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Experimental Tests To Characterize Behavior and Properties of HexPly® Continuous Fiber Unidirectional Composite and TuFF Discontinuous Fiber Composite

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Summary

This report summarizes test procedures for characterizing the quasistatic, room-temperature behavior of two IM7/PEKK (intermediate modulus 7/polyetherketoneketone) composite material systems: a continuous fiber (CF) carbon fiber polymer composite system from Hexcel® (Hexcel Corp.), referred to as "HUDC" (HexPly® unidirectional composite), and a discontinuous short fiber composite system provided by the University of Delaware, referred to as "TSFC" (Tailorable Universal Feedstock for Forming (TuFF) short fiber composite) or simply "TuFF." The report also presents data obtained from analysis of the laboratory tests for the two unidirectional composites. Comparison of the mechanical properties of the TuFF fiber composite with those of the CF composite indicated that the TuFF material system has nearly equivalent (less than 15% difference) elastic moduli in all three principal material directions. Similarly, the TuFF fiber composite's strengths under both tension and compression in the fiber direction, as well as the in-plane shear moduli, showed nearly equivalent values as compared to the CF composite. Improved transverse strength, in-plane shear strength, and both out-of-plane shear moduli were seen in the TuFF material. The TuFF material system, however, showed a significant reduction (~40%) in through-thickness tensile strength as compared to the CF material system.

1.0 Introduction and Background

This report summarizes test procedures for characterizing the quasistatic (QS), room-temperature (RT) behavior of two IM7/PEKK (intermediate modulus 7/polyetherketoneketone) composite material systems: (1) a continuous fiber (CF) unidirectional carbon fiber polymer composite system from Hexcel® (Hexcel Corp.), referred to as "HUDC" (HexPly® unidirectional composite), and (2) a discontinuous short fiber composite system provided by the University of Delaware and referred to as "TSFC" (Tailorable Universal Feedstock for Forming (TuFF) short fiber composite) or simply "TuFF." All testing reported in this document follows applicable ASTM International test standards as closely as possible, with any deviations reported. The overall objective was to develop a framework for the creation of MAT213

material input for use in the LS-DYNA® program (Livermore Software Technology Corp.). Details of the MAT213 material model and its implementation are available publicly (Refs. 1 to 3). These experiments were performed to generate the required inputs for MAT213; however, the measured properties from the experiments can be utilized by most composite impact models.

2.0 Methodology

2.1 Materials

Two IM7/PEKK composite material systems were investigated in this study: a continuous fiber (CF) unidirectional carbon fiber polymer composite system from Hexcel®, referred to as "HUDC," and a discontinuous short fiber provided by the University of Delaware and referred to as "TuFF" or "TSFC." Nominal composite characteristics are summarized in Table 1.

The CF panels were manufactured with a unidirectional thermoplastic prepreg provided by Hexcel® Corporation, with a 34% resin content and a fiber areal weight of 194 gsm (Ref. 4). All panels were compression molded using a 12- by 12-in. (305- by 305-mm) steel picture frame tool with Kapton® (DuPont Electronics, Inc.) film and mold release on both panel surfaces. First, the laminate stack was placed in the press and 30 psi (2 bars) pressure was applied. Next, the temperature was increased to 716 °F (380 °C). The pressure was then increased to 105 to 150 psi (7 to 10 bar) and held for 45 min. Lastly, panels were cooled to 160 °F (71 °C) at a rate between 5 and 10 °F/min (2.8 to 5.5 °C). The laminates were characterized by ultrasonic C-scan to confirm full consolidation.

The TuFF panels were manufactured at the University of Delaware using 3-mm-long IM7 TuFF fibers with a fiber areal weight of 120 gsm. TuFF fibers were infused with a PEKK resin film to create prepreg plies. A detailed description of the manufacturing process is described in Reference 5 and is summarized here. TuFF panels are fabricated in a twin hot press and a picture frame tool. First, the laminate stack is enveloped between two layers of Upilex®-50RN polyimide film (UBE Corp.) and sealed using vacuum sealant tape. Next, the panel is placed into a press, which is preheated to a temperature of 716 °F (380 °C), and held for 20 min. before pressure is applied. The pressure is first ramped to 100 psi (7 bar) at a rate of 2 psi/min and then rapidly increased to a consolidation pressure of 305 psi (21 bar) and held for 45 min. Once the consolidation pressure is reached, the temperature is decreased at a rate of 2.5 °C/min.

TABLE 1.—NOMINAL COMPOSITE CHARACTERISTICS

	Continuous	TuFF
Resin content, wt%	34	34
Cured ply thickness, in. (mm)	0.0073 (0.185)	0.0048 (0.122)
Fiber areal weight, g/m^2	194	120

2.2 Sample Preparation

Five different panel types (PTs), with designations and dimensions as shown in Table 2, were used to create test specimens. Characterization of composite behavior requires 12 stress-strain curves, as summarized in Table 3. The panel labeled PT1 was used for the 1-direction tension specimen. Two PT2 panels were used, from which tension (2-direction), compression (1- and 2-directions), shear 1-2 plane, and off-axis tension (45°, 1-2 plane) specimens were made. The two panels were labeled PT2-1 and PT2-2. The fourth panel, labeled PT3, was used for through-thickness testing. The fifth panel, labeled PT4, was used for double cantilever beam (DCB) and end-notched flexure (ENF) testing. Layup for all panels was unidirectional. T12 results are not available due to inconsistent results from HUDC specimens.

The test coupons were machined at Cincinnati Testing Laboratories (CTL Engineering, Inc.). Oil-based paint markers were used to perform specimen mapping on the provided panels. Upon completion of the mapping process, photographs were recorded to maintain traceability to the extraction locations. Initial specimen blanking was performed using a tile saw with a diamond wheel. The operator used water as the cutting fluid, and the blanks, approximately 1/8-in. (3.175-mm) oversized for all dimensions, were extracted. Upon completion of the blanking operation, precision grinding was performed on the specimen edges to produce a high-quality surface finish and ensure that there were no pulled fibers. The precision grinding was performed using a diamond wheel with a water-based coolant. Notching (in the case of the ASTM D5379 (Ref. 6) specimens) was performed using a dressed diamond wheel.

TABLE 2.—PANELS USED FOR TESTS

Panel type	Nominal dimensions (length by width), in. (mm)	Nominal thickness, in. (no. of piles)	
		HUDC	TSFC
PT1	12 by 12 (305 by 305)	0.04 (6)	0.03 (6)
PT2	12 by 12 (305 by 305)	0.12 (16)	0.10 (16)
PT3	12 by 12 (305 by 305)	0.90 (123)	0.90 (180)
PT4	12 by 12 (305 by 305)	0.18 (24)	0.18 (36)

TABLE 3.—SUMMARY OF TEST SUITE

Test ID	Description	Panel type
T1	Tension 1-direction	PT1
T2	Tension 2-direction	PT2-1
T3	Tension 3-direction	PT3
T4	Compression 1-direction	PT2-1
T5	Compression 2-direction	PT2-1
T6	Compression 3-direction	PT3
T7	Shear 1-2 plane	PT2-2
T8	Shear 2-3 plane	PT3
T9	Shear 1-3 plane	PT3
T10	Off-axis tension (45°, 1-2 plane)	PT2-2
T11	Off-axis compression (45°, 2-3 plane)	PT3
T12	Off-axis tension (45°, 1-3 plane)	PT3
T13	DCB	PT4
T14	ENF	PT4

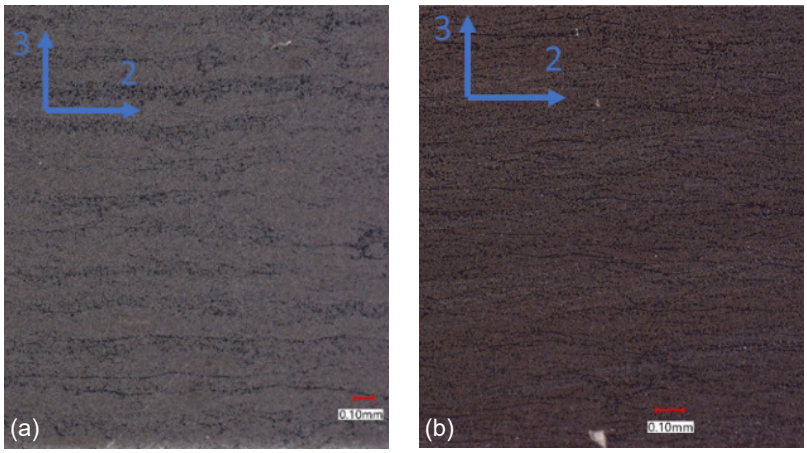


Figure 1.—Principal material directions shown in optical microscopy image of representative composite (unidirectional fibers oriented in 1-direction). (a) HUDC. (b) TSFC.

Upon completion of the machining process, each specimen was dimensionally inspected per the relevant ASTM test standards. The devices used for the inspection were those required by these test standards. The principal material directions for representative HUDC and TSFC composites are shown in Figure 1.

When required, G10 fiberglass tabs (Acculam® (D&K Custom Machine Design, Inc.) Epoxyglas G10 36- by 48-in. (91- by 122-cm) laminate sheets, National Electrical Manufacturer Association (NEMA) Grade FR4, MIL-I-24768/27) were used with the sample. The fiberglass tabs act as compliant surfaces that prevent specimens from crushing when placed in the hydraulic grips. They also act as stiffening elements when conducting shear tests. Fiberglass tabs with a nominal thickness of 0.062 in. (1.57 mm) were used in all cases. The tabs are bonded to the specified specimen surfaces using 3M® DP460 Scotch-Weld® (3M Company) toughened two-part epoxy (Ref. 7).

2.3 Test Machines, Fixtures, Equipment, and Software

All experiments were performed using three different test frames and the same camera system. Postprocessing of the experimental images was performed using the same software. Details are provided in this section.

Test Frame: The experimental procedure was performed using three different test frames—an MTS® 810 test frame (Figure 2(a)), an Instron 1332 test frame (Figure 2(i)), and a MTS Exceed® test frame (Figure 2(j)), all by Illinois Tool Works. Flat tension specimens were held in the frame with MTS® 647.10A hydraulic grips (Figure 2(b)). The hydraulic grips were aligned by clamping a rigid, flat steel plate and allowing the heads to freely rotate into position. After aligning the hydraulic grips, the specimen was placed into the test frame. Verticality of the specimen was ensured by using a laser alignment system (Figure 2(c)). The specimen was gripped up to the end of the fiberglass tabs. Shear specimens were held in the test frame using a Wyoming Test Fixtures (Wyoming Test Fixtures, Inc.) Iosipescu shear test fixture (Figure 2(d). Custom fixtures for compression tests were used to test compression cubes (Figure 2(e). Alignment of the specimen was ensured using 0.2-in. (5.08-mm) deep square notches machined into the center of the fixtures (Figure 2(f)). Flat (in-plane) compression specimens were tested using a Wyoming Test Fixtures combined loading compression (CLC) fixture (Figure 2(g) and Figure 2(h)). The CLC fixture transfers load into the compression specimens through both shear load transfer and end load transfer, which lessens the need for excessive clamping forces.

Force data were gathered using the load cell. All experiments were performed under displacement control conditions. The displacement rate refers to the rate of displacement of the test frame actuator and is set using the system controller.

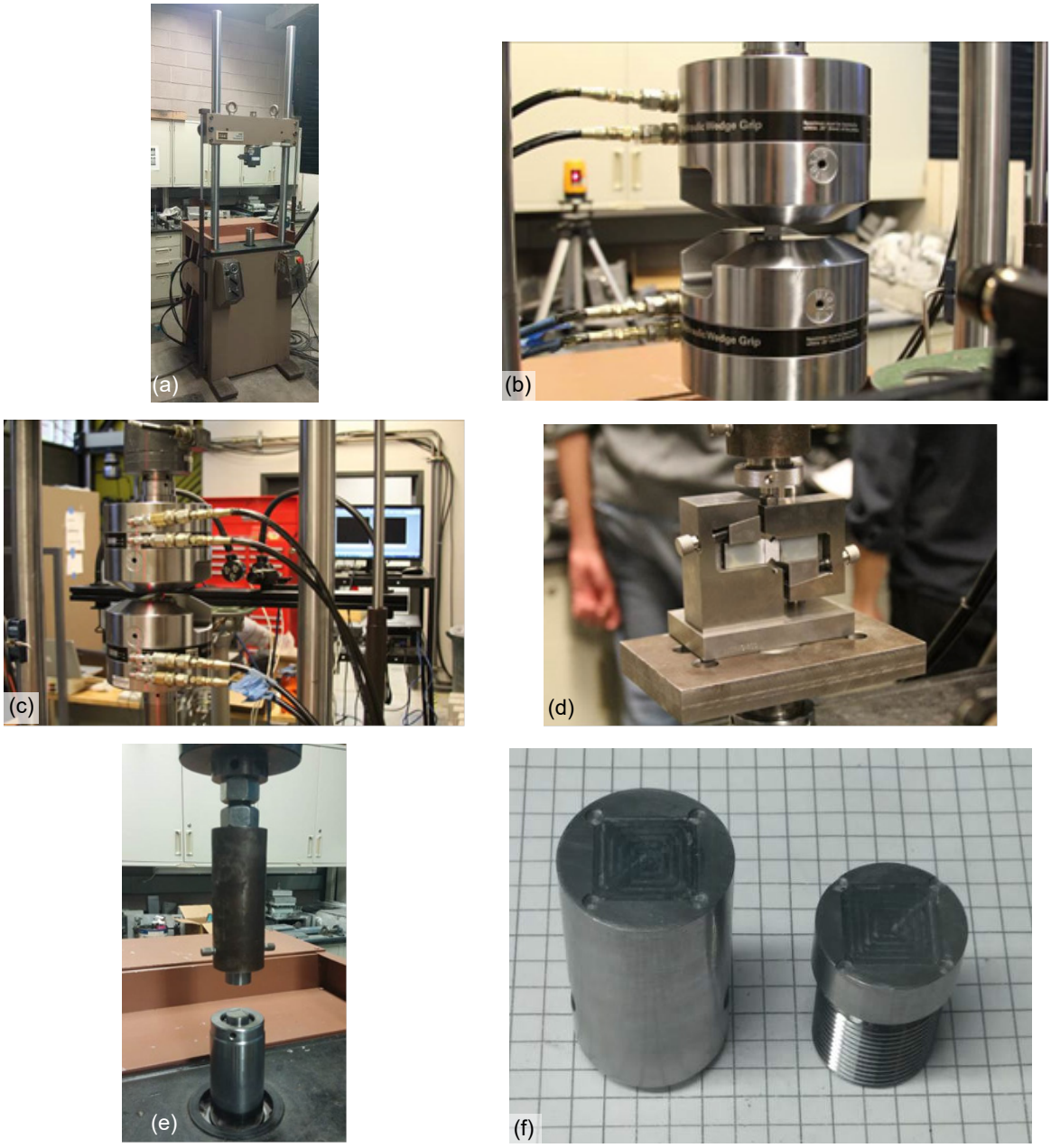
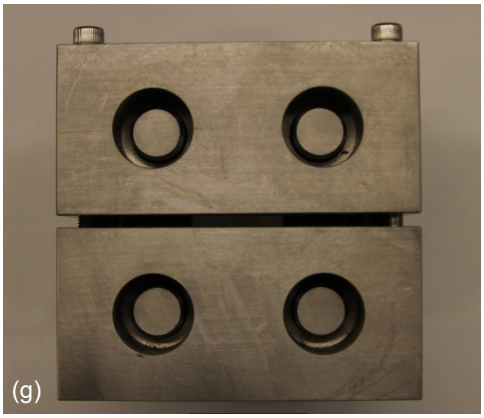
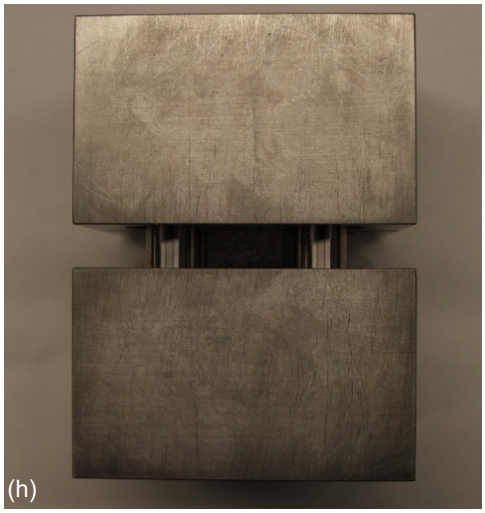


Figure 2.—Experimental equipment. (a) MTS® 810 test frame. (b) Hydraulic grips. (c) Specimen alignment. (d) Iosipescu shear test fixture. (e) Compression cube fixture. (f) Custom fixture for compression tests. (g) CLC compression fixture (top). (h) CLC fixture front showing C2 specimen. (i) Instron® 1332 test frame. (j) MTS Exceed® test frame. (k) Spring-loaded fixture. (l) Three-point bend fixture. (m) Two DIC cameras and high-speed camera. (n) LED lighting fixture. (o) Manual tightened tension fixture.





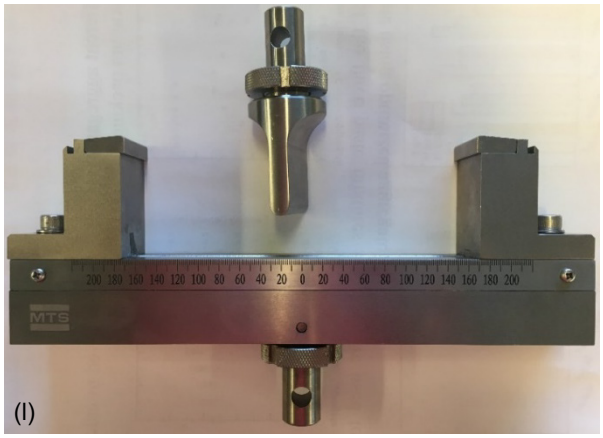


Figure 2.—Continued.

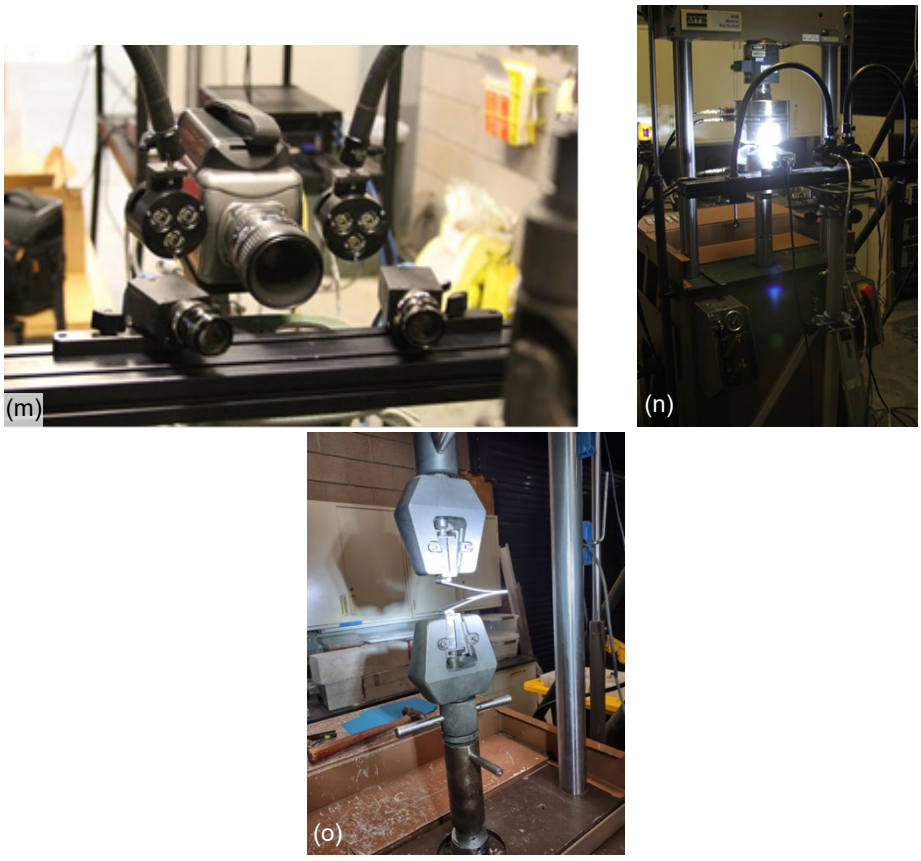


Figure 2.—Concluded.

Digital Image Correlation (DIC) Equipment: Two Point Grey Grasshopper®3 cameras (Teledyne FLIR, LLC) were used to capture images of the specimen throughout the duration of the experiment (Figure 2(m)). Light-emitting diode (LED) lamps were used to properly illuminate the specimen during the experiment. The cameras and lights were fixed to the same frame (Figure 2(n)). The frame was leveled using a bubble level to ensure that the cameras were aligned and that the field of view was both horizontal and vertical.

Unless otherwise noted, images were captured at 5-s intervals throughout the experiment using VIC-Snap 9 DIC software from Correlated Solutions, Inc. (Ref. 8) to obtain the strain field on the surface of the specimen.

Postprocessing: The images captured during the experiment were processed for the purpose of obtaining a full strain field using virtual imaging correlation (VIC) software VIC-3D version 9 from Correlated Solutions, Inc. (Ref. 8). The Lagrangian definition of strain was chosen to perform the analysis. A functionality within the VIC-3D software was used to smooth the strain data using a decay filter algorithm. For the initial processing, the entire speckled region of the specimen was analyzed. After the analysis and smoothing were completed, a smaller region with constant strain was taken as the representative strain induced in the specimen during the experiment. The region of interest is typically chosen so that the strain field is as uniform in that region as possible. Typically, this region is away from the edges of the specimen and away from areas of strain concentrations that may be present where the specimens are gripped. In this report, this area or region from which the strain values were obtained and reported is referred to as the "strain gage section" (SGS). Sample images are shown in Figure 3. The selection of the SGS was somewhat arbitrary, and alternative methods have been suggested by others (Ref. 9).

