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A dynamic test methodology for analyzing the strain-rate effect on the longitudinal compressive behavior of fiber-reinforced composites

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ABSTRACT

This paper presents an experimental study of the strain-rate effect on the longitudinal compressive strength of UD carbon-epoxy IM7/8552 and UD carbon-fiber-reinforced polyamide-6. A test setup for dynamic measurements using a split-Hopkinson pressure bar was developed to achieve valid compressive failure in the specimen's free gauge section. The setup presented improves on the dynamic compression fixture developed in an earlier study [Koerber and Camanho, Composites Part A 2011;42]. Greater static and dynamic longitudinal compressive strength values of an IM7/8552 UD laminate were achieved than in this earlier study. The absolute values obtained for the UD laminate were nonetheless still thought to underestimate the actual material property. Realistic dynamic longitudinal compressive strength values were achieved for the first time by testing a multi-directional laminate, which yielded the desired valid failure mode, then calculating the longitudinal compressive strength of the embedded 0°-UD ply using a procedure based on classical laminate theory. For IM7/8552, a dynamic compressive strength of 2008 MPa at 100 s^{-1} was measured compared to a static value of 1454 MPa. This corresponds to a strength increase of 40% confirming the quantitative strain-rate effect observed in the earlier study. A 60% strength increase was measured for UD carbon-fiber-reinforced polyamide-6 at the same strain-rate levels.

1. Introduction

Their potential for weight reduction and overall energy-efficiency improvement renders lightweight constructions made of composite materials increasingly attractive in the aerospace and automotive industries. These fiber-reinforced thermoset or thermoplastic matrix composite materials feature extraordinary strength to weight and stiffness to weight ratios. However, the potential for optimizing the composite structures' mechanical performance has not yet been fully exhausted and improved understanding of the materials' mechanical behavior is still needed. Strain-rate dependency is one of the material behaviors of fiber-reinforced composites being focused on because many primary structural applications involve exposure to impact and crash loads.

Longitudinal compressive stress-strain behavior is investigated in this study at different strain rates for a carbon-epoxy and a carbon-fiber-reinforced thermoplastic composite material. Strain-rate-dependent material data about the longitudinal compressive strength of composite materials is generally rare although important. The longitudinal compressive strength of unidirectional (UD) composites is significantly less than the longitudinal tensile strength and can therefore be a driver for composite-structure design. Whereas it is well accepted that the longitudinal tensile strength of UD carbon composites is not strain-rate sensitive [1–3], significant rate sensitivity was observed for longitudinal compressive strength in earlier studies.

Hsiao and Daniel [4] used a falling-weight impact tower and thick composite specimens with bonded-steel end caps to investigate longitudinal compressive strength at high strain rates. The thick composite laminates were end loaded for the high-strain-rate tests. An increase in the longitudinal compressive strength with increasing strain rate was measured. No rate effect was observed for the longitudinal compressive Young's modulus. Premature crushing failure at the specimens' ends caused dynamically measured longitudinal compressive strength values to be underestimated. Bing and Sun [5] used a split-Hopkinson pressure bar (SHPB) to investigate the off-axis compression behavior of UD composite specimens at different strain rates. Linear extrapolation was applied to the measured off-axis strength data to compute the

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composite's longitudinal compressive strengths at high strain rates. Wiegand [6] used an SHPB to characterize the quasi-static and dynamic compression behavior of a cross-ply epoxy composite. The laminate was inserted into slotted end caps and fastened with additional clamps. The specimens exhibited failure near the grip-termination region. A linear increase in compressive strength with increasing strain rate was found; however, compressive strength in the fiber direction on the ply level was not further investigated. Koerber and Camanho [7] used an SHPB system for dynamic tests to measure the effects of strain rate on the longitudinal compressive strength and longitudinal compressive Young's modulus of UD IM7/8552. Although analysis of the strain rate's effect on the longitudinal compressive modulus was conclusive, all of the specimens, measured at quasi-static and dynamic strain rates exhibited preliminary failure mode at the loading surfaces. A qualitative evaluation of the strain-rate effect on longitudinal compressive strength was possible because the failure mode was the same at all strain rates. The measured static and dynamic strengths values were thought to be significantly lower than the actual values, due to the observed preliminary failure mode. Characterization of the strain rate's effect on the longitudinal compressive stress-strain behavior of UD carbon composites is still challenging and subject to debate.

