
L - Length of narrow section	45.5 mm
G - Reduced gauge length	36.4 mm
R - Radius of fillet	12.7 mm
Tab bevel angle	0°

Table 2. 2x2 twill weave laminate composites rectangular specimen dimensions.

Specimen 2D fabric laminate	2x2 Twill weave
Geometry	Rectangular
LO - Overall length	137 mm
W - Width	10.0 mm
T - Thickness	2.73 mm
I - Tab length	38.0 mm
L - Length of parallel section	62.0 mm
G - Reduced gauge length	25.4 mm
Tab bevel angle	0°

TESTING METHODS

Initially, each UD specimen in the 0° direction, with a shorter gauge length ($L = 9.53$ mm), was tested individually on a servohydraulic test machine with a 50 kN load cell capacity. An extensometer was used for strain measurements. The extensometer had a gauge length of $G = 8.6$ mm and was calibrated in units of strain. Uniaxial tensile tests were conducted with the displacement rate programmed for each test to provide engineering plastic strain rates nominally 0.0001 mm/mm/s, 0.01 mm/mm/s and 0.5 mm/mm/s.

A second set of specimens with a longer gauge length ($L = 45.5$ mm) were individually tested on a high strain rate (HSR) servohydraulic test machine with a 12 kN load cell capacity. These specimens were modified from the previous in terms of a longer gauge length ($L = 45.5$ mm) to accommodate their placement for subsequent tests conducted on the HSR machine.

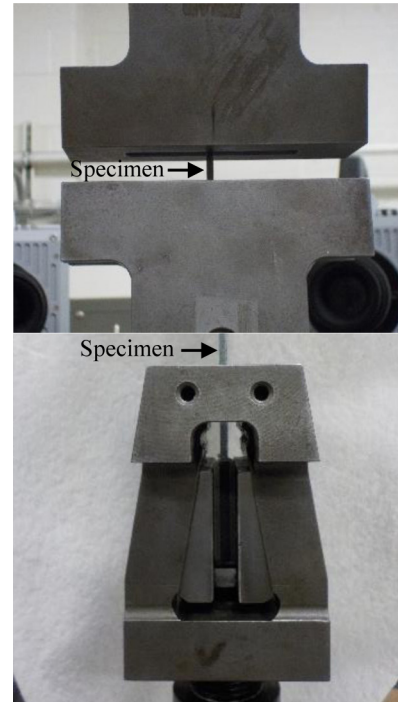


Figure 3. High-strain rate (HSR) wedge-grip system (front and side views).

Surface Strain Measurements

On the HSR testing machine, strain measurements were collected using high-speed DIC cameras and acquisition system. DIC is capable of quantitative measurement of severe surface strain gradients at a close location, hence representing high spatial resolution [14]. DIC working principles have been explained in [14-15]. In this study, the high-speed DIC cameras are Photron Fastcam SA5 and are used in combination with 200 mm Nikon lenses with locking focus rings and apertures. The DIC cameras were mounted to a continuous aluminum bar to warrant that their spacing and orientation remained unchanged during each experiment. The setup with a specimen mounted in the HSR grips is shown in Figures 3 and 4.

In order to capture surface strain measurements using DIC methods, digital images before and after deformation and tracing displacement of small subsets of the area of interest are compared. The tracing process is possible when observed surface has speckle patterns, which in the case of the presented results, was obtained by manually spraying matte white primer base paint on the specimen and matte black paint for speckle patterns (~50/50 black/white) as shown in Figure 5. When applying speckle patterns, each rectangular subset of a few pixels has a unique distribution of grey level.