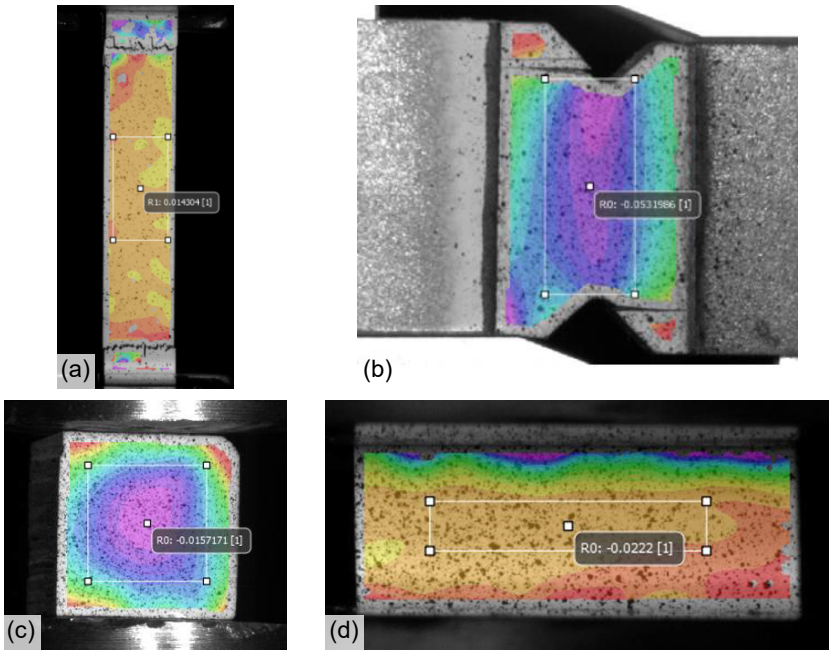


Figure 3.—Typical SGS specimens. (a) Tension specimens. (b) Shear specimens. (c) Compression specimens (cube). (d) Compression specimens (flat panel).

Measurement Instruments: A Pittsburgh® (Harbor Freight Tools USA, Inc.) 4-in. (10-cm) digital caliper was used to obtain specimen dimensions. Width and thickness were measured at three equally spaced intervals, and the average value was used for calculation of cross-sectional areas.

2.4 Typical Test Procedure

The procedure for conducting experiments was the same for each specimen unless otherwise noted. For all experiments, prior to loading the specimen, the DIC system was calibrated using VIC-3D version 9. Calibration is done only when the cameras must be moved or if new fixtures will cause the plane of the specimen to be moved away from where the cameras are initially placed.

2.5 Postprocessing of Test Data

After the experiments were completed, force data were obtained as a function of time from the test frame's controller, and strain data were obtained as a function of time from DIC analysis. The stress in the specimen was taken as the average stress across the respective cross section of the specimen. For tension and compression specimens, the cross section perpendicular to the direction of loading was used to calculate the cross-sectional area. The average stress was calculated using the following equation:

$$\sigma = \frac{F}{A} \tag{1}$$

where F is the normal force reported by the load cell at the current time-step and A is the cross-sectional area. For shear specimens, the surface between the notches, through the thickness of the specimen, was used to calculate the cross-sectional area. The average shear stress was calculated using the equation

$$\tau = \frac{V}{A} \tag{2}$$

where V is the shear force reported by the load cell at the current time-step and A is the cross-sectional area.

The strain reported from VIC-3D version 9 in the region of interest was used in conjunction with the calculated stress to generate a true stress-strain curve for any given specimen. Several parameters were obtained from the stress-strain curves of each individual specimen for the purpose of determining how consistent the data were. Table 4 describes the parameters and how they were obtained from the available data.

TABLE 4.—DESCRIPTIONS OF PARAMETERS USED IN THIS REPORT

Parameter	Definition	Method
Loading rate	Constant rate at which the actuator on the test frame is displaced	Chosen by the experimenter as a fixed parameter at the beginning of the procedure. The rate is prescribed as a displacement over a certain period of time.
Strain rate	The rate at which strain is induced in the specimen during a given experiment	The strain measure of interest is plotted as a function of time, and the average strain rate during the experiment is obtained by performing a linear regression. The slope of the resulting best-fit line is taken as the average strain rate.
Modulus	The slope of the initial linear region of the true stress-strain curve	The analyst determines the region that is most linear in the initial portion of the curve and performs a linear regression on the data. The slope of the resulting best-fit line is taken as the modulus.
Poisson's ratio	The negative ratio of transverse strain to normal strain	Both elastic and plastic Poisson's ratios may be obtained by plotting transverse strain as a function of normal strain. The analyst determines where the onset of plasticity occurs from the stress-strain curve. The corresponding normal strain point on the transverse strain-normal strain curve is used as the point that separates the elastic and plastic zones. A linear regression is performed on each zone separately, and the slope is taken as the respective Poisson's ratio.
Peak stress	Maximum stress achieved during a given experiment	Selected from stress data obtained through scaling the force data reported by the load cell
Ultimate strain	Strain measured at peak stress	Selected as the largest strain when the specimen exhibits brittle failure with no postpeak strength
Failure strain	Strain measured when the specimen fails	Selected as the strain when there is a large drop in stress and the specimen no longer loads back up to that peak stress point. Typically, this is when the test is terminated, and it is used when the specimen does not exhibit brittle failure.
Transverse strain	Strain induced in the specimen perpendicular to the direction of loading in tension and compression tests. In shear tests, it is defined as strain induced in specimen parallel to the movement of the actuator.	Obtained through DIC measurements
Longitudinal strain	Strain induced in the specimen parallel to the direction of loading in tension and compression tests. In shear tests, it is defined as strain induced in specimen perpendicular to the movement of the actuator.	Obtained through DIC measurements
Shear strain	Tensorial shear strain induced in the principal plane being observed	Obtained through DIC measurements

3.0 Quasistatic Room Temperature (QS-RT) Test Details and Results

Details of each test are discussed in this section. Units are given as reported in the experiments. Applicable ASTM standards are used. However, there are deviations from the standards for some tests; these deviations are noted in the report. Results are summarized in the Appendix (Table A.1).

3.1 Test T1: In-Plane 0° Tension Test

Experimental Setup: This test is used to generate the tension stress-strain curve in the 1-direction. An MTS® 810 test frame (Figure 2(a)) was used to perform the 1-direction tension test.

Specimen Geometry: ASTM D3039, Standard Test Method for Tensile Properties of Polymer Matrix Composites Materials (Ref. 10), is applicable for this test. The specimen geometry details are shown in Figure 4. Shaded regions indicate where the fiberglass tabs are bonded to the specimen. The average specimen dimensions in the gage section for the three tested replicates for HUDC and TSFC are shown in Table 5 and Table 6, respectively.

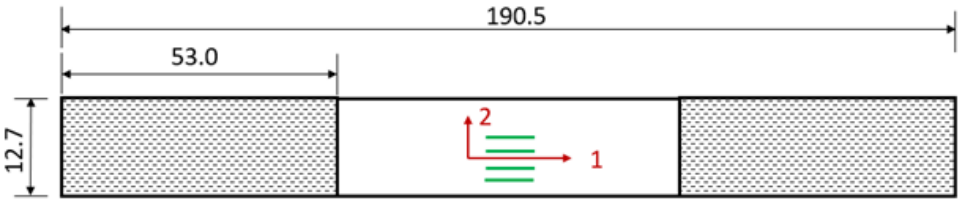


Figure 4.—Typical specimen geometry and layout (all dimensions in mm).

TABLE 5.—1-DIRECTION TENSION TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate ID	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_T1-1	0.50 (12.7)	0.046 (1.2)	0.023 (14.84)
HUDC_T1-2	0.50 (12.7)	0.046 (1.2)	0.023 (14.84)
HUDC_T1-3	0.50 (12.7)	0.046 (1.2)	0.023 (14.84)

TABLE 6.—1-DIRECTION TENSION TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate ID	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_T1-1	0.50 (12.7)	0.032 (0.81)	0.016 (10.32)
TSFC_T1-2	0.50 (12.7)	0.031 (0.78)	0.016 (10.32)
TSFC_T1-3	0.50 (12.7)	0.030 (0.76)	0.015 (10.32)

3.1.1 HUDC Results

Specimen Photographs: Photographs of the specimens before testing and after testing are shown in Figure 5 and Figure 6, respectively, for the HUDC material. The specimens exhibited longitudinal cracks in the matrix between the fibers at failure.

Test Results: A summary of results from the tests on the HUDC material is shown in Table 7. Figure 7 shows the individual stress-strain curves for the specimens tested.

Figure 5.—1-direction tension specimens before testing. (a) HUDC_T1-1. (b) HUDC_T1-2. (c) HUDC_T1-3.

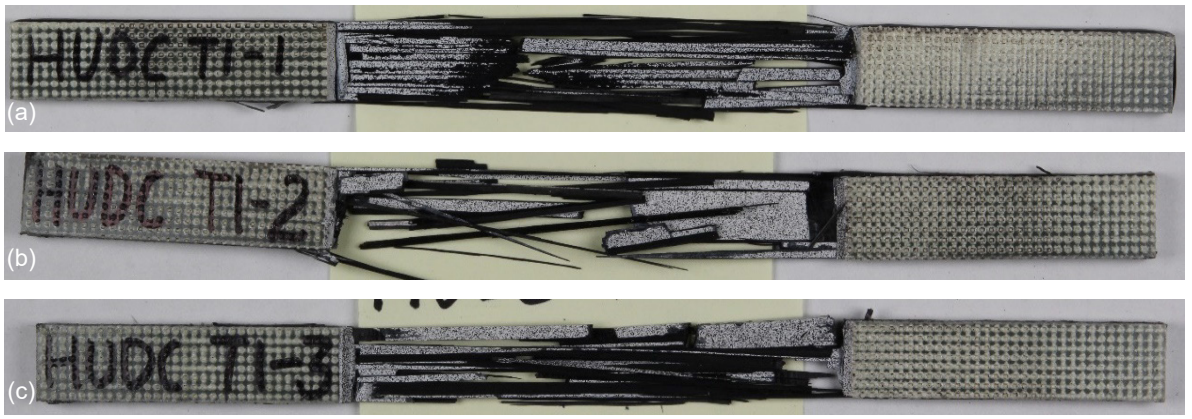


Figure 6.—1-direction tension specimens after testing. (a) HUDC_T1-1. (b) HUDC_T1-2. (c) HUDC_T1-3.

TABLE 7.—SUMMARY OF 1-DIRECTION TENSION TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{11}, psi	Poisson's ratio, ν_{12}	Ultimate strain	Peak stress, psi
HUDC_T1-1	0.02	5.06×10^{-5}	23,402,625	0.351	0.0163	394,553
HUDC_T1-2	0.02	5.27×10^{-5}	23,328,185	0.346	0.0162	400,219
HUDC_T1-3	0.02	5.37×10^{-5}	23,180,953	0.340	0.0163	405,735
Average	------	5.23×10^{-5}	23,303,921	0.346	0.0162	400,169
Standard deviation	------	1.58×10^{-6}	112,811	0.0052	0.00006	5,591
Coefficient of variation	------	3.0%	0.5%	1.5%	0.3%	1.4%

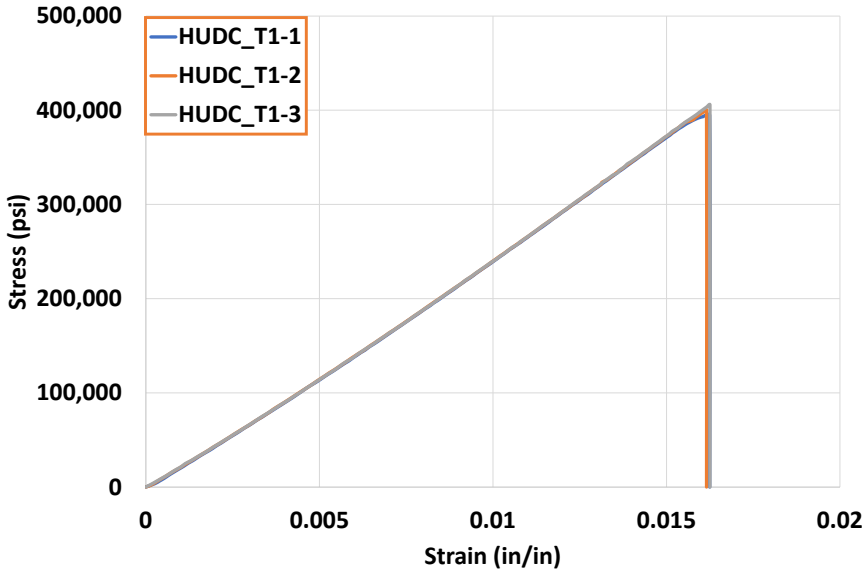


Figure 7.—1-direction tension stress-strain curves for HUDC material.

3.1.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 8 and Figure 9, respectively, for the TSFC material. The specimens exhibited longitudinal cracks in the matrix between the fibers at failure.

Test Results: A summary of results from the tests on the TSFC material is shown in Table 8. Figure 10 shows the individual stress-strain curves for the specimens tested.

Figure 8.—1-direction tension specimens before testing. (a) TSFC_T1-1. (b) TSFC_T1-2. (c) TSFC_T1-3.

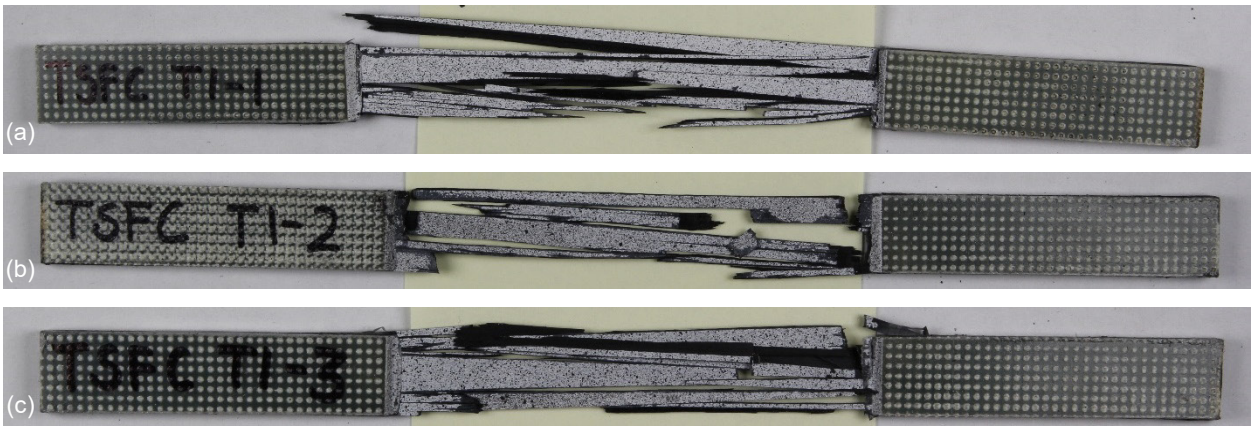


Figure 9.—1-direction tension specimens after testing. (a) TSFC_T1-1. (b) TSFC_T1-2. (c) TSFC_T1-3.

TABLE 8.—SUMMARY OF 1-DIRECTION TENSION TEST RESULTS

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{11}, psi	Poisson's ratio, ν_{12}	Ultimate strain	Peak stress, psi
TSFC_T1-1	0.02	6.14×10^{-5}	19,992,671	0.370	0.0169	345,606
TSFC_T1-2	0.02	5.83×10^{-5}	19,849,664	0.364	0.0174	375,105
TSFC_T1-3	0.02	6.32×10^{-5}	20,131,202	0.374	0.0164	359,451
Average	-------	6.10×10^{-5}	19,991,179	0.369	0.0166	360,054
Standard deviation	-------	2.48×10^{-6}	140,775	0.0051	0.00073	14,759
Coefficient of variation	-------	4.1%	0.7%	1.4%	4.4%	4.1%

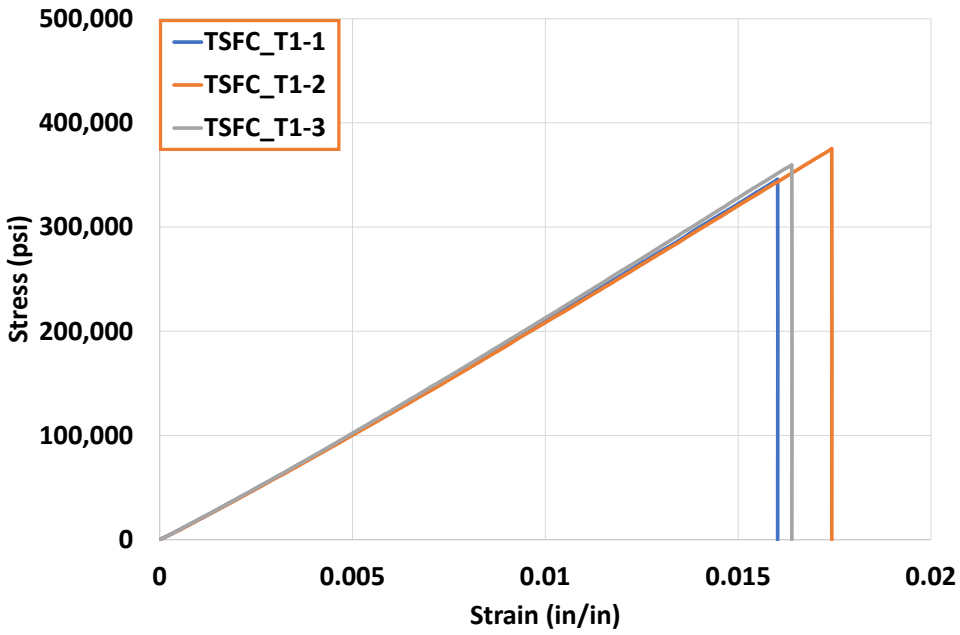


Figure 10.—1-direction tension stress-strain curves for TSFC material.

3.2 Test T2: In-Plane 90° Tension Test

Experimental Setup: This test is used to generate the tension stress-strain curve in the 2-direction. An MTS® 810 test frame (Figure 2(a)) was used to perform the 2-direction tension test.

Specimen Geometry: The specimen dimensions, taken from ASTM D3039 (Ref. 10), and specimen layout are shown in Figure 11. Shaded regions indicate where the fiberglass tabs are bonded to the specimen. The average specimen dimensions in the gage section are shown in Table 9 and Table 10 for the three tested replicates.

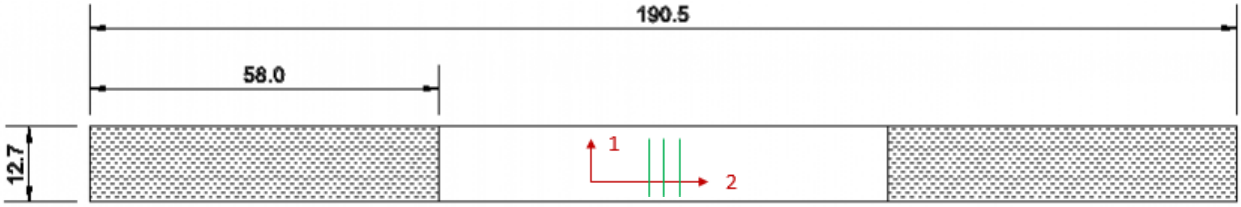


Figure 11.—Typical 90-degree tension specimen geometry and layout (dimensions in mm).

TABLE 9.—2-DIRECTION TENSION TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate ID	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_T2-1	0.50 (12.7)	0.12 (3.05)	0.06 (38.70)
HUDC_T2-2	0.50 (12.7)	0.12 (3.05)	0.059 (38.06)
HUDC_T2-3	0.50 (12.7)	0.12 (3.05)	0.059 (38.06)

TABLE 10.—2-DIRECTION TENSION TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate ID	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_T2-1	0.50 (12.7)	0.082 (2.08)	0.041 (26.45)
TSFC_T2-2	0.50 (12.7)	0.082 (2.08)	0.041 (26.45)
TSFC_T2-4	0.50 (12.7)	0.082 (2.08)	0.041 (26.45)

3.2.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 12 and Figure 13, respectively, for the HUDC material. The specimens exhibited brittle cracking in the matrix near the grip before the tests were terminated and at failure.

Test Results: A summary of results from the tests on the HUDC material is shown in Table 11. Figure 14 shows the individual stress-strain curves for the specimens tested.

Figure 12.—2-direction tension specimens before testing. (a) HUDC_T2-1. (b) HUDC_T2-2. (c) HUDC_T2-3.

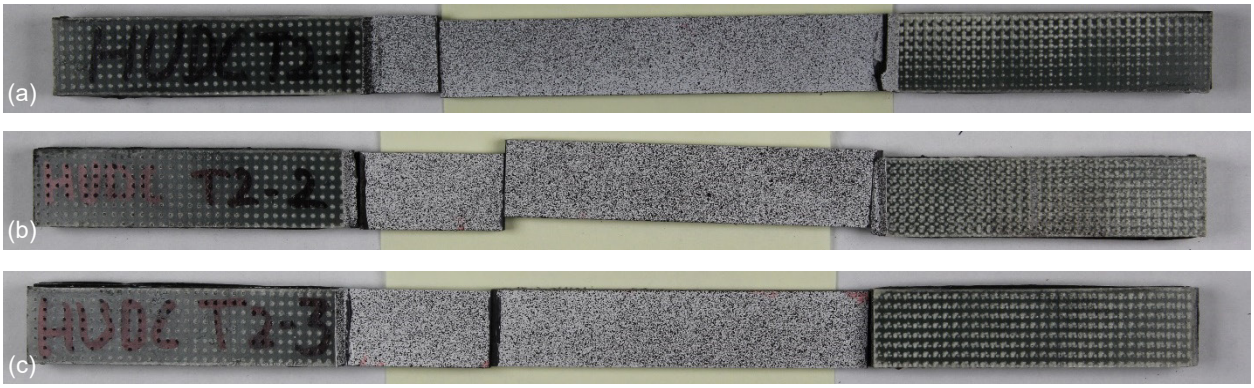


Figure 13.—2-direction tension specimens after testing. (a) HUDC_T2-1. (b) HUDC_T2-2. (c) HUDC_T2-3.

TABLE 11.—SUMMARY OF 2-DIRECTION TENSION TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{22}, psi	Poisson's ratio, ν_{21}	Ultimate strain	Peak stress, psi
HUDC_T2-1	0.0025	1.08×10^{-5}	1,345,291	0.0303	0.0108	12,987
HUDC_T2-2	0.0025	1.09×10^{-5}	1,315,670	0.0297	0.0100	12,306
HUDC_T2-3	0.0025	1.11×10^{-5}	1,297,098	0.0268	0.0105	12,554
Average	-------	1.09×10^{-5}	1,319,353	0.0289	0.0105	12,616
Standard deviation	-------	1.50×10^{-7}	24,307	0.0019	0.00040	345
Coefficient of variation	-------	1.4%	1.8%	6.5%	3.9%	2.7%

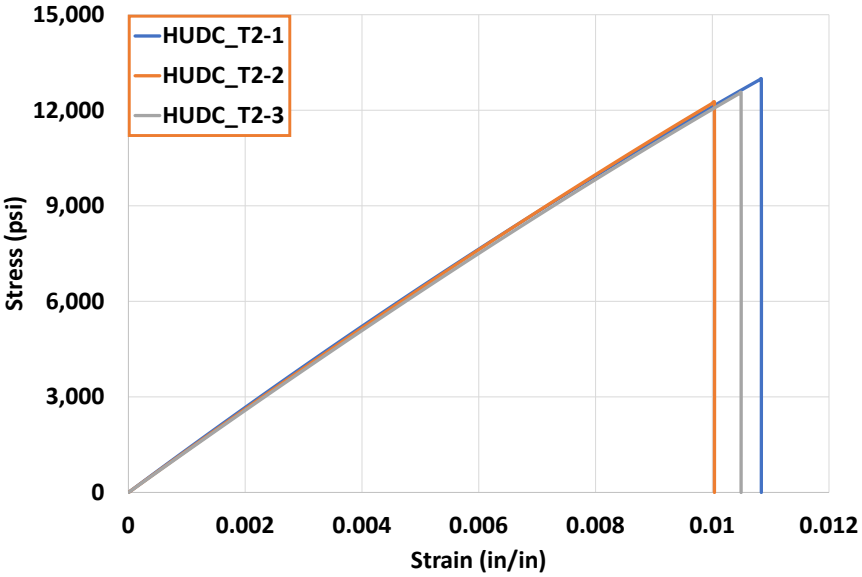


Figure 14.—2-direction tension stress-strain curves for HUDC material.