This study aims to develop an SHPB compression-test methodology for investigating the strain rate's effect on the longitudinal compression response of UD carbon composites. Particular emphasis is placed on generating a valid failure mode during quasi-static and high-strain-rate loading, which was not achieved in earlier studies such as [4,7]. The main advantage of SHPB systems over drop towers or servohydraulic testing machines is that the measured stress-strain response is much less influenced by inertia effects in the load chain, thereby enabling high-quality dynamic stress-strain response to be measured. UD and quasi-isotropic (QI) IM7/8552 carbon-epoxy composite and UD carbon-fiber-reinforced polyamide-6 (PA 6) composite laminates were tested to demonstrate that the developed testing method is suitable for different laminate layups and different types of matrices. Greater static and dynamic strengths were achieved for high-strength UD IM7/8552 carbon-epoxy composite laminate than during an earlier study [7]. The static compressive strength closely resembled the longitudinal compressive strength reported in an earlier study [8] for this composite-material system. However, the observed damage location suggested that the measured strength stemmed from premature failure. Valid failure in the middle of the specimen caused significantly higher strengths to be determined via back-calculation of a UD ply's longitudinal compressive strength using experimental data from the QI laminate. A quantitatively higher strain-rate sensitivity than that for epoxy-based composite was found for the thermoplastic composite also investigated in this study. It bears noting that a complete data set for the dynamic in-plane mechanical response of an IM7/8552 UD carbon-epoxy laminate at strain rates in the 100 s^{-1} to 300 s^{-1} range now exists given the results of this study and earlier research published by the authors in [7,9,10].

2. Experimental procedure

2.1. Material

Two types of carbon-fiber-reinforced composite material systems were investigated: the HexPly® IM7/8552 thermoset prepreg material system [11], which is used mainly for primary structure components in the aerospace industry operating in environments up to 121 °C, and Celstran® CFR-TP PA6 CF60-01, a 60% carbon-fiber-by-weight polyamide-6 unidirectional fiber-reinforced thermoplastic composite tape [12]. The latter material system is used in industrial, automotive, and sporting goods applications and is commonly processed using automated fiber-placement technologies.

For IM7/8552, two laminates—a 14-ply, unidirectional laminate and a 16-ply, quasi-isotropic $[(90^\circ/0^\circ/+45^\circ/-45^\circ)_2]_{2S}$ laminate—were manufactured on a 75t Cannon hot press by applying the curing cycle recommended in the material's data sheet [11]. A unidirectional plate with 14 plies was manufactured for the carbon-fiber-reinforced polyamide-6 composite. The thermoplastic laminate was made of single tape stripes laid parallel and brick-like above each other. To better handle the stack, the frame was welded at a few points using an ultrasonic welding apparatus (ProteUS, EM-Systeme GmbH) with a 30 kHz sonotrode frequency. Using a RUCKS hot press and a compression mold, the thermoplastic composite plates were consolidated for 15 min at 260 °C and 0.5 MPa pressure.

2.2. Specimen

Unidirectional carbon-fiber-reinforced composite materials to be tested dynamically in the fiber direction manifest great failure strength. Various difficulties impede the testing of such high-performance composite materials. The main problems are preventing premature failure at the loading ends and material failure due to specimen bending. Denting the incident- and transmission-bar ends when loading the compression specimen should also be avoided. A compression device made of steel and suitable for high-strain-rate loading in a split-Hopkinson pressure bar as well as for quasi-static tests in a universal testing machine was developed based on these requirements (see Fig. 1).

The device's design was motivated by the well-established combined-loading-compression (CLC) device used in the ASTM D6641/D6641M [13] standard. This loading principle of introducing the compressive force into the specimen via combined end and shear loading has been found to be most suitable for testing unidirectional composite laminates. It was thus adopted for development of the high-strain-rate compression-test device presented. A simple compression device with less mass is needed for the Hopkinson-bar setup in contrast to the CLC-test fixture with its massive loading blocks, alignment rods, and fixture bolts. This is why screwed or bolted joints are infeasible for introducing force into the specimen. An adhesive joint between the specimen and the end caps was therefore chosen. With this joining technique, a region of shear is created that transmits force from the specimen's flanks to the free gauge length. The laminate is also loaded at the end surfaces, which requires exact tolerances of the composite laminate and the slotted steel end cap. The external clamps, adjacent to the free gauge section, are needed to apply additional pressure to the specimen's end caps thus enhancing internal friction between specimen's surface, the adhesive, and the end cap. All three loading mechanisms mutually contribute to introducing load into the specimen. The end cap's 18 mm diameter equals that of the bars used.

The flat, rectangular 110 mm × 8 mm × 2 mm (length × width × thickness) specimens were cut using a water-cooled diamond saw and glued into the slotted end caps using Scotch-Weld™ DP 490 adhesive from 3M for the thermoset IM7/8552 specimens and BETAMATE™ 1822 from Dow Automotive for the thermoplastic polyamide-6 specimens. While the adhesive cures, the specimens lie in a V-shaped notch of a plate rail and are fastened to ensure the specimen's and the end caps' axial alignment and parallel end surfaces. This leaves a 10 mm long free gauge section in the middle of the specimen. The tube, which can slide freely on PA bearings, surrounds the specimen and serves to