3.2.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 15 and Figure 16, respectively, for the TSFC material. The specimens exhibited brittle cracking in the matrix near the grip before the tests were terminated and at failure.

Test Results: A summary of results from the tests on the TSFC material is shown in Table 12. Figure 17 shows the individual stress-strain curves for the specimens tested.

Figure 15.—2-direction tension specimens before testing. (a) TSFC_T2-1. (b) TSFC_T2-2. (c) TSFC_T2-4.

Figure 16.—2-direction tension specimens after testing. (a) TSFC_T2-1. (b) TSFC_T2-2. (c) TSFC_T2-4.

TABLE 12.—SUMMARY OF 2-DIRECTION TENSION TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{22}, psi	Poisson's ratio, ν_{21}	Ultimate strain	Peak stress, psi
TSFC_T2-1	0.0025	1.11×10^{-5}	1,386,757	0.0319	0.0152	16,061
TSFC_T2-2	0.0025	1.22×10^{-5}	1,364,836	0.0346	0.0166	16,288
TSFC_T2-4	0.0025	1.24×10^{-5}	1,305,351	0.0267	0.0166	16,204
Average	-------	1.19×10^{-5}	1,352,315	0.0311	0.0161	16,184
Standard deviation	-------	7.00×10^{-7}	42,123	0.0040	0.00080	115
Coefficient of variation	-------	5.9%	3.1%	12.9%	5.0%	0.7%

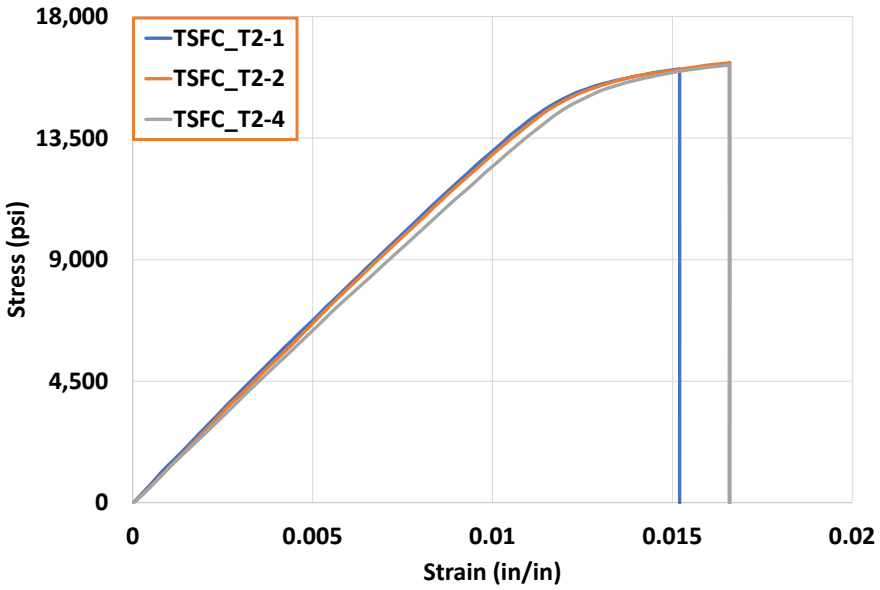


Figure 17.—2-direction tension stress-strain curves for TSFC material.

3.3 Test T3: Out-of-Plane Tension Test

Experimental Setup: The experimental procedure was performed using an MTS Exceed® test frame (Figure 2(j)). The specimens are held in the frame with spring-loaded grips (Figure 2(k)). Only the fiberglass tab layup is held by the spring-loaded grips. The region of the specimens bonded to the tabs is kept outside of the grips to minimize stress concentrations. This test is used to generate the tension stress-strain curve in the through-thickness or 3-direction.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 18. The ASTM standard could not be followed when creating the specimens because the specimen geometry is dictated by the thickness of the test panel. Two principal planes, 1-3 and 2-3, are considered when gathering strain data during this test. The average specimen dimensions of HUDC and TSFC materials in the gage section are shown in Table 13 and Table 14, respectively, for the three tested replicates.

Specimen Preparation: The maximum length of the specimen is dictated by the thickness of the 123-ply panel for HUDC and the 180-ply panel for TSFC. A specimen must be long enough to be properly secured in the hydraulic grips. Three layers of fiberglass tabs were used to create a pocket where the specimen could be inserted. A notch with the same width and thickness as the specimen was cut out of the middle layer of the fiberglass layup. Figure 19 shows a rendering of the fiberglass tabbing system. Approximately one-third of either end of the specimen was then placed inside the pocket and bonded to the fiberglass tabs using 3M® DP460 Scotch-Weld® toughened two-part epoxy.

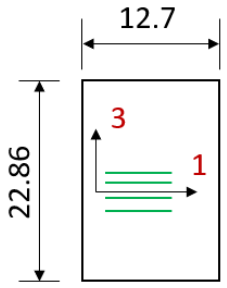


Figure 18.—Typical specimen geometry and layout (dimensions in mm).

TABLE 13.—3-DIRECTION TENSION TEST
SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_T13-3	0.50 (12.7)	0.060 (1.52)	0.030 (19.35)
HUDC_T13-4	0.50 (12.7)	0.058 (1.47)	0.029 (18.71)
HUDC_T13-6	0.50 (12.7)	0.062 (1.57)	0.031 (20.00)
HUDC_T23-1	0.51 (12.9)	0.060 (1.52)	0.030 (19.35)

TABLE 14.—3-DIRECTION TENSION TEST SPECIMEN
DIMENSIONS FOR TSFC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_T13-2	0.51 (12.8)	0.061 (1.55)	0.031 (19.80)
TSFC_T13-3	0.51 (12.8)	0.061 (1.54)	0.031 (19.80)
TSFC_T13-4	0.50 (12.8)	0.061 (1.54)	0.031 (19.70)
TSFC_T23-1	0.50 (12.8)	0.061 (1.52)	0.030 (19.35)

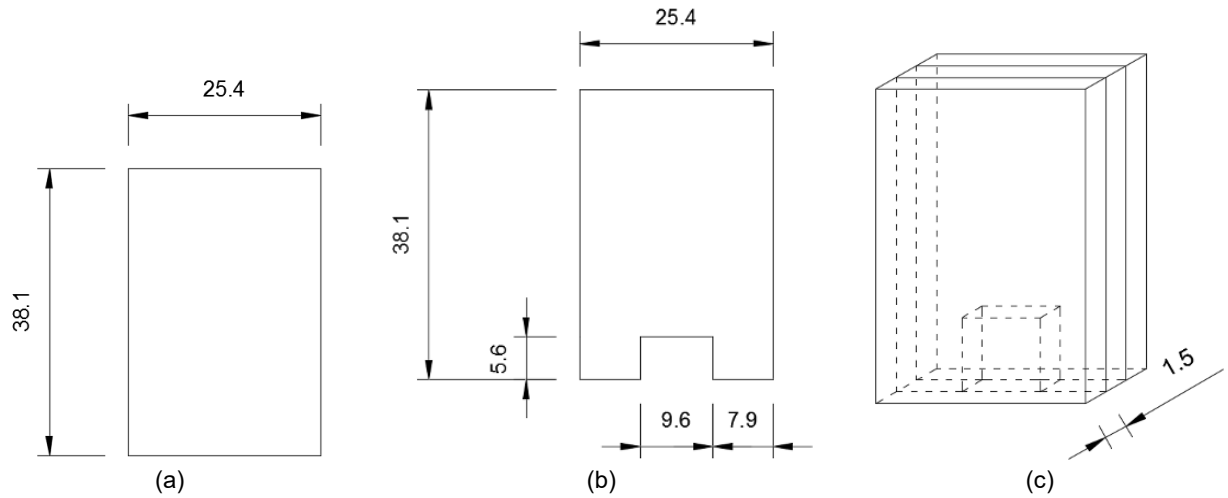


Figure 19.—Fiberglass tab layup geometry. (a) Outer layers. (b) Center layer. (c) Overall layup (dimensions in mm).

3.3.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 20 and Figure 21, respectively, for the HUDC material.

Test Results: A summary of results from the tests on the HUDC material is shown in Table 15. Figure 22 shows the individual stress-strain curves for the specimens. Three samples in Table 15 refer to samples tested in the 13 plane and 1 sample in the 23 plane. The last sample shows that the material is not transversely isotropic.

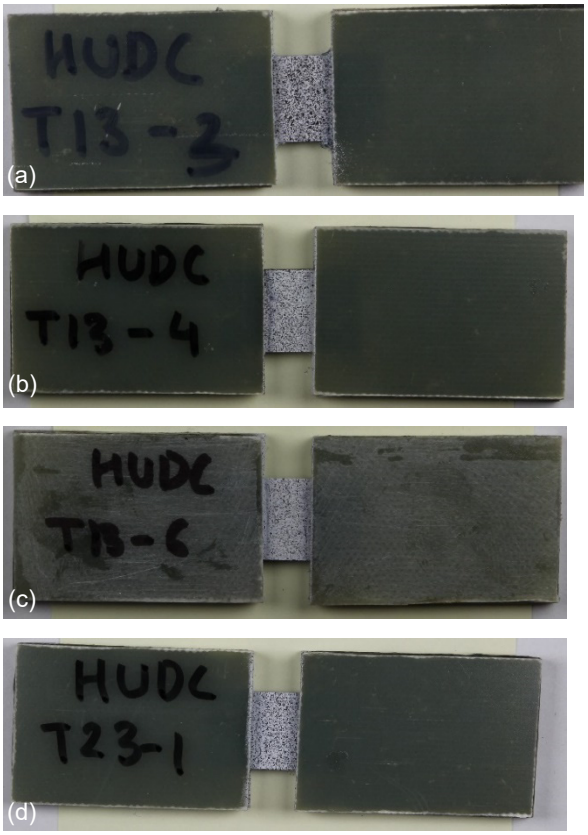


Figure 20.—3-direction tension specimens prior to testing. (a) HUDC_T13-3. (b) HUDC_T13-4. (c) HUDC_T13-6. (d) HUDC_T23-1.

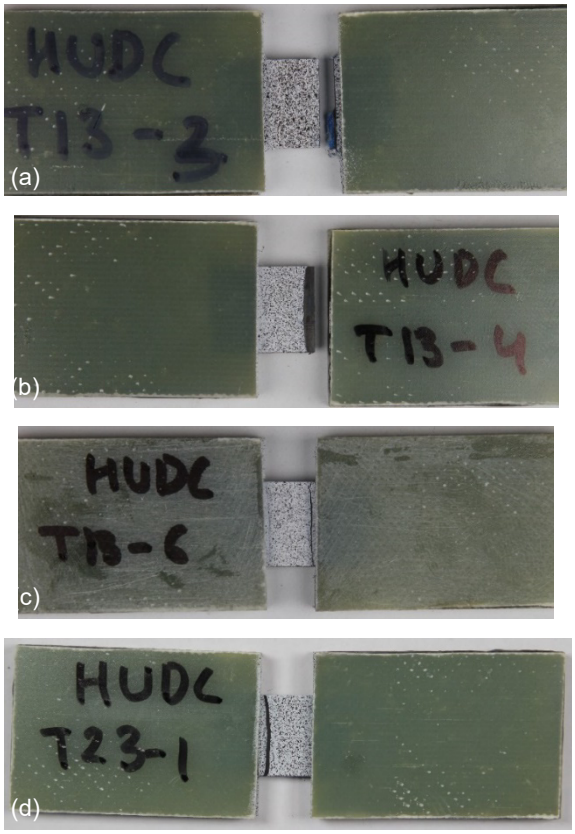


Figure 21.—3-direction tension specimens after testing. (a) HUDC_T13-3. (b) HUDCT13-4. (c) HUDC_T13-6. (d) HUDC_T23-1.

TABLE 15.—SUMMARY OF 3-DIRECTION TENSION TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{33}, psi	Poisson's ratio, ν_{31}	Poisson's ratio, ν_{32}	Failure strain	Peak stress, psi
HUDC_T13-3	0.001	2.39×10^{-6}	1,325,621	0.0153	-------	0.00490	6,588
HUDC_T13-4	0.001	1.50×10^{-6}	1,389,961	0.0218	-------	0.00542	6,768
HUDC_T13-6	0.001	2.29×10^{-6}	1,185,752	0.0195	-------	0.00548	5,815
HUDC_T23-1	0.001	1.87×10^{-6}	1,206,023	-------	0.3476	0.00451	4,918
Average	-------	0	1,300,445	0.019		0.00527	6,390
Standard deviation	-------	0	85,248	0.003		0.00026	413
Coefficient of variation	-------	19.3%	6.6%	14.3%		4.9%	6.5%

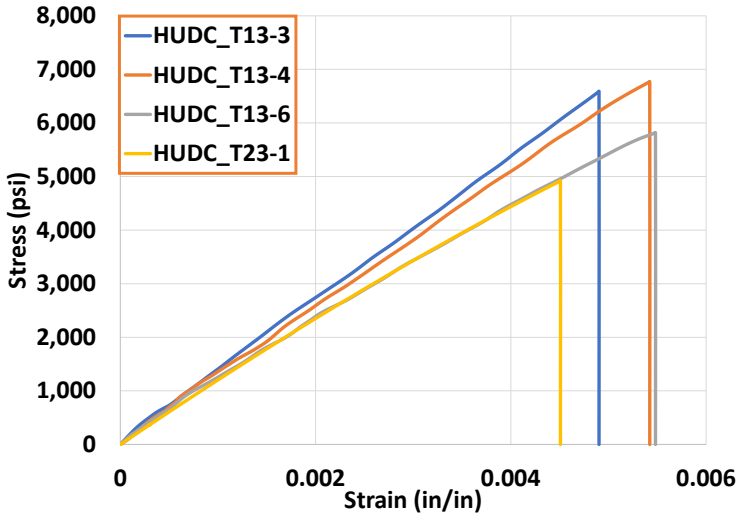


Figure 22.—3-direction tension stress-strain curves for HUDC material.

3.3.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 23 and Figure 24, respectively, for the TSFC material.

Test Results: A summary of results from the tests on the TSFC material is shown in Table 16. Figure 25 shows the individual stress-strain curves for the specimens. Three samples in Table 16 refer to samples tested in the 13 plane and 1 sample in the 23 plane. The last sample shows that the material is not transversely isotropic.

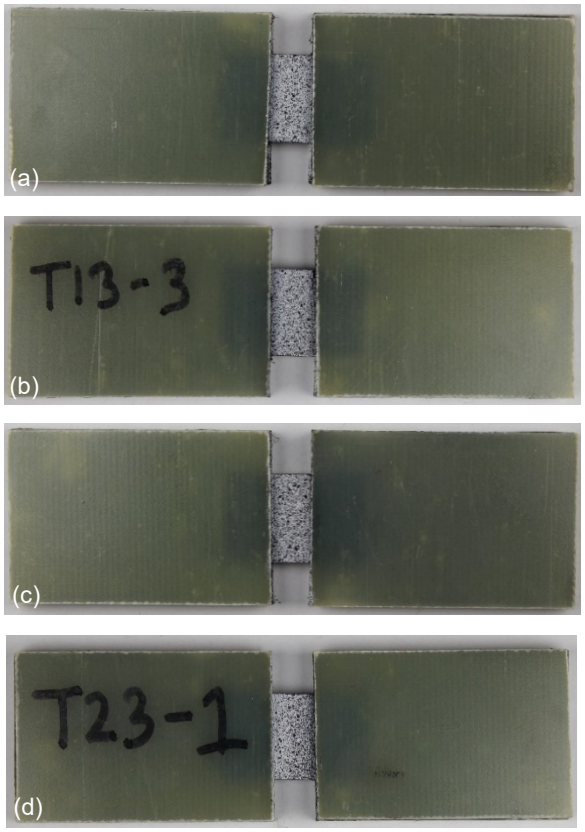


Figure 23.—3-direction tension specimens prior to testing. (a) TSFC_T13-2. (b) TSFC_T13-3. (c) TSFC_T13-4. (d) TSFC_T23-1.

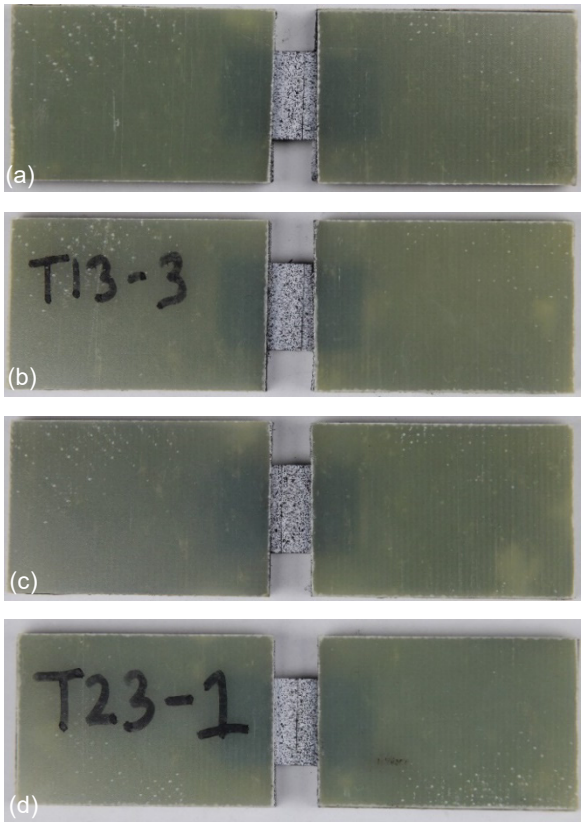


Figure 24.—3-direction tension specimens after testing. (a) TSFC_T13-2. (b) TSFCT13-3. (c) TSFC_T13-4. (d) TSFC_T23-1.

TABLE 16.—SUMMARY OF 3-DIRECTION TENSION TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{33}, psi	Poisson's ratio, ν_{31}	Poisson's ratio, ν_{32}	Failure strain	Peak stress, psi
TSFC_T13-2	0.001	1.71×10^{-6}	1,222,254	0.0127	-------	0.00360	4,104
TSFC_T13-3	0.001	1.84×10^{-6}	1,157,740	0.0178	-------	0.00389	4,359
TSFC_T13-4	0.001	1.81×10^{-6}	1,217,841	-------	-------	0.00383	3,679
TSFC_T23-1	0.001	1.74×10^{-6}	1,609,383	-------	0.4092	0.00392	4,141
Average	-------	1.79×10^{-6}	1,199,278	0.015		0.00377	4,047
Standard deviation	-------	5.56×10^{-8}	29,427	0.003		0.00013	281
Coefficient of variation	-------	3.1%	2.5%	16.7%		3.3%	6.9%

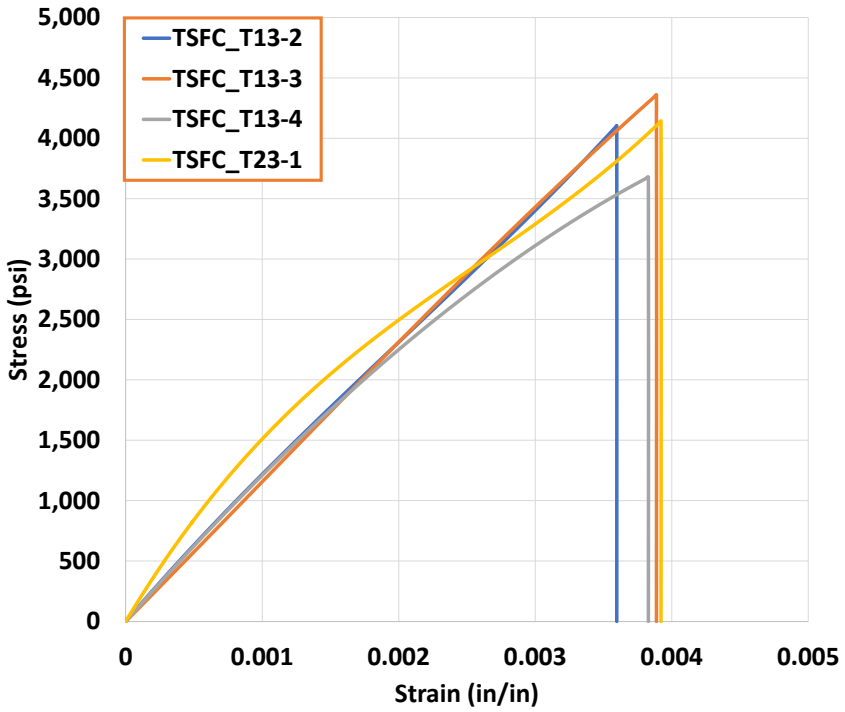


Figure 25.—3-direction tension stress-strain curves for TSFC material.

3.4 Test T4: In-Plane 0° Compression Test

Experimental Setup: This test is used to generate the compressive stress-strain curve in the 1-direction. An Instron 1332 test frame (Figure 2(i)) was used to perform the 1-direction compression test.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 26. The geometry shown is in accordance with the guidelines set forth by ASTM D6641, Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials Using a CLC Test Fixture (Ref. 11). The average specimen dimensions in the gage section are shown Table 17 and Table 18 for the three tested replicates.

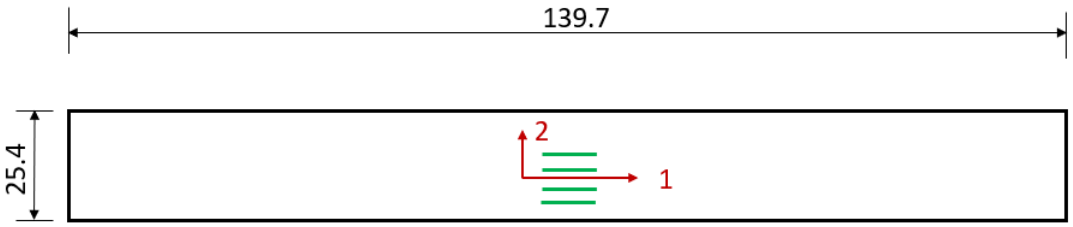


Figure 26.—Typical compression specimen geometry and layout (dimensions in mm).

TABLE 17.—1-DIRECTION COMPRESSION TEST
SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate ID	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_C1-1	1.00 (25.4)	0.12 (3.05)	0.12 (77.42)
HUDC_C1-2	1.00 (25.4)	0.12 (3.05)	0.12 (77.42)
HUDC_C1-3	1.00 (25.4)	0.12 (3.05)	0.12 (77.42)

TABLE 18.—1-DIRECTION COMPRESSION TEST
SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate ID	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_C1-1	1.00 (25.4)	0.08 (2.03)	0.08 (51.61)
TSFC_C1-2	1.00 (25.4)	0.08 (2.03)	0.08 (51.61)
TSFC_C1-3	1.00 (25.4)	0.08 (2.03)	0.08 (51.61)

3.4.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 27 and Figure 28, respectively, for the HUDC material.

Test Results: A summary of results from the tests on the HUDC material is shown in Table 19. Figure 29 shows the stress-strain curves of the specimens tested up until failure by end-crushing.

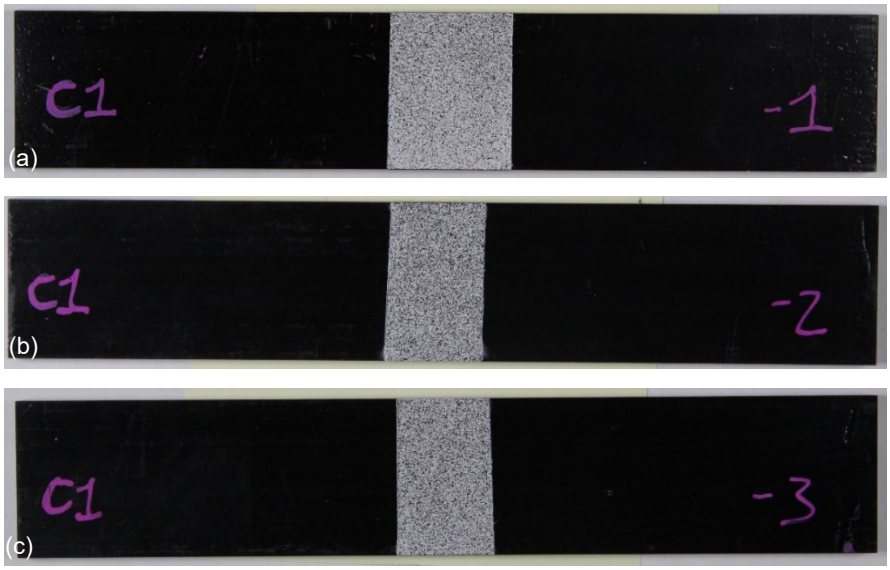


Figure 27.—1-direction compression specimens before testing. (a) HUDC_C1-1. (b) HUDC_C1-2. (c) HUDC_C1-3.

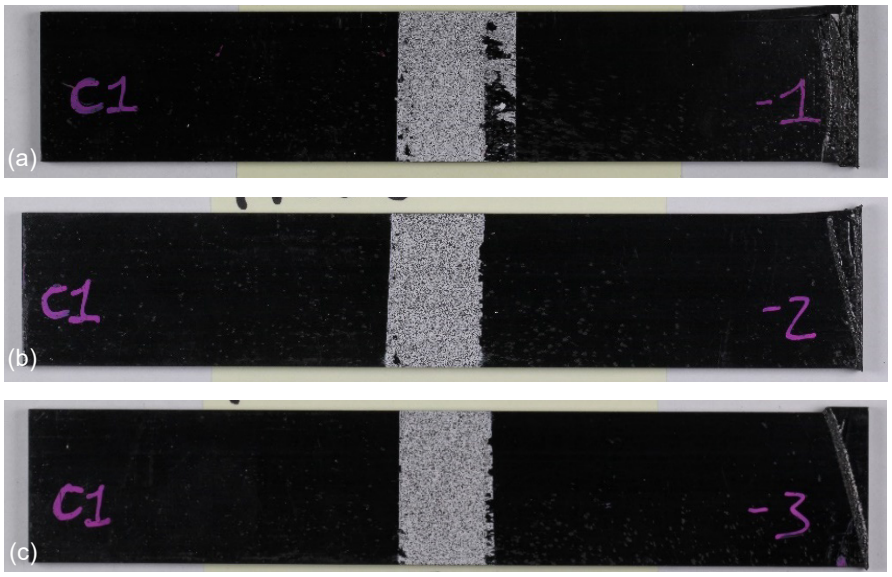


Figure 28.—1-direction compression specimens after testing (a) HUDCC1-1. (b) HUDCC1-2. (c) HUDCC1-3.

TABLE 19.—SUMMARY OF 1-DIRECTION COMPRESSION TEST RESULTS FOR HUDC

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{11}, psi	Ultimate strain	Peak stress, psi
HUDC_C1-1	0.01	1.82×10^{-5}	22,237,273	0.0537	116,597
HUDC_C1-2	0.01	1.68×10^{-5}	21,867,899	0.00520	108,218
HUDC_C1-3	0.01	1.78×10^{-5}	21,698,603	0.00550	113,961
Average	-------	1.76×10^{-5}	21,934,592	0.00536	112,925
Standard deviation	-------	7.21×10^{-7}	275,458	0.00015	4,284
Coefficient of variation	-------	4.1%	1.3%	2.7%	3.8%

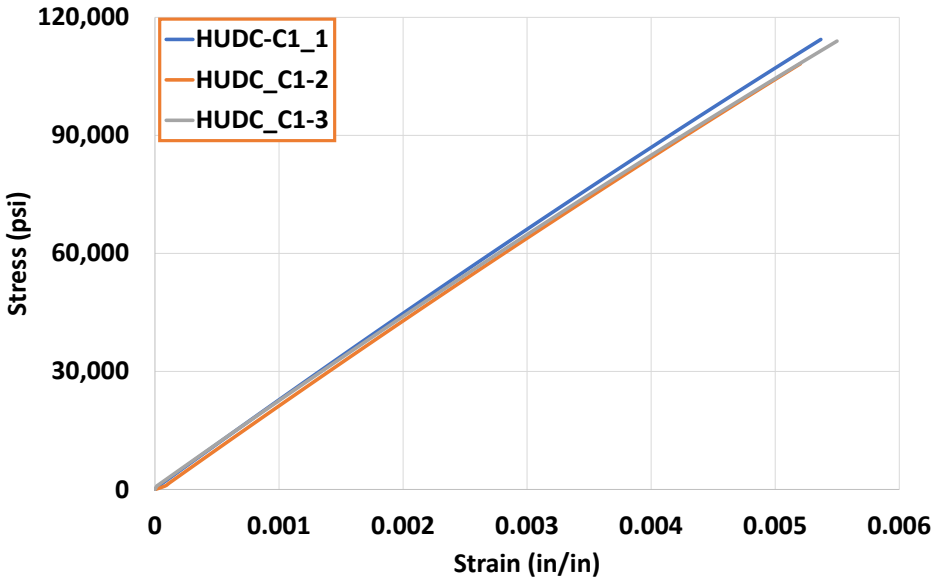


Figure 29.—1-direction compression stress-strain curves for HUDC material.

3.4.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 30 and Figure 31, respectively, for the TSFC material.

Test Results: A summary of results from the tests on the TSFC material is shown in Table 20. Figure 32 shows the stress-strain curves of the specimens tested up until failure by end-crushing.

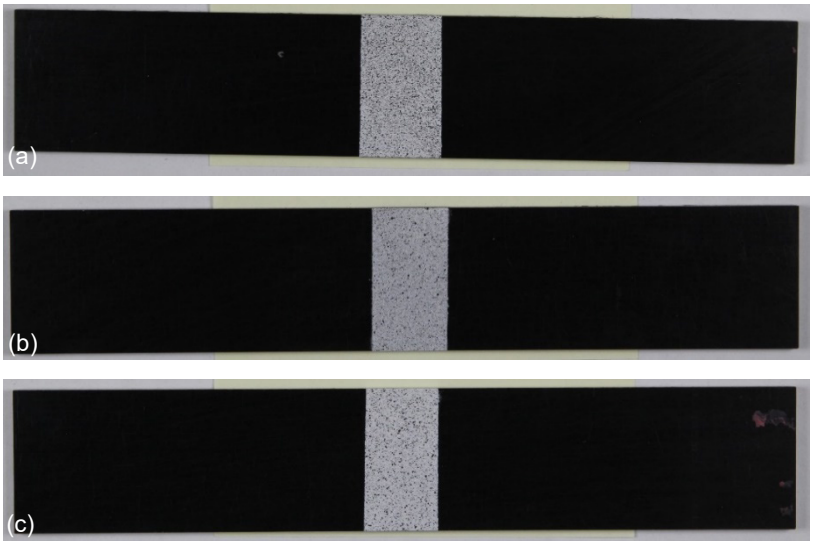


Figure 30.—1-direction compression specimens before testing. (a) TSFC_C1-1. (b) TSFC_C1-2. (c) TSFC_C1-3.

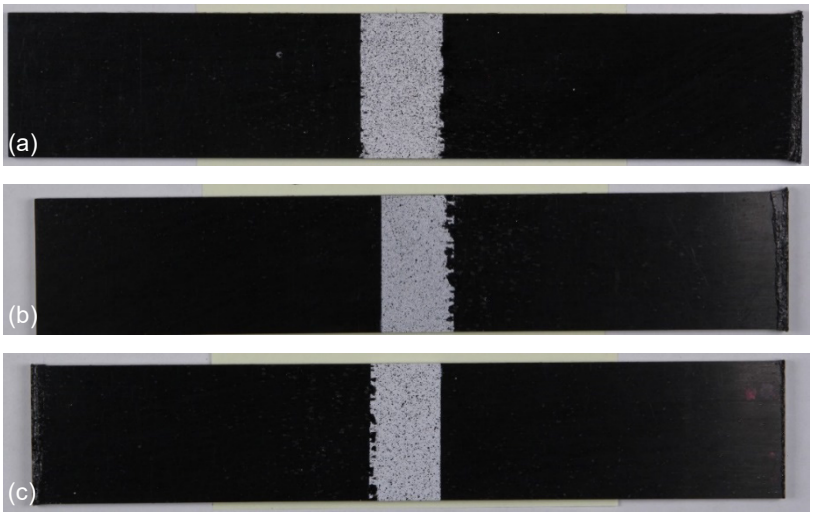


Figure 31.—1-direction compression specimens after testing. (a) TSFC_C1-1. (b) TSFC_C1-2. (c) TSFC_C1-3.

TABLE 20.—SUMMARY OF 1-DIRECTION COMPRESSION TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{11}, psi	Ultimate strain	Peak stress, psi
TSFC_C1-1	0.01	2.09×10^{-5}	19,735,350	0.00703	124,982
TSFC_C1-2	0.01	2.16×10^{-5}	19,299,067	0.00692	123,658
TSFC_C1-3	0.01	2.10×10^{-5}	19,479,077	0.00646	116,092
Average	-------	2.12×10^{-5}	19,504,498	0.00680	121,577
Standard deviation	-------	3.79×10^{-7}	219,250	0.00031	4,756
Coefficient of variation	-------	1.8%	1.1%	4.5%	3.9%

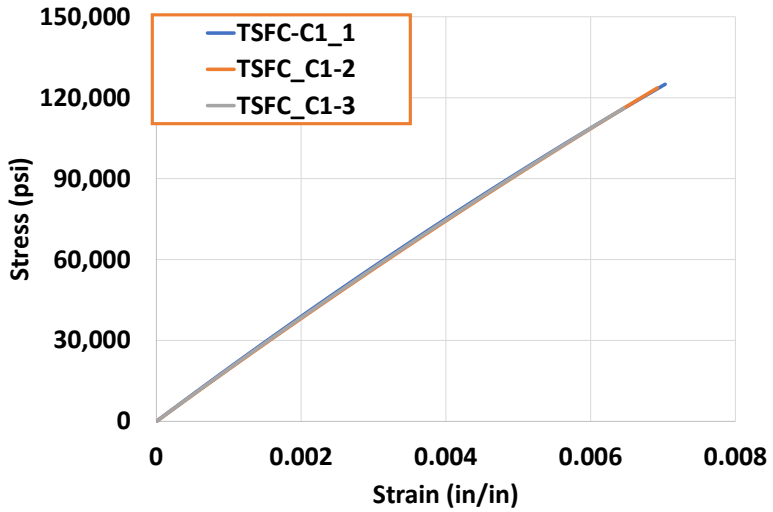


Figure 32.—1-direction compression stress-strain curves for TSFC material.

3.5 Test T5: In-Plane 90° Compression Test

Experimental Setup: This test is used to generate the compressive stress-strain curve in the 2-direction. An MTS® 810 test frame (Figure 2(a)) was used to perform the 2-direction compression test.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 33. The geometry shown is in accordance with the guidelines set forth by ASTM D3410, Standard Test Method for Compressive Properties of Polymer Matrix Composite Materials With Unsupported Gage Section by Shear Loading (Ref. 12). The average specimen dimensions in the gage section are shown in Table 21 and Table 22 for the HUDC and TSFC materials, respectively, for the three tested replicates.

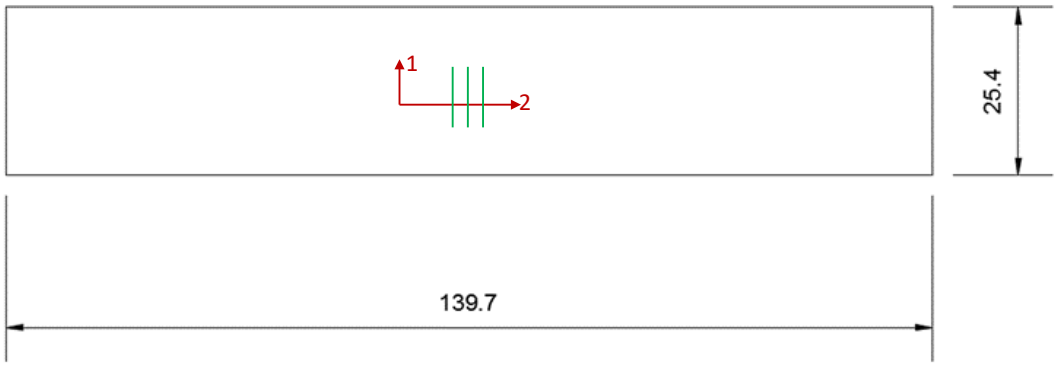


Figure 33.—Typical specimen geometry and layout (all dimensions in mm).

TABLE 21.—2-DIRECTION COMPRESSION TEST
SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_C2-1	1.00 (25.4)	0.12 (3.05)	0.12 (77.42)
HUDC_C2-2	1.00 (25.4)	0.12 (3.05)	0.12 (77.42)
HUDC_C2-3	1.00 (25.4)	0.12 (3.05)	0.12 (77.42)

TABLE 22.—2-DIRECTION COMPRESSION TEST
SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_C2-1	1.00 (25.4)	0.08 (2.03)	0.08 (51.61)
TSFC_C2-2	1.00 (25.4)	0.08 (2.03)	0.08 (51.61)
TSFC_C2-3	1.00 (25.4)	0.08 (2.03)	0.08 (51.61)

3.5.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 34 and Figure 35, respectively, for the HUDC material.

Test Results: A summary of results from the tests on the HUDC material is shown in Table 23. The individual stress-strain curves for the specimens tested is shown in Figure 36. The specimens exhibited crushing of the matrix in the middle of the gage section, identified as the BGM (brooming, gage, middle) mode of failure in the ASTM standard.

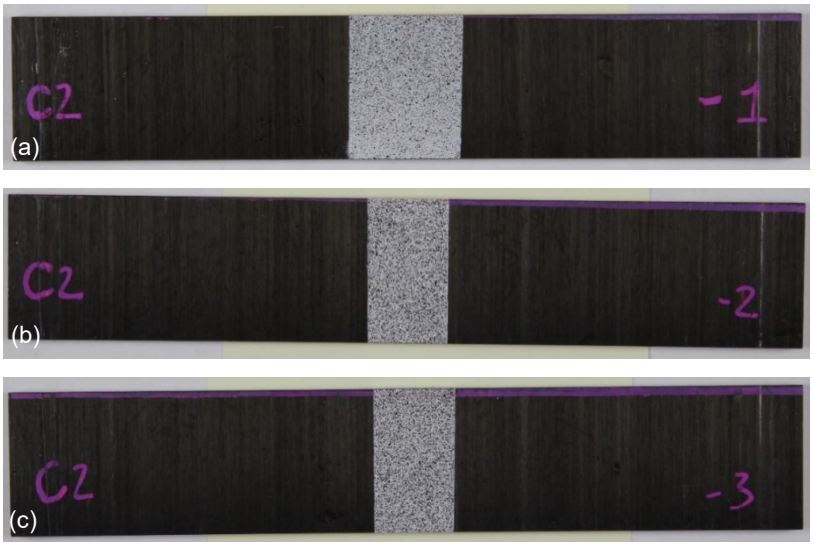


Figure 34.—2-direction compression specimens prior to testing. (a) HUDC_C2-1. (b) HUDC_C2-2. (c) HUDC_C2-3.

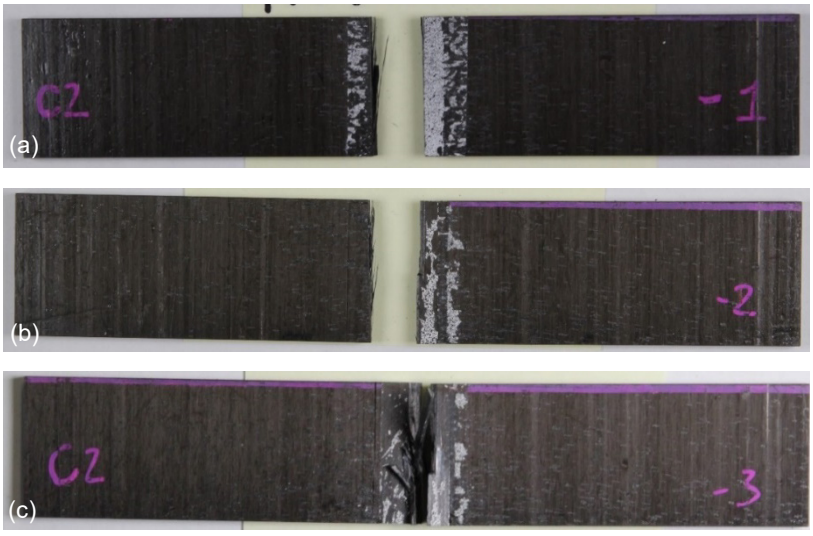


Figure 35.—2-direction compression specimens after testing. (a) HUDC_C2-1. (b) HUDC_C2-2. (c) HUDC_C2-3.

TABLE 23.—SUMMARY OF 2-DIRECTION COMPRESSION TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{22}, psi	Ultimate strain	Peak stress, psi
HUDC_C2-1	0.01	7.93×10^{-5}	1,262,700	0.0606	31,229
HUDC_C2-2	0.01	7.30×10^{-5}	1,247,939	0.0589	31,174
HUDC_C2-3	0.01	6.93×10^{-5}	1,294,459	0.0604	31,909
Average	-----	7.39×10^{-5}	1,268,366	0.0600	31,437
Standard deviation	-----	5.06×10^{-5}	23,772	0.00094	409
Coefficient of variation	-----	6.8%	1.9%	1.6%	1.3%

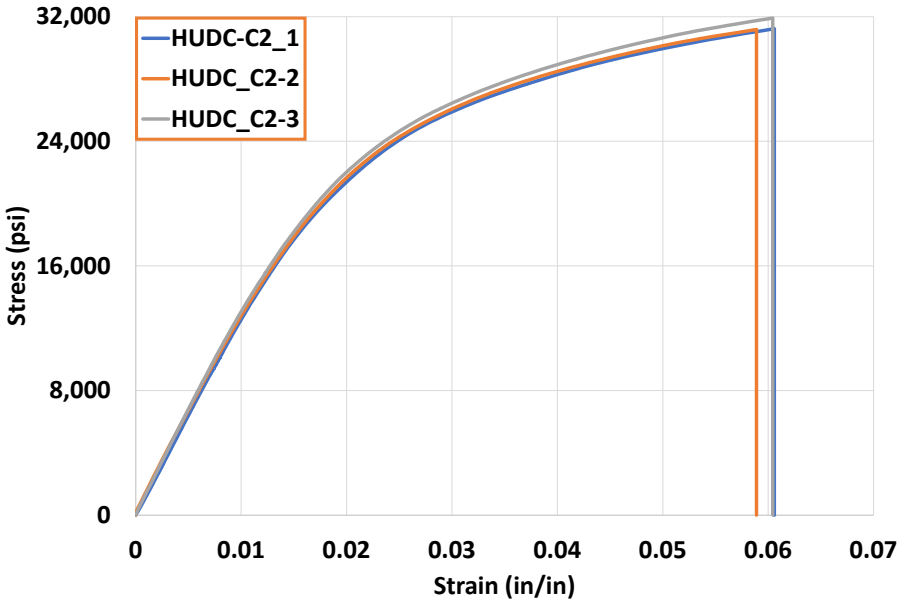


Figure 36.—2-direction compression stress-strain curves for HUDC material.

3.5.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 37 and Figure 38, respectively, for the TSFC material.

Test Results: A summary of results from the tests on the TSFC material is shown in Table 24. The individual stress-strain curves for the specimens are shown in Figure 39. The specimens exhibited crushing of the matrix in the middle of the gage section, identified as the BGM mode of failure in the ASTM standard.

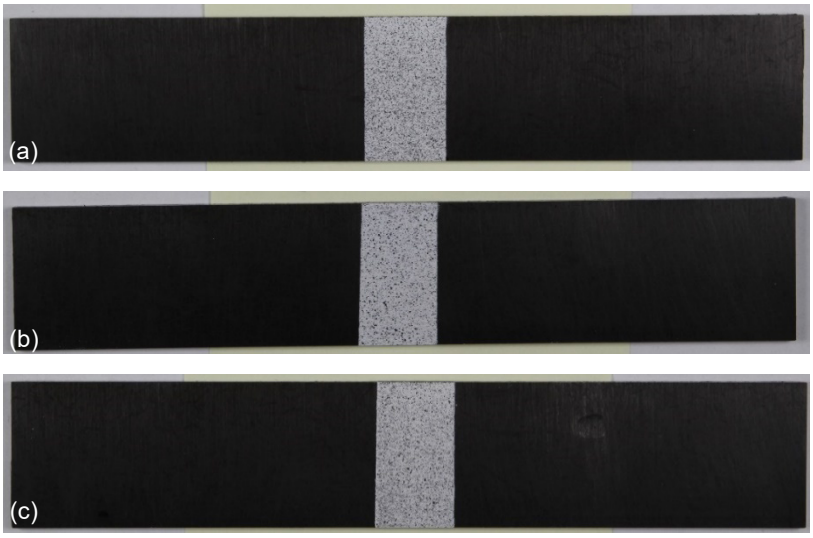


Figure 37.—2-direction compression specimens before testing. (a) TSFC_C2-1. (b) TSFC_C2-2. (c) TSFC_C2-3.

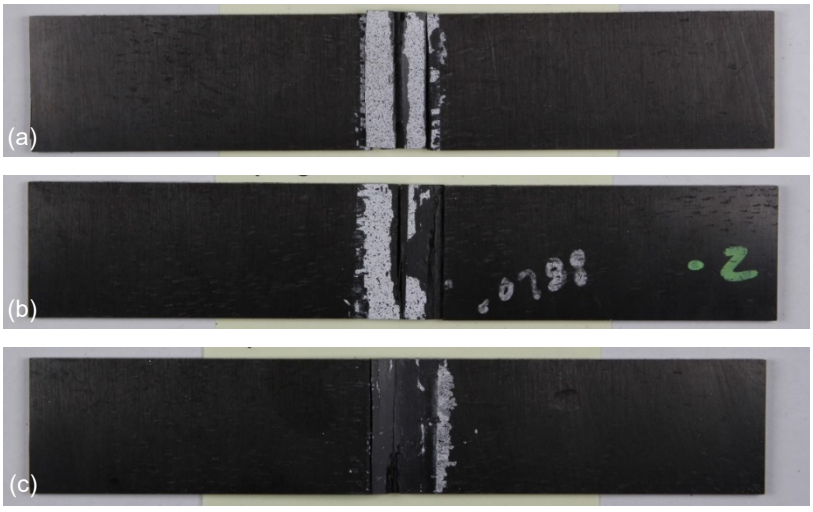


Figure 38.—2-direction compression specimens after testing. (a) TSFC_C2-1. (b) TSFC_C2-2. (c) TSFC_C2-3.

TABLE 24.—SUMMARY OF 2-DIRECTION COMPRESSION TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{22}, psi	Ultimate strain	Peak stress, psi
TSFC_C2-1	0.01	7.53×10^{-5}	1,299,852	0.0979	29,154
TSFC_C2-2	0.01	7.89×10^{-5}	1,311,728	0.0926	28,847
TSFC_C2-3	0.01	8.63×10^{-5}	1,307,045	0.0963	28,970
Average	-----	8.02×10^{-5}	1,306,208	0.0956	28,990
Standard deviation	-----	5.61×10^{-6}	5,982	0.00272	154
Coefficient of variation	-----	7.0%	0.5%	2.8%	0.5%

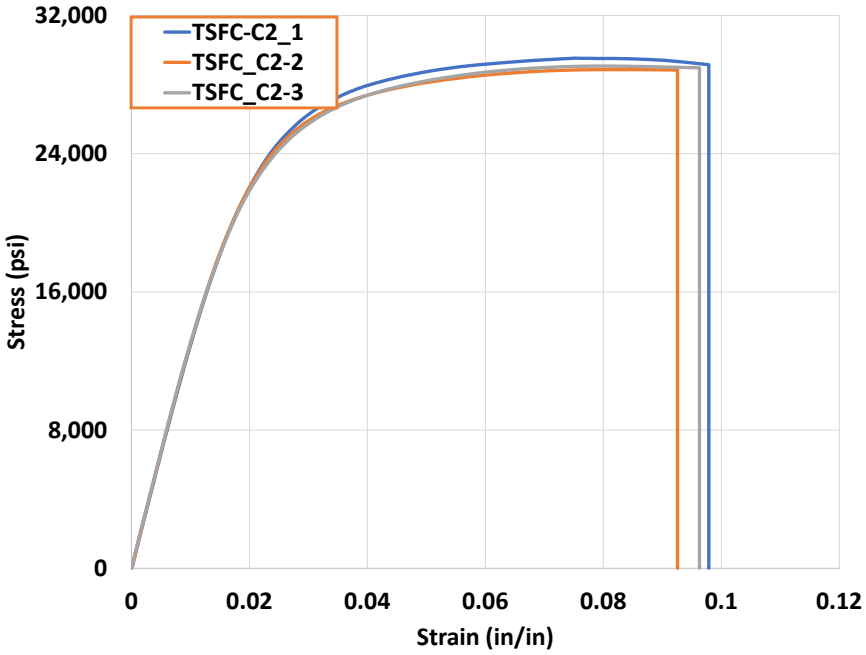


Figure 39.—2-direction compression stress-strain curves for TSFC material.

3.6 Test T6: Out-of-Plane Compression Test

Experimental Setup: This test is used to generate compressive stress-strain curves in the through-thickness or 3-direction. An Instron 1332 test frame (Figure 2(i)) was used to perform the 3-direction compression test.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 40. The geometry shown is a modified version of the geometry set forth by ASTM D7291, Standard Test Method for Through-Thickness "Flatwise" Tensile Strength and Elastic Modulus of a Fiber-Reinforced Polymer Matrix Composite Material (Ref. 13). A cuboid was used in place of a cylindrical specimen for ease of machining and sample preparation. The dimensions of the cuboid are less than the dimensions of the cylinder due to the thickness of the available panel. ASTM D7291 sets guidelines for through-thickness tensile properties. This ASTM document was used because there is no standard available that sets guidelines for obtaining through-thickness compressive properties of fiber-reinforced composites. Only one principal plane, plane 1-3, is considered when gathering strain data during any given test. The average specimen dimensions in the gage section for the three tested replicates for the HUDC and TSFC materials are shown in Table 25 and Table 26, respectively.

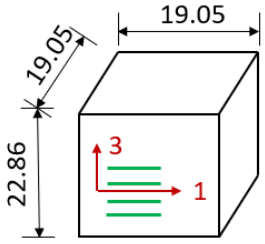


Figure 40.—Typical specimen geometry and layout 1-3 plane speckled (all dimensions in mm).

TABLE 25.—3-DIRECTION COMPRESSION TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_C3-1	0.76 (19.3)	0.76 (19.3)	0.57 (369.63)
HUDC_C3-2	0.76 (19.3)	0.76 (19.3)	0.57 (368.65)
HUDC_C3-3	0.76 (19.3)	0.75 (19.1)	0.57 (367.35)

TABLE 26.—3-DIRECTION COMPRESSION TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_C3-1	0.76 (19.19)	0.76 (19.20)	0.57 (368.6)
TSFC_C3-2	0.75 (19.17)	0.76 (19.19)	0.57 (368.0)
TSFC_C3-3	0.76 (19.19)	0.75 (19.17)	0.57 (368.0)

3.6.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 41 and Figure 42, respectively, for the HUDC material. The specimens exhibited a brittle failure of the matrix in the 1-3 plane before the tests were terminated.

Test Results: A summary of results from the tests on the HUDC material is shown in Table 27. Figure 42 shows the individual stress-strain curves for the specimens.

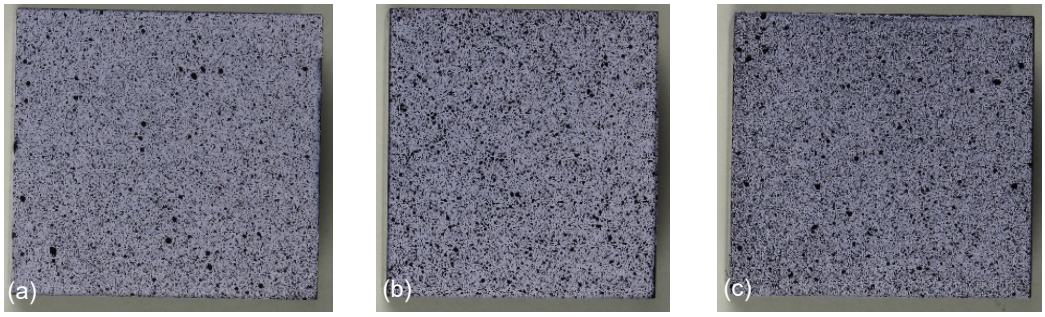


Figure 41.—3-direction compression specimens prior to testing. (a) HUDC_C3-1. (b) HUDC_C3-2. (c) HUDC_C3-3.

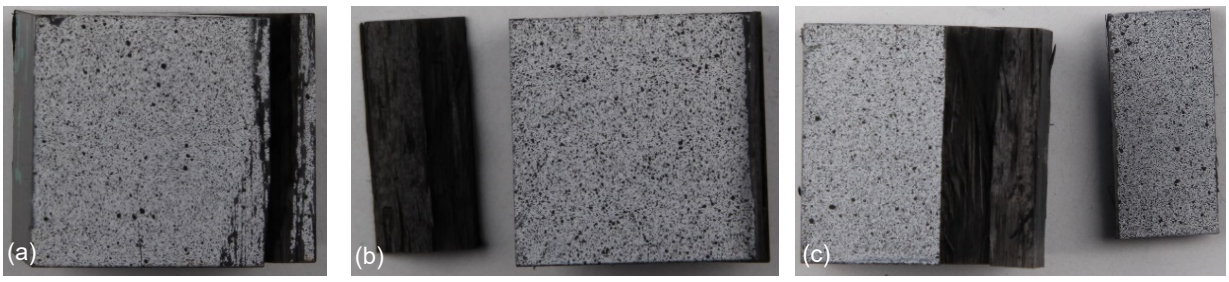


Figure 42.—3-direction compression specimens after testing. (a) HUDC_C3-1. (b) HUDC_C3-2. (c) HUDC_C3-3.

TABLE 27.—SUMMARY OF THE 3-DIRECTION COMPRESSION TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{33}, psi	Ultimate strain	Peak stress, psi
HUDC_C3-1	0.01	8.70×10^{-5}	1,487,975	0.0334	32,367
HUDC_C3-2	0.01	9.36×10^{-5}	1,480,108	0.0336	33,589
HUDC_C3-3	0.01	9.48×10^{-5}	1,479,424	0.0324	32,373
Average	----	9.18×10^{-5}	1,482,502	0.0332	32,776
Standard deviation	----	3.43×10^{-5}	3,880	0.00050	575
Coefficient of variation	----	3.74%	0.26%	1.51%	1.75%

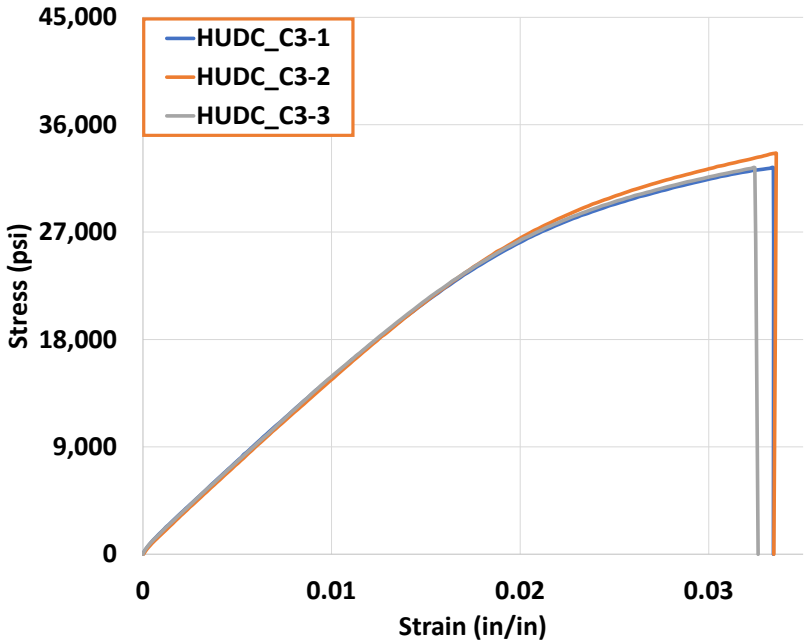


Figure 43.—3-direction compression stress-strain curves for TSFC material.

3.6.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 44 and Figure 45, respectively, for the TSFC material. The specimens exhibited a brittle failure of the matrix in the 1-3 plane before the tests were terminated.

Test Results: A summary of results from the tests on the TSFC material is shown in Table 28. Figure 46 shows the individual stress-strain curves for the specimens.

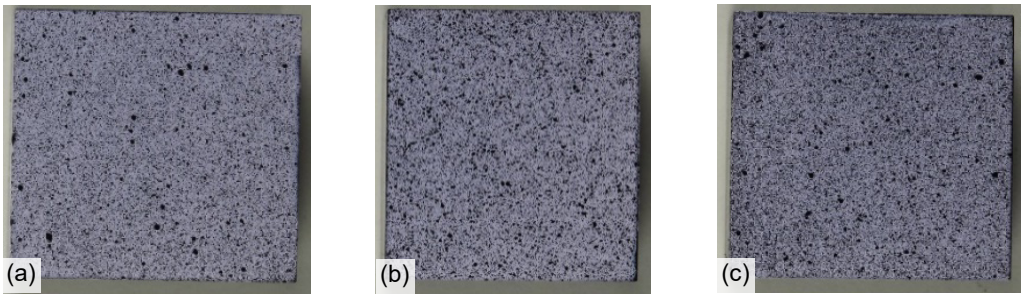


Figure 44.—3-direction compression specimens prior to testing. (a) TSFC_C3-1. (b) TSFC_C3-2. (c)TSFC_C3-3.

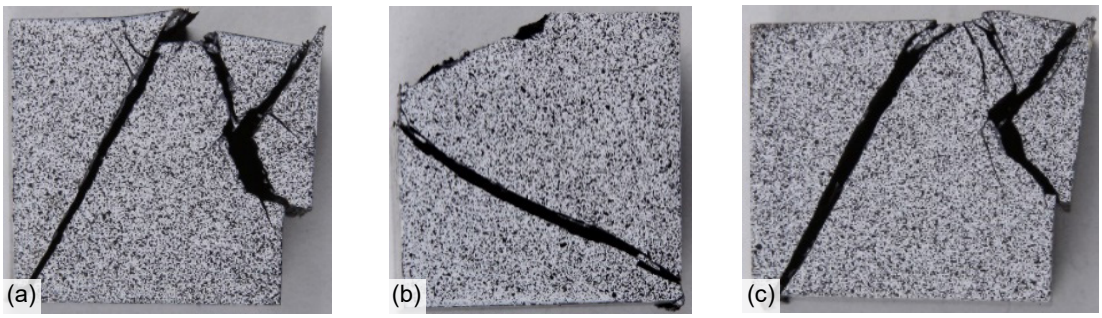


Figure 45.—3-direction compression specimens after testing. (a) TSFC_C3-1. (b) TSFC_C3-2. (c) TSFC_C3-3.

TABLE 28.—SUMMARY OF THE 3-DIRECTION COMPRESSION TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	E_{33}, psi	Ultimate strain	Peak stress, psi
TSFC_C3-1	0.01	1.30×10^{-4}	1,309,427	0.0610	36,678
TSFC_C3-2	0.01	1.31×10^{-4}	1,300,720	0.0623	36,421
TSFC_C3-3	0.01	1.29×10^{-4}	1,310,451	0.0630	36,929
Average	--------	1.30×10^{-4}	1,306,866	0.0623	36,676
Standard deviation	--------	8.16×10^{-7}	4,366	0.0009	207
Coefficient of variation	--------	0.63%	0.33%	1.48%	0.57%

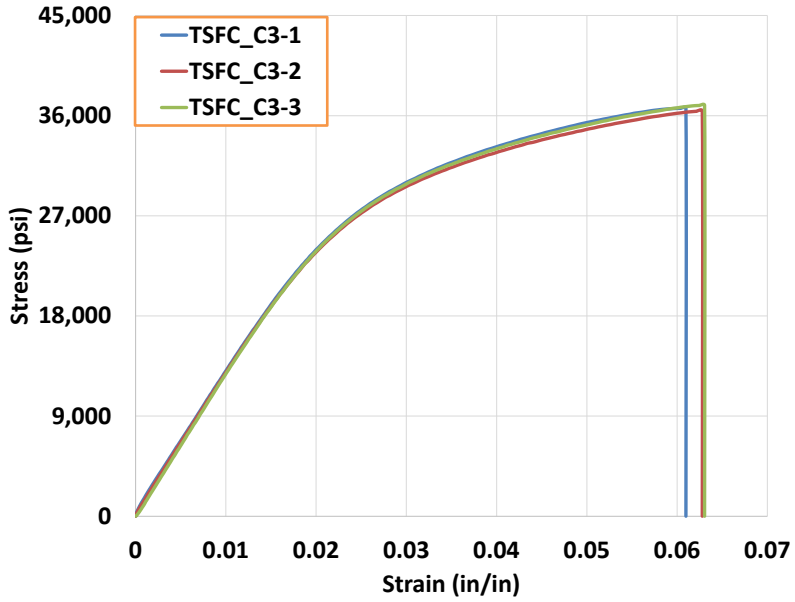


Figure 46.—3-direction compression stress-strain curves for TSFC material.

3.7 Test T7: Shear Test in the 1-2 Plane

Experimental Setup: This test is used to generate the shear stress-strain curve in the 1-2 plane. An MTS® 810 test frame (Figure 2(a)) was used to perform the 1-2 plane shear test.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 47. The geometry shown is in accordance with the guidelines set forth by ASTM D5379/D5379M-12 (Ref. 6). Shaded regions indicate where fiberglass tabs are bonded to the specimen. The average specimen dimensions in the gage section for HUDC and TSFC are shown in Table 29 and Table 30, respectively, for the three tested replicates. The ligament height is defined as the distance between the notches. Figure 48 and Figure 49 show the modes of failure observed in the shear specimens, which are like those deemed acceptable by the ASTM standard.

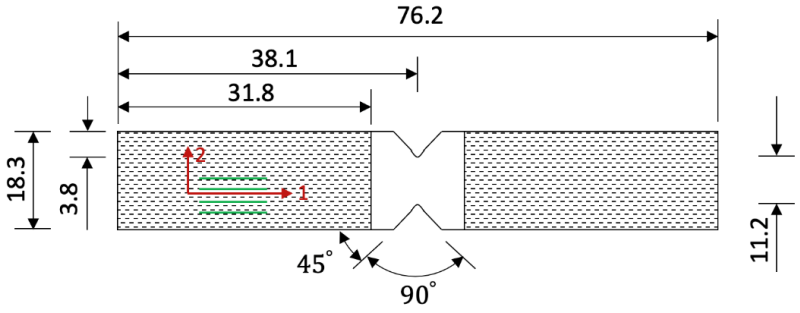


Figure 47.—Typical v-notch shear specimen geometry (all dimensions in mm).

TABLE 29.—1-2 PLANE SHEAR TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate	Ligament height, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_S12-1	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)
HUDC_S12-2	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)
HUDC_S12-3	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)

TABLE 30.—1-2 PLANE SHEAR TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate	Ligament height, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_S12-1	0.50 (12.7)	0.08 (2.03)	0.04 (25.81)
TSFC_S12-2	0.50 (12.7)	0.08 (2.03)	0.04 (25.81)
TSFC_S12-3	0.50 (12.7)	0.08 (2.03)	0.04 (25.81)

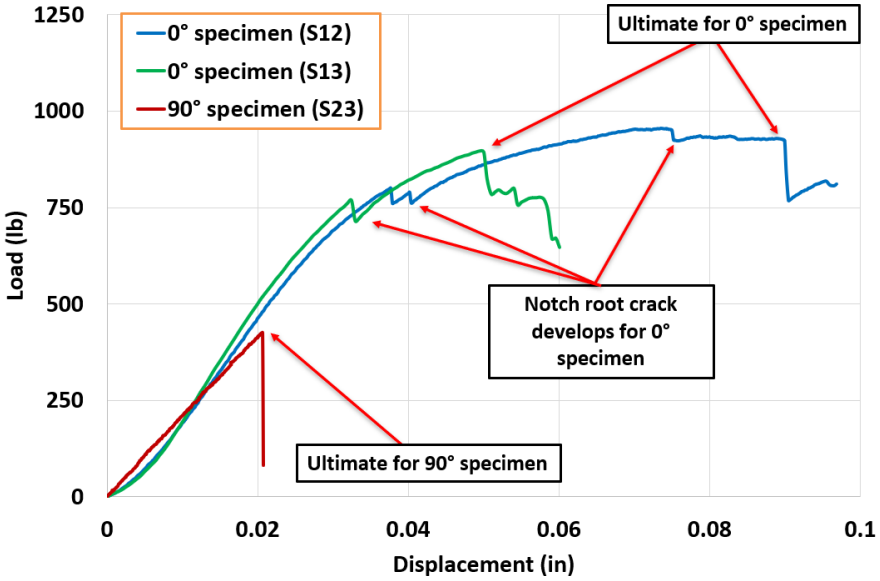


Figure 48.—Common shear failure modes in v-notched shear specimens.

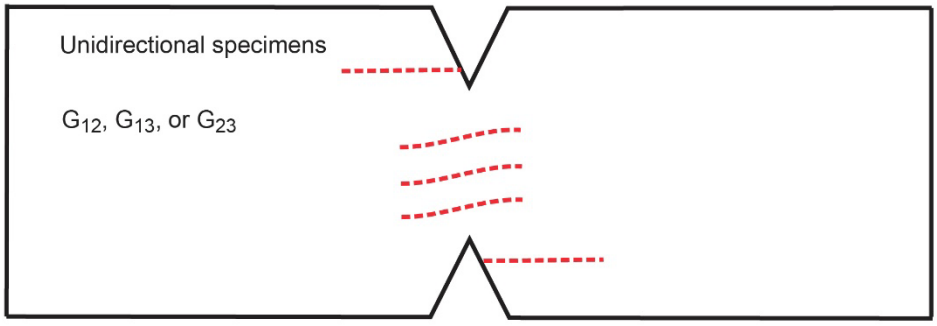


Figure 49.—Horizontal cracking in gage section between notches (HGN) failure mode.

3.7.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 50 and Figure 51, respectively, for the HUDC material. As shown in Figure 49, the specimens exhibited horizontal cracking in the gage section, identified in the ASTM standard as the HGN (horizontal, gage, notch) mode of failure.

Test Results: A summary of results from the tests on the HUDC material is reported in Table 31 with shear modulus in terms of engineering shear strain, not tensorial shear strain. Figure 52 shows the individual stress-strain curves for the specimens. Stress-strain curves were terminated at 0.025 tensorial shear strain. These tests were carried out beyond 0.05 engineering strain but not to failure.

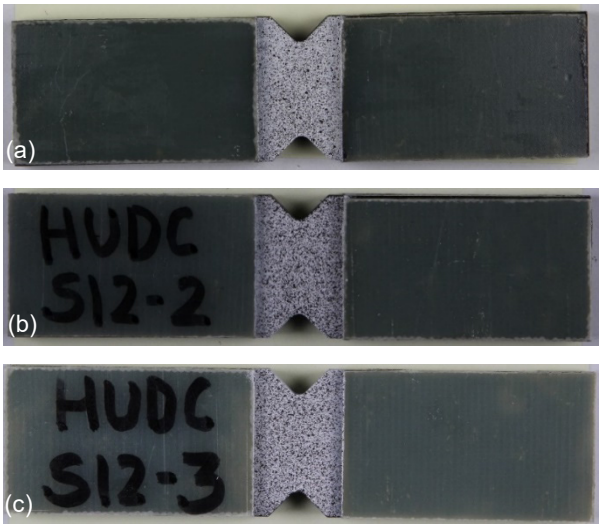


Figure 50.—1-2 plane shear specimens prior to testing. (a) HUDC_S12-1. (b) HUDC_S12-2. (c) HUDC_S12-3.

Figure 51.—1-2 plane shear specimens after testing. (a) HUDC_S12-1. (b) HUDC_S12-2. (c) HUDC_S12-3.

TABLE 31.—SUMMARY OF THE 1-2 PLANE SHEAR TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Engineering strain rate, 1/s	Tensorial strain rate, 1/s	G_{12}, psi	Ultimate strain	Ultimate strain (tensorial)	Peak stress, psi
HUDC_S12-1	0.0025	1.87×10^{-4}	9.53×10^{-5}	891,999	0.05	0.025	12,408
HUDC_S12-2	0.0025	1.70×10^{-4}	8.49×10^{-5}	941,966	0.05	0.025	12,091
HUDC_S12-3	0.0025	1.82×10^{-4}	9.08×10^{-5}	947,714	0.05	0.025	11,788
Average	--------	1.79×10^{-4}	8.97×10^{-5}	927,226	0.05	0.025	12,095
Standard deviation	--------	8.80×10^{-6}	4.40×10^{-6}	30,643	0.00	0.00	310
Coefficient of variation	--------	4.90%	4.90%	3.30%	0.00%	0.00%	2.56%

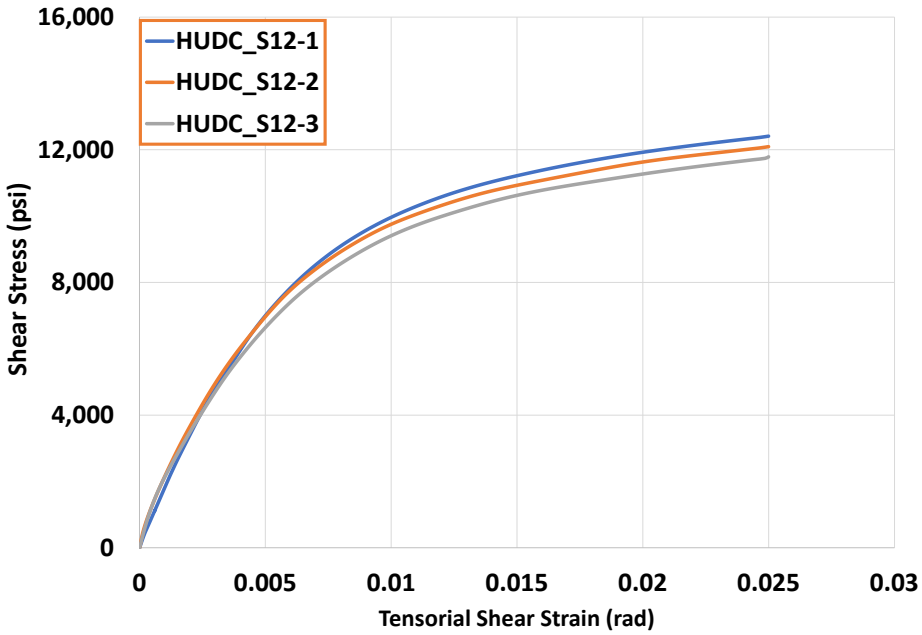


Figure 52.—1-2 plane shear stress-tensorial strain curves for HUDC material.

3.7.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 53 and Figure 54, respectively, for the TSFC material. The specimens exhibited HGN failure, as shown in Figure 49.

Test Results: A summary of results from the tests on the TSFC material is reported in Table 32 with shear modulus in terms of engineering shear strain, not tensorial shear strain. Figure 55 shows the individual stress-strain curves for the specimens. Stress-strain curves were terminated at 0.025 tensorial shear strain. These tests were carried out beyond 0.05 engineering strain but not to failure.

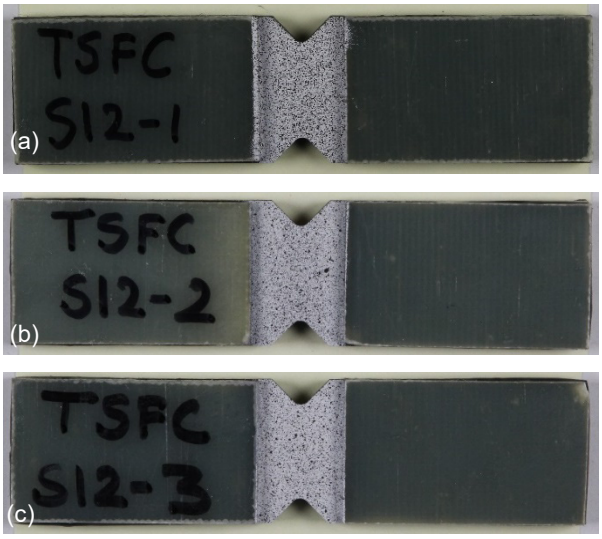


Figure 53.—1-2 plane shear specimens prior to testing. (a) TSFC_S12-1. (b) TSFC_S12-2. (c) TSFC_S12-3.

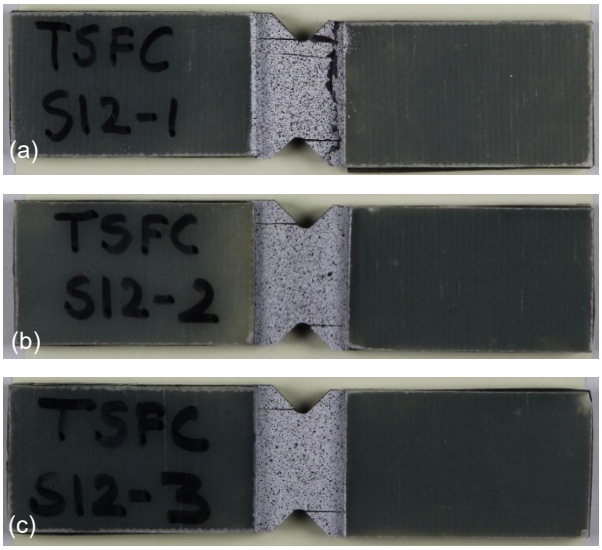


Figure 54.—1-2 plane shear specimens after testing. (a) TSFC_S12-1. (b) TSFC_S12-2. (c) TSFC_S12-3.

TABLE 32.—SUMMARY OF THE 1-2 PLANE SHEAR TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Engineering strain rate, 1/s	Tensorial strain rate, 1/s	G_{12}, psi	Ultimate strain	Ultimate strain (tensorial)	Peak stress, psi
TSFC_S12-1	0.005	1.60×10^{-4}	7.99×10^{-5}	798,804	0.05	0.025	16,246
TSFC_S12-2	0.005	1.62×10^{-4}	8.11×10^{-5}	829,702	0.05	0.025	16,885
TSFC_S12-3	0.005	1.59×10^{-4}	7.94×10^{-5}	779,852	0.05	0.025	17,135
Average	--------	1.60×10^{-4}	8.01×10^{-5}	802,786	0.05	0.025	16,775
Standard deviation	--------	1.75×10^{-6}	8.74×10^{-7}	25,162	0.00	0.00	459
Coefficient of variation	--------	1.09%	1.09%	3.13%	0.00%	0.00%	2.737%

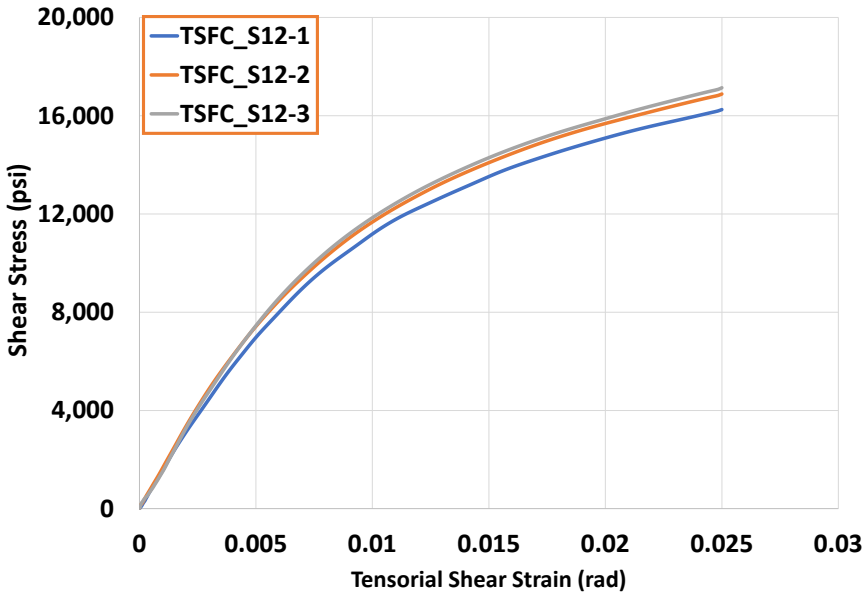


Figure 55.—1-2 plane shear stress-tensorial strain curves for TSFC material.

3.8 Test T8: Shear Test in the 2-3 Plane

Experimental Setup: This test is used to generate the shear stress-strain curve in the 2-3 plane. An MTS® 810 test frame (Figure 2(a)) was used to perform the 2-3 plane shear test.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 56. The geometry shown is in accordance with the guidelines set forth by ASTM D5379/D5379M-12 (Ref. 6). Shaded regions indicate where fiberglass tabs are bonded to the specimen. The average specimen dimensions in the gage section for HUDC and TSFC are shown in Table 33 and Table 34, respectively, for the three tested replicates. The ligament height is defined as the distance between the notches.

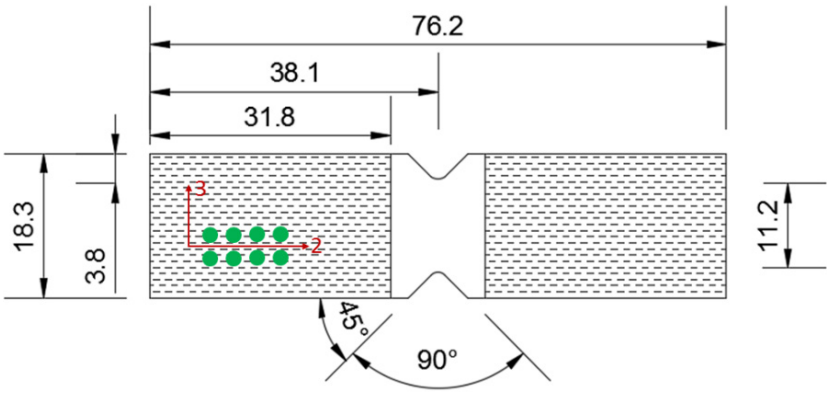


Figure 56.—Typical v-notch shear specimen geometry (all dimensions in mm).

TABLE 33.—2-3 PLANE SHEAR TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_S23-2	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)
HUDC_S23-4	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)
HUDC_S23-6	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)

TABLE 34.—2-3 PLANE SHEAR TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_S23-1	0.495 (12.57)	0.12 (3.03)	0.059 (38.16)
TSFC_S23-3	0.495 (12.56)	0.12 (3.05)	0.059 (38.28)
TSFC_S23-6	0.496 (12.60)	0.12 (3.07)	0.060 (38.66)

3.8.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 57 and Figure 58, respectively, for the HUDC material. The specimens exhibited angled cracking adjacent to the notch region, referred to as failure mode “ANA” (angled, notch region, adjacent to notches) in ASTM Standard D5379 (Ref. 6).

Test Results: A summary of results from the tests on the HUDC material is reported in Table 35 in terms of engineering shear strain. Figure 59 shows the individual stress-strain curves for the specimens.

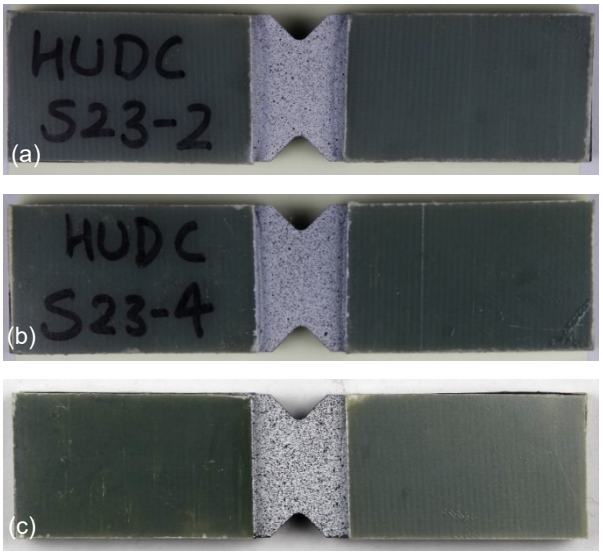


Figure 57.—2-3 plane shear specimens prior to testing. (a) HUDC_S23-2. (b) HUDC_S23-4. (c) HUDCS23-6.

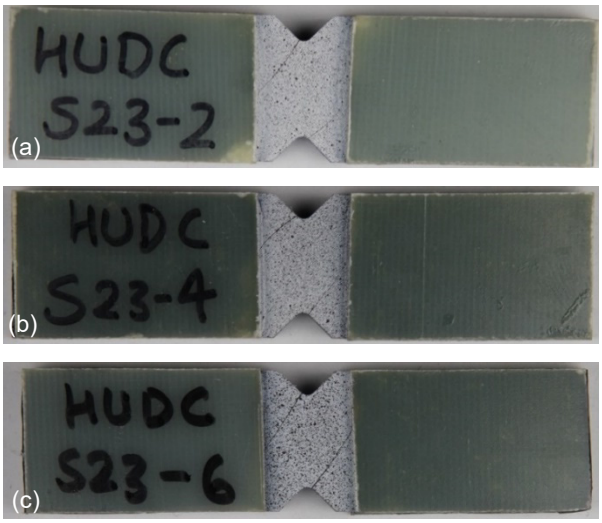


Figure 58.—2-3 plane shear specimens after testing. (a) HUDCS23-2. (b) HUDCS23-4. (c) HUDCS23-6.

TABLE 35.—SUMMARY OF THE 23-PLANE SHEAR TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Engineering strain rate, 1/s	Tensorial strain rate	G_{23}, psi	Ultimate strain	Tensorial ultimate strain	Peak stress, psi
HUDC_S23-2	0.001	5.15×10^{-6}	2.58×10^{-6}	565,648	0.01165	0.00583	7,203
HUDC_S23-4	0.001	7.21×10^{-6}	3.61×10^{-6}	562,318	0.001100	0.00550	6,577
HUDC_S23-6	0.001	6.69×10^{-6}	3.35×10^{-6}	516,672	0.01240	0.00620	7,420
Average	------	6.35×10^{-6}	3.18×10^{-6}	548,212	0.01168	0.00584	7,067
Standard deviation	------	1.07×10^{-6}	5.36×10^{-7}	27,366	0.00070	0.00035	438
Coefficient of variation	------	16.9%	16.9%	5.0%	6.0%	6.0%	6.2%

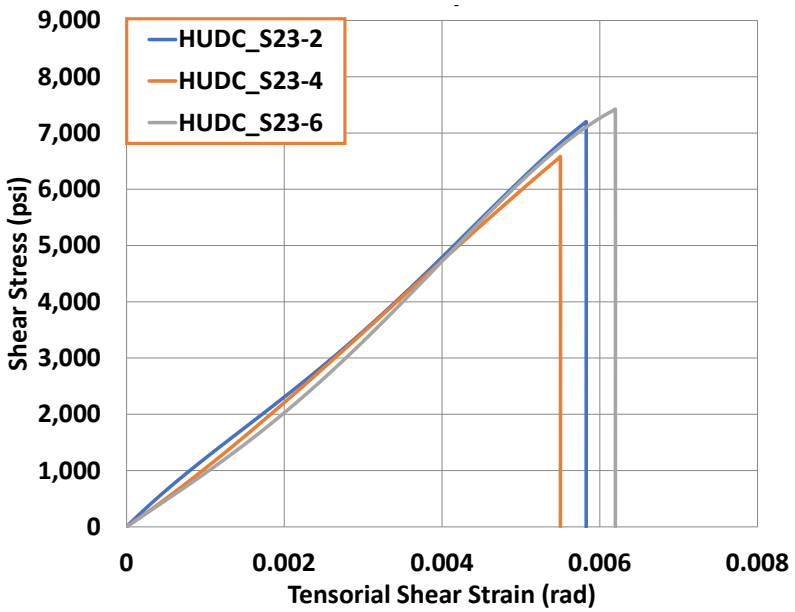


Figure 59.—2-3 plane shear stress-tensorial strain curves for HUDC material.

3.8.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 60 and Figure 61, respectively, for the TSFC material. The specimens exhibited angle cracking adjacent to the notch region (ANA failure mode).

Test Results: A summary of results from the tests on the TSFC material is reported in Table 36 and is in terms of engineering shear strain. Figure 62 shows the individual stress-strain curves for the specimens tested.

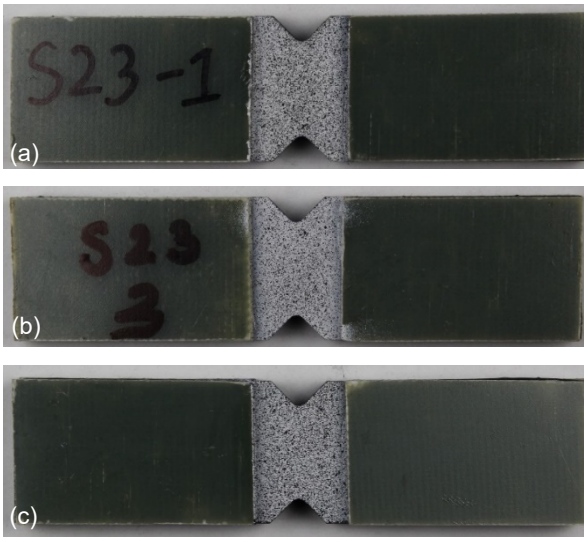


Figure 60.—2-3 plane shear specimens prior to testing. (a) TSFC_S23-1. (b) TSFC_S23-3. (c) TSFC_S23-6.

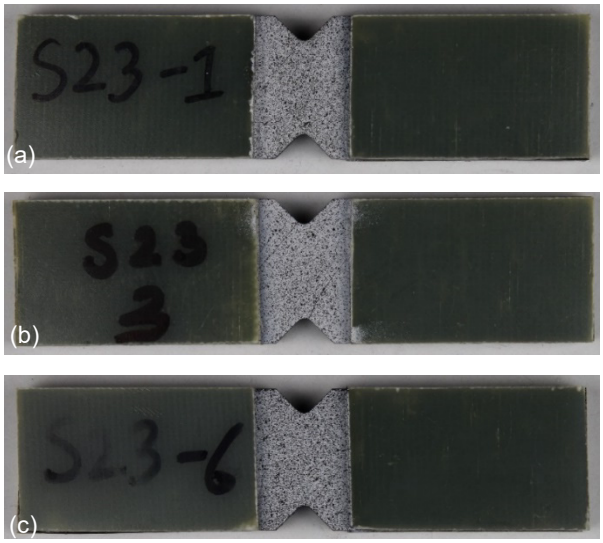


Figure 61.—2-3 plane shear specimens after testing. (a) TSFCS23-1. (b) TSFCS23-3. (c) TSFCS23-6.

TABLE 36.—SUMMARY OF THE 2-3 PLANE SHEAR TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Engineering strain rate, 1/s	Tensorial strain rate	G_{23}, psi	Ultimate strain	Tensorial ultimate strain	Peak stress, psi
TSFC_S23-1	0.001	1.70×10^{-5}	8.50×10^{-6}	699,853	0.00946	0.00473	6,472
TSFC_S23-3	0.001	1.54×10^{-5}	7.70×10^{-6}	792,359	0.01008	0.00504	7,925
TSDC_S23-6	0.001	1.45×10^{-5}	7.25×10^{-6}	749,516	0.00978	0.00489	6,772
Average	-------	1.56×10^{-5}	7.82×10^{-6}	747,243	0.00978	0.00489	7,056
Standard deviation	-------	1.27×10^{-6}	6.33×10^{-7}	46,295	0.00031	0.00016	767
Coefficient of variation	-------	8.1%	8.1%	6.2%	3.2%	3.2%	10.9%

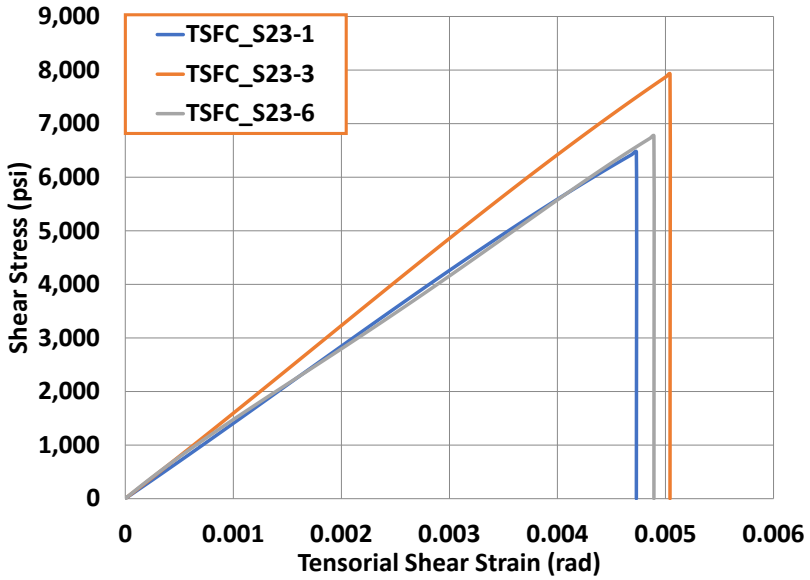


Figure 62.—2-3 plane shear stress-tensorial strain curves for TSFC material.

3.9 Test T9: Shear Test in the 1-3 Plane

Experimental Setup: This test is used to generate the shear stress-strain curve in the 1-3 plane. An MTS® 810 test frame (Figure 2(a)) was used to test 1-3 plane shear specimen.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 63. The geometry shown is in accordance with the guidelines set forth by ASTM D5379/D5379M-12 (Ref. 6). Shaded regions indicate where fiberglass tabs are bonded to the specimen. The average specimen dimensions in the gage section for HUDC and TSFC, respectively, are shown in Table 37 and Table 38 for the three tested replicates. The ligament height is defined as the distance between the notches.

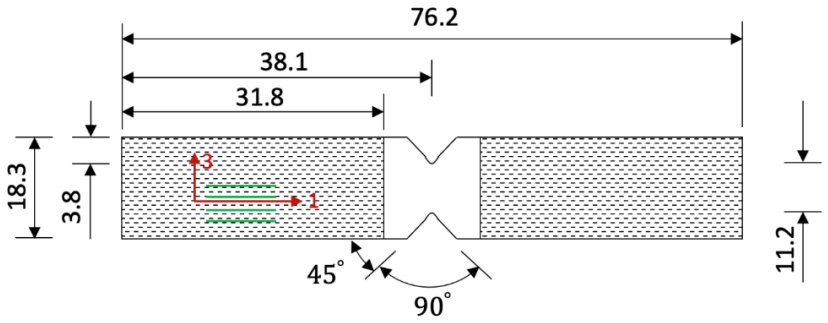


Figure 63.—Typical specimen geometry and layout (dimensions shown in mm).

TABLE 37.—1-3 PLANE SHEAR TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate	Ligament height, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_S13-1	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)
HUDC_S13-2	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)
HUDC_S13-4	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)

TABLE 38.—1-3 PLANE SHEAR TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate	Ligament height, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_S13-1	0.496 (12.6)	0.12 (3.07)	0.060 (38.72)
TSFC_S13-2	0.496 (12.59)	0.12 (3.07)	0.060 (38.54)
TSFC_S13-3	0.496 (12.58)	0.12 (3.06)	0.060 (38.52)

3.9.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 64 and Figure 65, respectively, for the HUDC material.

Test Results: A summary of results from the tests on the HUDC material is reported in Table 39. Shear moduli are shown in terms of engineering shear strain. Figure 66 shows the individual stress-strain curves for the specimens tested. Similar to the shear tests in the 1-2 plane, stress-strain curves were terminated at 0.025 tensorial shear strain. These tests were carried out beyond 0.05 engineering strain but not to failure.

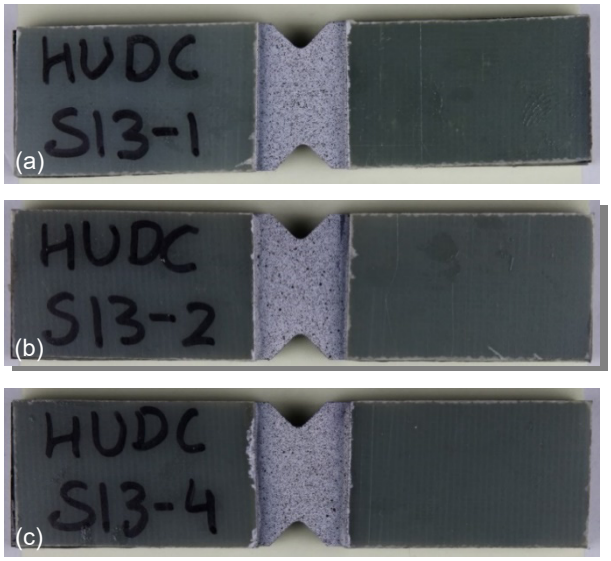


Figure 64.—1-3 plane shear specimens prior to testing. (a) HUDC_S13-1. (b) HUDC_S13-2. (c) HUDC_S13-4.

Figure 65.—1-3 plane shear specimens after testing. (a) HUDC_S13-1. (b) HUDC_S13-2. (c) HUDC_S13-4.

TABLE 39.—SUMMARY OF 1-3 PLANE SHEAR TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Engineering strain rate, 1/s	Tensorial strain rate	G_{13}, psi	Ultimate strain	Tensorial ultimate strain	Peak stress, psi
HUDC_S13-1	0.01	2.17×10^{-4}	1.09×10^{-4}	1,639,315	0.05	0.025	14,509
HUDC_S13-2	0.01	2.11×10^{-4}	1.06×10^{-4}	1,905,705	0.05	0.025	14,456
HUDC_S13-4	0.01	2.11×10^{-4}	1.06×10^{-4}	1,237,659	0.05	0.025	14,332
Average	-----	0	0	1,594,226	0.05	0.025	14,429
Standard deviation	-----	0	0	336,298	0.00	0.00	96
Coefficient of variation	-----	1.6%	1.6%	21.1%	0.0%	0.0%	0.7%

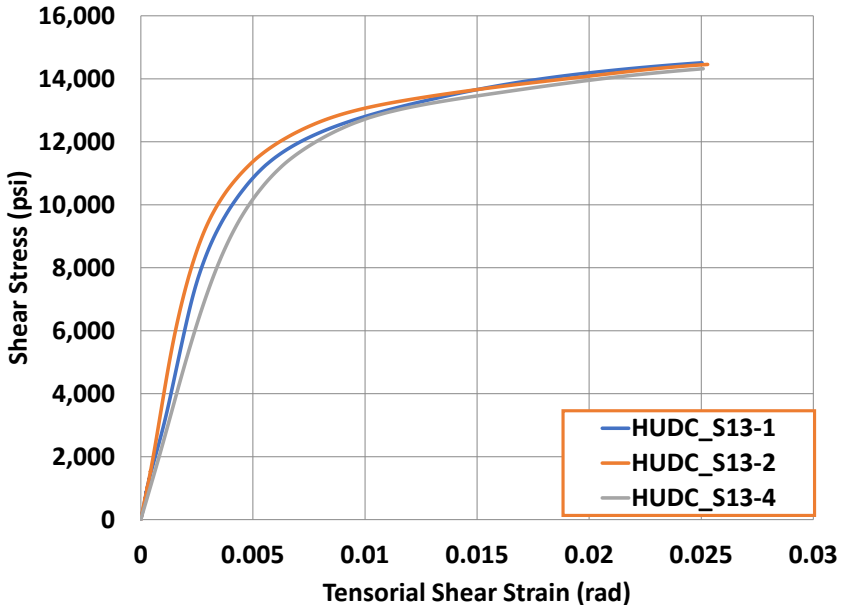


Figure 66.—1-3 plane shear stress-tensorial strain curves for HUDC material.

3.9.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 67 and Figure 68, respectively, for the TSFC material.

Test Results: A summary of results from the tests on the TSFC material is reported in Table 40. Shear moduli are shown in terms of engineering shear strain. Figure 69 shows the individual stress-strain curves for the specimens tested. Stress-strain curves were terminated at 0.025 tensorial shear strain. These tests were carried out beyond 0.05 engineering strain but not to failure, like the shear tests in the 1-2 plane.

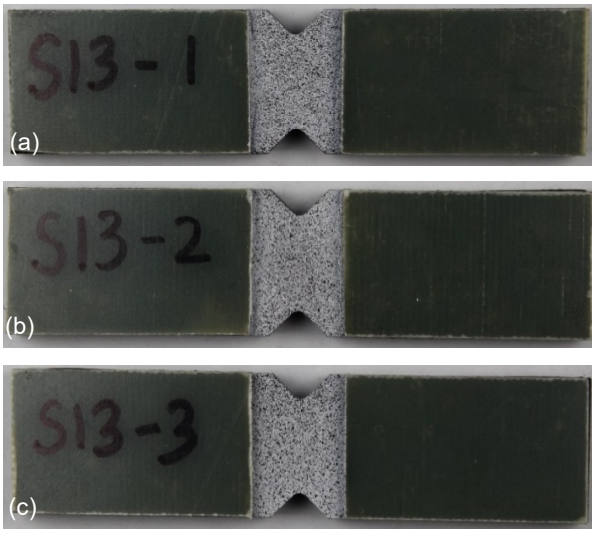


Figure 67.—1-3 plane shear specimens prior to testing. (a) TSFC_S13-1. (b) TSFC_S13-2. (c) TSFC_S13-3.

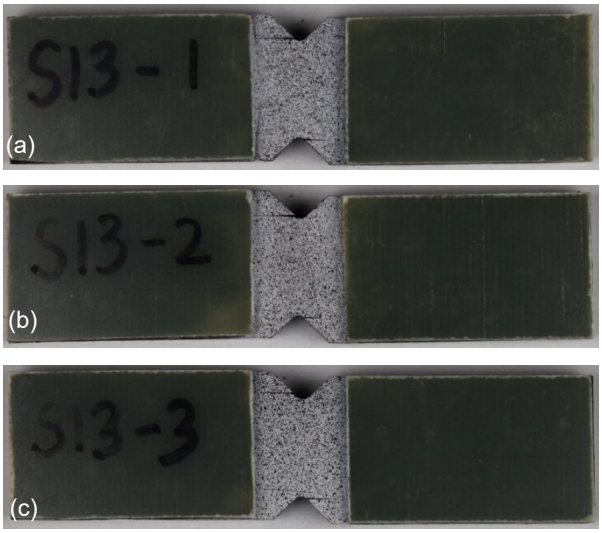


Figure 68.—1-3 plane shear specimens after testing. (a) TSFC_S13-1. (b) TSFC_S13-2. (c) TSFC_S13-3.

TABLE 40.—SUMMARY OF 1-3 PLANE SHEAR TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Engineering strain rate, 1/s	Tensorial strain rate	G_{13}, psi	Ultimate strain	Tensorial ultimate strain	Peak stress, psi
TSFC_S13-1	0.01	2.23×10^{-4}	1.16×10^{-4}	2,214,997	0.05	0.025	14,176
TSFC_S13-2	0.01	2.32×10^{-4}	1.16×10^{-4}	1,628,605	0.05	0.025	14,080
TSFC_S13-3	0.01	2.38×10^{-4}	1.19×10^{-4}	1,995,194	0.05	0.025	14,221
Average	------	0	0	1,946,265	0.05	0.025	14,159
Standard deviation	------	0	0	296,242	0.00	0.00	72
Coefficient of variation	------	3.3%	3.3%	15.2%	0.0%	0.0%	0.5%

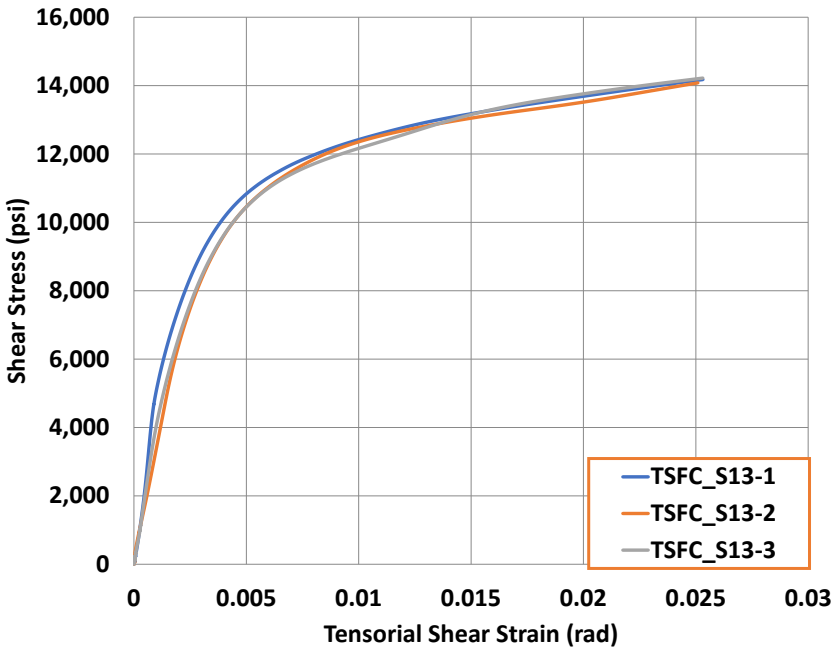


Figure 69.—1-3 plane shear stress-tensorial strain curves for TSFC material.

3.10 Test T10: 45° Off-Axis Tension Test in the 1-2 Plane

Experimental Setup: This test is used to generate the 45° off-axis tension stress-strain curve in the 1-2 plane. An MTS® 810 test frame (Figure 2(a)) was used to perform these tests.

Specimen Geometry: The specimen dimensions and layout, shown in Figure 70, are taken from ASTM D3039 (Ref. 10). Shaded regions indicate where the oblique fiberglass tabs are bonded to the specimen. The average specimen dimensions in the gage section for HUDC and TSFC, respectively, are shown in Table 41 and Table 42 for the three tested replicates.

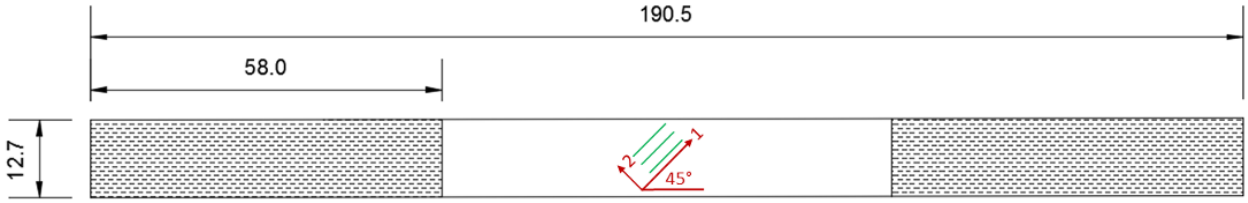


Figure 70.—Specimen geometry and layout (ASTM D3039 geometry).

TABLE 41.—1-2 PLANE 45° OFF-AXIS TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_O12-4	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)
HUDC_O12-5	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)
HUDC_O12-6	0.50 (12.7)	0.12 (3.05)	0.06 (38.71)

TABLE 42.—1-2 PLANE 45° OFF-AXIS TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_O12-2	0.50 (12.7)	0.08 (2.03)	0.041 (25.81)
TSFC_O12-4	0.50 (12.7)	0.08 (2.03)	0.041 (25.81)
TSFC_O12-5	0.50 (12.7)	0.08 (2.03)	0.041 (25.81)

3.10.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 71 and Figure 72, respectively, for the HUDC material.

Test Results: A summary of results from the tests on the HUDC material is reported in Table 43. Figure 73 shows the individual longitudinal stress-strain curves for the specimens tested.

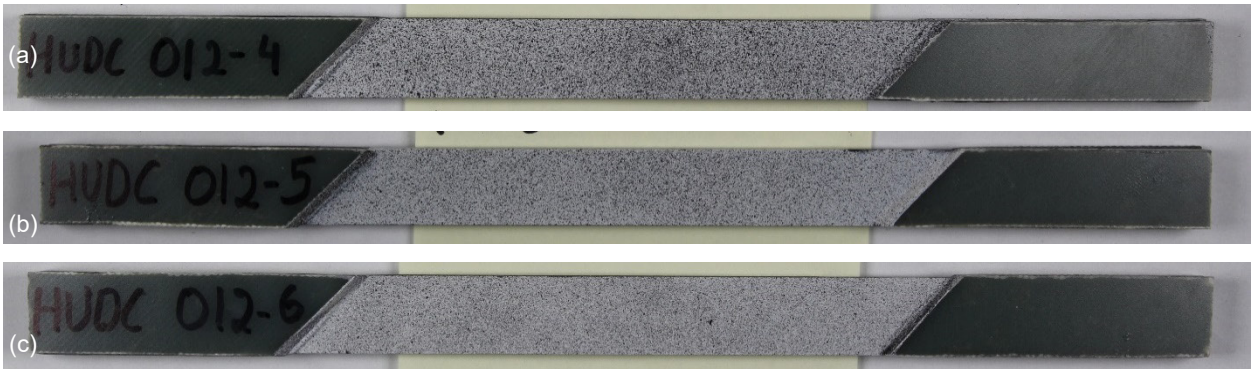


Figure 71.—1-2 plane 45° off-axis tension specimens prior to testing. (a) HUDC_O12-4. (b) HUDC_O12-5. (c) HUDC_O12-6.

Figure 72.—1-2 plane 45° off-axis tension specimens after testing. (a) HUDC_O12-4. (b) HUDC_O12-5. (c) HUDC_O12-6.

TABLE 43.—SUMMARY OF 1-2 PLANE 45° OFF-AXIS TENSION TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	Modulus, psi	Ultimate longitudinal strain	Peak stress, psi
HUDC_O12-4	0.01	4.58×10^{-5}	1,925,669	0.0322	18,869
HUDC_O12-5	0.01	4.34×10^{-5}	1,823,985	0.0318	19,343
HUDC_O12-6	0.01	4.16×10^{-5}	1,872,178	0.0267	18,754
Average	-----	4.36×10^{-5}	1,873,944	0.0302	18,989
Standard deviation	-----	2.11×10^{-6}	50,865	0.00307	312
Coefficient of variation	-----	4.8%	2.7%	10.2%	1.6%

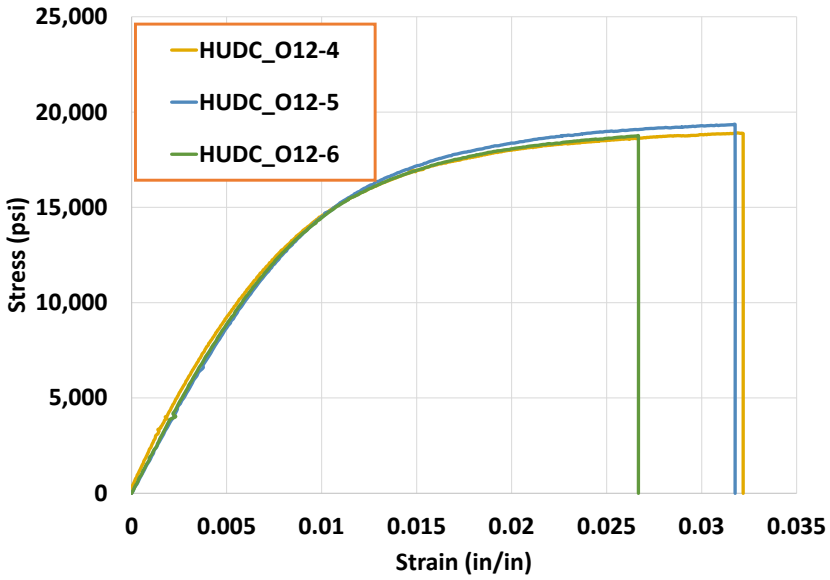


Figure 73.—1-2 plane 45° off-axis tension stress-longitudinal strain curves for HUDC material.

3.10.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 74 and Figure 75, respectively, for the TSFC material.

Test Results: A summary of results from the tests on the TSFC material is reported in Table 44. Figure 76 shows the individual longitudinal stress-strain curves for the specimens tested.

Figure 74.—1-2 plane 45° off-axis tension specimens prior to testing. (a) TSFC_O12-2. (b) TSFC_O12-4. (c) TSFC_O12-5.

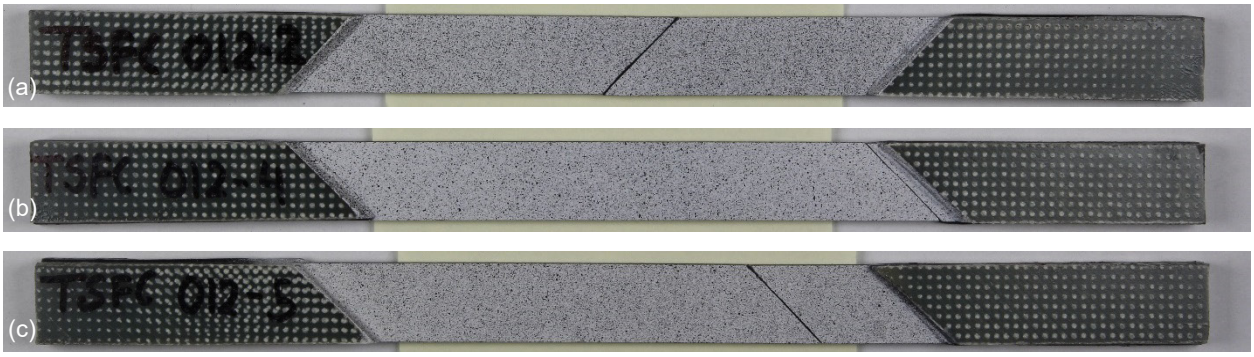


Figure 75.—1-2 plane 45° off-axis tension specimens after testing. (a) TSFC_O12-2. (b) TSFC_O12-4. (c) TSFC_O12-5.

TABLE 44.—SUMMARY OF 1-2 PLANE 45° OFF-AXIS TENSION TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	Modulus, psi	Ultimate longitudinal strain	Peak stress, psi
TSFC_O12-2	0.01	4.54×10^{-5}	1,942,338	0.0448	24,155
TSFC_O12-4	0.01	4.37×10^{-5}	1,990,695	0.0422	24,343
TSFC_O12-5	0.01	4.54×10^{-5}	1,881,553	0.0418	23,670
Average	-----	4.48×10^{-5}	1,938,212	0.0429	24,056
Standard deviation	-----	9.81×10^{-7}	54,690	0.00168	347
Coefficient of variation	-----	2.2%	2.8%	3.9%	1.4%

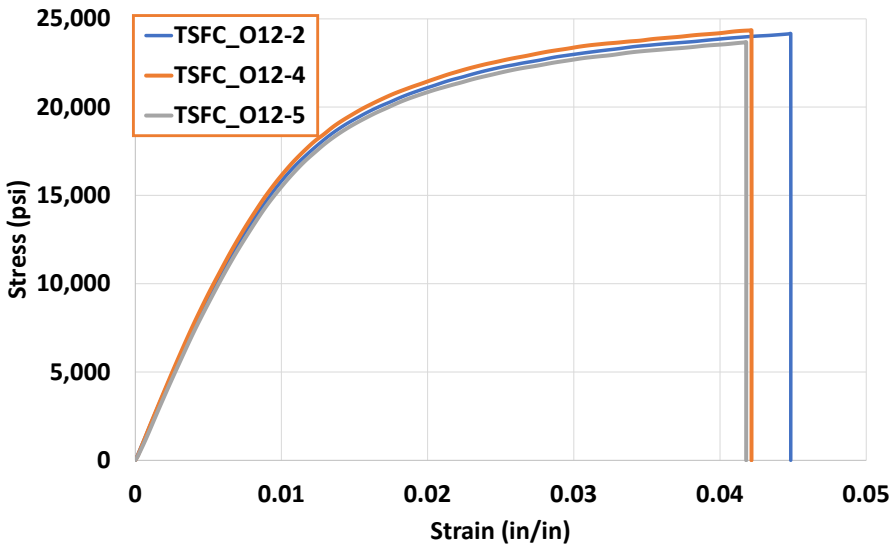


Figure 76.—1-2 plane 45° off-axis tension stress-longitudinal strain curves for TSFC material.

3.11 T11 Test: 45° Off-Axis Compression Test in the 2-3 Plane

Experimental Setup: This test is used to generate the 45° off-axis compression stress-strain curve in the 2-3 plane. An MTS® 810 test frame (Figure 2(a)) was used to perform these tests.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 77. The geometry shown is a modified version of the geometry set forth by ASTM D7291 (Ref. 13). A cube was used in place of a cylindrical specimen for ease of machining and sample preparation. However, due to the limitation of the maximum specimen size presented by the thickness of the available panels, the size of the specimen was modified by making the specimens dimensions smaller. ASTM D7291 sets guidelines for through-thickness tensile properties. This ASTM was used because there is no standard available that sets guidelines for obtaining through-thickness compressive properties of fiber-reinforced composites. The average specimen dimensions in the gage section for HUDC and TSFC, respectively, are shown in Table 45 and Table 46 for the three tested replicates.

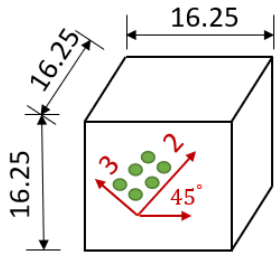


Figure 77.—Specimen geometry and layout (dimensions shown in mm).

TABLE 45.—2-3 PLANE 45° OFF-AXIS COMPRESSION TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
HUDC_O23-2	0.57 (14.45)	0.90 (22.86)	0.51 (329.03)
HUDC_O23-3	0.57 (14.45)	0.90 (22.86)	0.51 (329.03)
HUDC_O23-4	0.57 (14.45)	0.90 (22.86)	0.51 (329.03)

TABLE 46.—2-3 PLANE 45° OFF-AXIS COMPRESSION TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate	Width, in. (mm)	Thickness, in. (mm)	Cross sectional area, in^2 (mm^2)
TSFC_O23-3	0.65 (16.41)	0.59 (15.02)	0.38 (246.65)
TSFC_O23-4	0.65 (16.41)	0.59 (15.05)	0.38 (246.87)
TSFC_O23-6	0.65 (16.40)	0.59 (15.04)	0.38 (246.61)

3.11.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 78 and Figure 79, respectively, for the HUDC material. The specimens exhibited brittle failure of the matrix in the 2-3 plane before the tests were terminated.

Test Results: A summary of results from the tests on the HUDC material is reported in Table 47. Figure 80 shows the individual longitudinal stress-strain curves for each of the specimens tested.

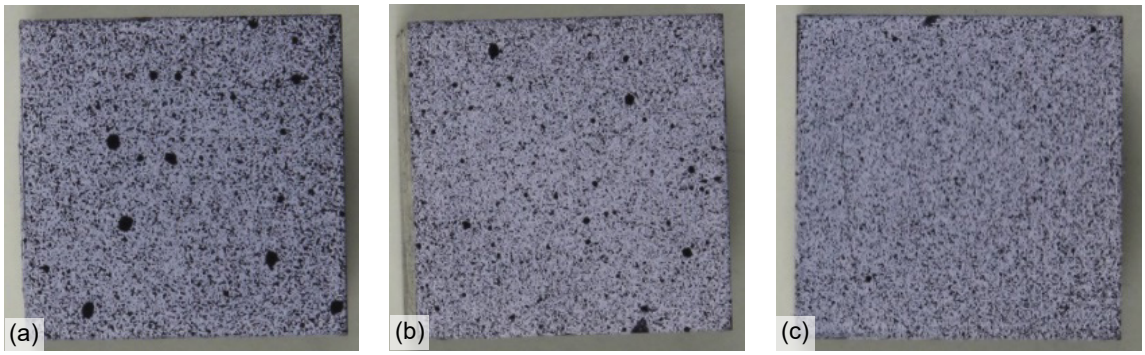


Figure 78.—2-3 plane 45° off-axis compression test specimens prior to testing. (a) HUDC_O23-2. (b) HUDC_O23-3. (c) HUDC_O23-4.

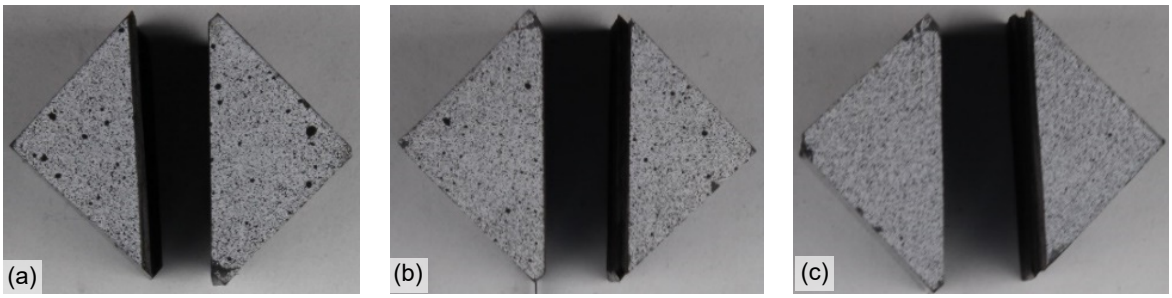


Figure 79.—2-3 plane 45° off-axis compression test specimens after testing. (a) HUDC_O23-2. (b) HUDC_O23-3. (c) HUDC_O23-4.

TABLE 47.—SUMMARY OF 2-3 PLANE 45° OFF-AXIS COMPRESSION TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	Modulus, psi	Ultimate longitudinal strain	Peak stress, psi
HUDC_O23-2	0.005	7.47×10^{-5}	1,623,845	0.0345	30,702
HUDC_O23-3	0.005	7.47×10^{-5}	1,678,471	0.0312	28,884
HUDC_O23-4	0.005	7.47×10^{-5}	1,426,433	0.0352	30,444
Average	-------	0	1,576,250	0.0336	30,010
Standard deviation	-------	0	132,589	0.00213	983
Coefficient of variation	-------	1.1%	8.4%	6.3%	3.3%

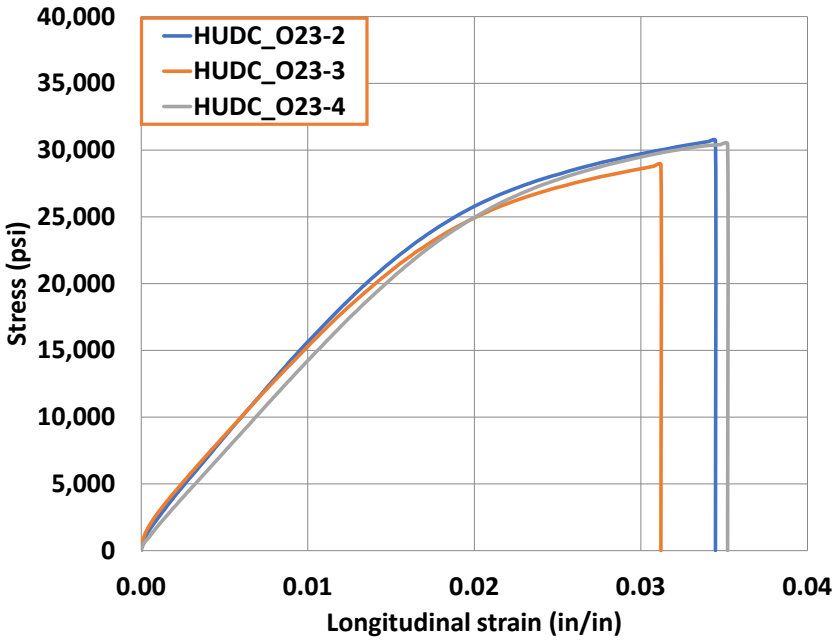


Figure 80.—2-3 plane 45° off-axis compression stress-longitudinal strain curves for HUDC material.

3.11.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 81 and Figure 82, respectively, for the TSFC material. The specimens exhibited brittle failure of the matrix in the 2-3 plane before the tests were terminated.

Test Results: A summary of results from the tests on the TSFC material is reported in Table 48. Figure 83 shows the individual longitudinal stress-strain curves for the specimens tested.

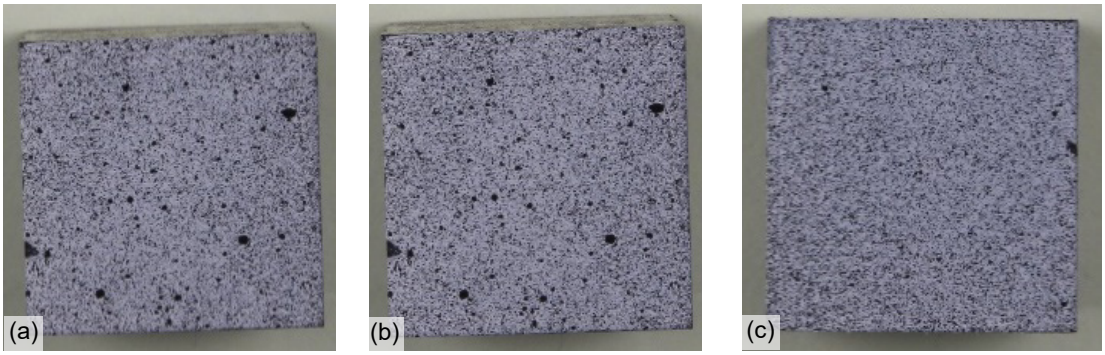


Figure 81.—2-3 plane 45° off-axis compression test specimens prior to testing (a) TSFC_O23-3. (b) TSFC_O23-4. (c) TSFC_O23-6.

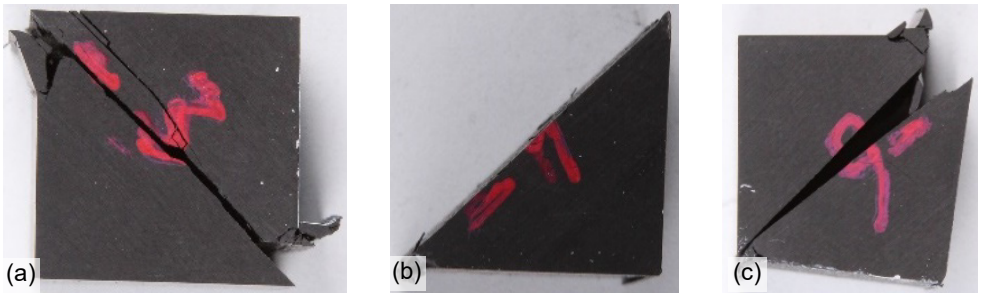


Figure 82.—2-3 plane 45° off-axis compression test specimens after testing (a) TSFC_O23-3. (b) TSFC_O23-4. (c) TSFC_O23-6.

TABLE 48.—SUMMARY OF 2-3 PLANE 45° OFF-AXIS COMPRESSION TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Strain rate, 1/s	Modulus, psi	Ultimate longitudinal strain	Peak stress, psi
TSFC_O23-3	0.005	4.71×10^{-5}	1,534,188	0.0302	30,497
TSFC_O23-4	0.005	4.84×10^{-5}	1,502,941	0.0301	29,458
TSFC_O23-6	0.005	5.06×10^{-5}	1,427,346	0.0306	30,339
Average	-------	0	1,488,158	0.0303	30,098
Standard deviation	-------	0	54,934	0.00026	560
Coefficient of variation	-------	3.6%	3.7%	0.9%	1.9%

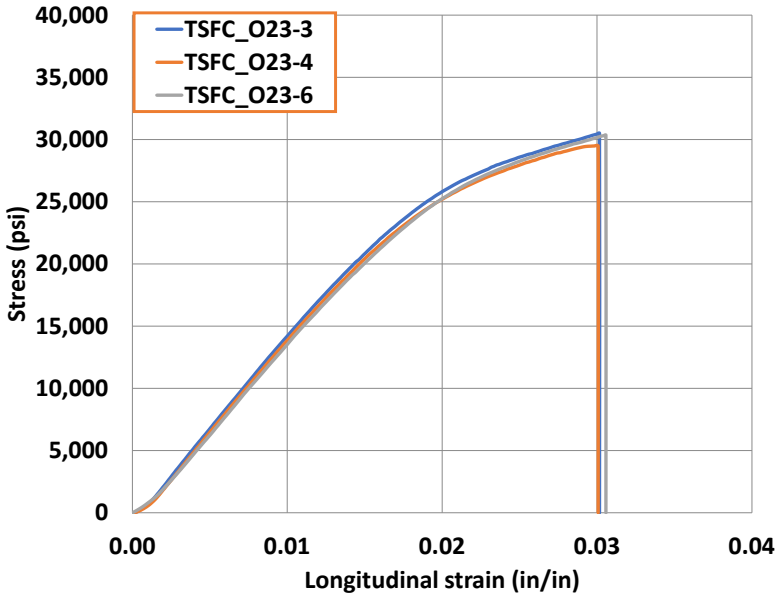


Figure 83.—2-3 plane 45° off-axis compression stress-longitudinal strain curves for TSFC material.

3.12 Test T13: Double Cantilever Beam (DCB) Test

Experimental Setup: The experimental procedure was performed using an MTS Exceed® test frame (Figure 2(j)) with spring-loaded grips (Figure 2(k)) and a manually tightened tension fixture (Figure 2(o)). ASTM D5528, Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites (Ref. 14), was used as a guideline to create the experimental setup for both the non-precracked (NPC) and precracked (PC) conditions. The NPC condition implies that the insert acted as the source of initial delamination with no further cracking induced in the specimen. Testing in the NPC condition to a desired crack propagation yielded the PC condition (i.e., in the PC condition, cracking had been induced in the specimen beyond the initial insert). A loading rate of 1.2 mm/min was used for all tests. The NPC tests were loaded until a controlled crack growth of 5 mm was reached. The PC tests were loaded until the complete separation of the top and bottom halves of the specimen took place.

Specimen Geometry: The specimen geometry, based on ASTM D5528 (Ref. 14), and specimen layout are shown in Figure 84, where L is the length, $2h$ is specimen thickness, a_i is the crack length from the edge of the sample, and a_0 is the crack length from the load line of action. For the HUDC material, two sets of DCB specimens were tested. The first set (HUDC_DCB-1, 2, and 3) was tested using a spring-loaded grip, and the second set (HUDC_DCB-5 and 6) was tested using a manually tightened tension fixture. The spring-loaded grip applied pressure based on the spring constant, which was insufficient to securely hold the specimen, resulting in a 3-mm slippage of the gripped piano hinge. In contrast, no slippage was observed with the manually applied grip pressure. The average specimen dimensions for both sets of HUDC tests are shown in Table 49 and Table 50. All TSFC tests were performed using the manually tightened tension fixture. The specimen dimensions are summarized in Table 51 for the three tested replicates.

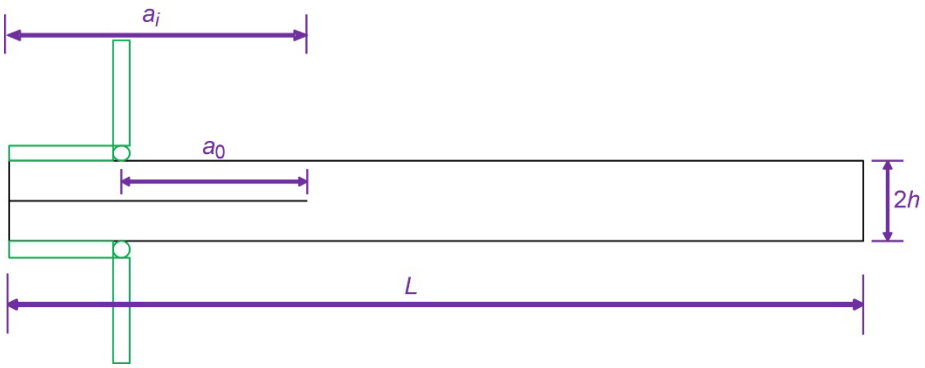


Figure 84.—Typical double cantilever beam specimen geometry and layout. Length, L; height, h; crack length from edge of sample, a_i; crack length from load line of action, a_0.

TABLE 49.—DCB TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL USING SPRING-LOADED GRIP FIXTURE

Replicate ID	a_i, in. NPC	a_i, in. PC	a_0, in. NPC	a_0, in. PC	h, in.	[a]b, in.	L, in.
HUDC_DCB-1	2.252	2.449	1.502	1.801	0.088	1.003	5.5
HUDC_DCB-2	2.289	2.486	1.539	1.775	0.087	1.002	5.5
HUDC_DCB-3	2.241	2.438	1.491	1.754	0.087	1.004	5.5
Average	2.261	2.458	1.511	1.777	0.087	1.003	5.5
Standard deviation	0.025	0.025	0.025	0.023	0.00050	0.001	0.000
Coefficient of variation	1.1%	1.0%	1.7%	1.3%	0.6%	0.1%	0.0%

[a]Width of specimen.

TABLE 50.—DCB TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL TESTED USING MANUALLY TIGHTENED TENSION FIXTURE

Replicate ID	a_i, in. NPC	a_i, in. PC	a_0, in. NPC	a_0, in. PC	h, in.	[a]b, in.	L, in.
HUDC_DCB-5	2.246	2.443	1.736	1.987	0.087	1.006	5.5
HUDC_DCB-6	2.269	2.466	1.759	2.020	0.087	1.006	5.5
Average	2.257	2.454	1.747	2.003	0.087	1.006	5.5
Standard deviation	0.016	0.016	0.016	0.023	0.00033	0.000	0.000
Coefficient of variation	0.7%	0.7%	0.9%	1.1%	0.4%	0.0%	0.0%

[a]Width of specimen.

TABLE 51.—DCB TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL USING MANUALLY TIGHTENED TENSION FIXTURE

Replicate ID	a_i, in. NPC	a_i, in. PC	a_0, in. NPC	a_0, in. PC	h, in.	[a]b, in.	L, in.
TSFC_DCB-2	2.393	2.590	1.883	2.103	0.074	1.00	5.5
TSFC_DCB-4	2.462	2.659	1.952	2.149	0.074	1.01	5.5
TSFC_DCB-6	2.451	2.648	1.941	2.138	0.074	1.00	5.5
Average	2.435	2.632	1.925	2.130	0.074	1.01	5.5
Standard deviation	0.037	0.037	0.037	0.037	0.00013	0.001	0.000
Coefficient of variation	1.5%	1.4%	1.9%	1.8%	0.2%	0.1%	0.0%

[a]Width of specimen.

3.12.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 85 and Figure 86, respectively, for the HUDC material.

Test Results: A summary of results from the tests on the HUDC material using spring-loaded grips and manually tightened grips is reported in Table 52 and Table 53, respectively. Figure 87 plots the experimentally measured load against displacement that occurred at the load point. Fracture energies were calculated using the linear fracture mechanics method (Eq. (3)) at varying crack propagation lengths to generate R-curves. The resulting R-curves are presented in Figure 88.

$$G_I = \frac{P^2 a^2}{bEI} = \frac{12P^2 a^2}{b^2 h^3 E} \tag{3}$$

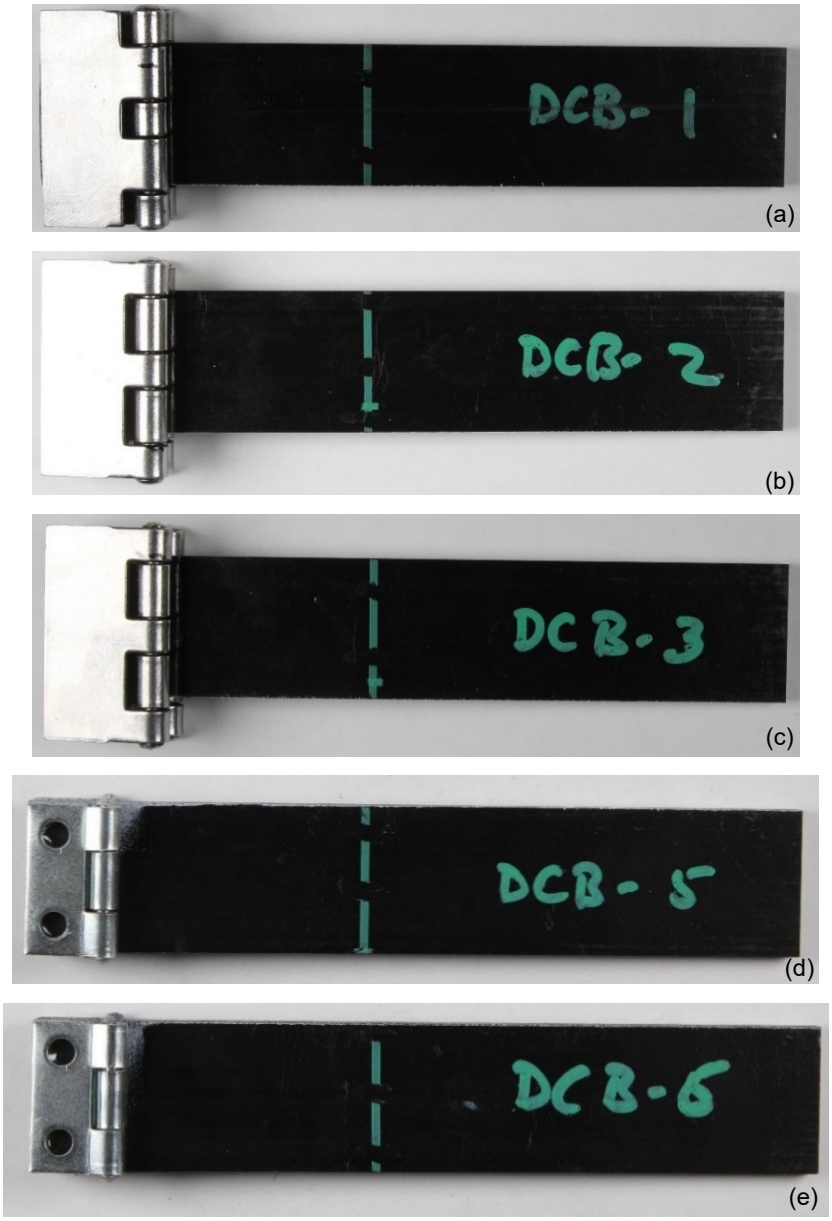


Figure 85.—DCB specimens prior to testing. (a) HUDC_DCB-1. (b) HUDC_DCB-2. (c) HUDC_DCB-3. (d) HUDC_DCB-5. (e) HUDC_DCB-6.

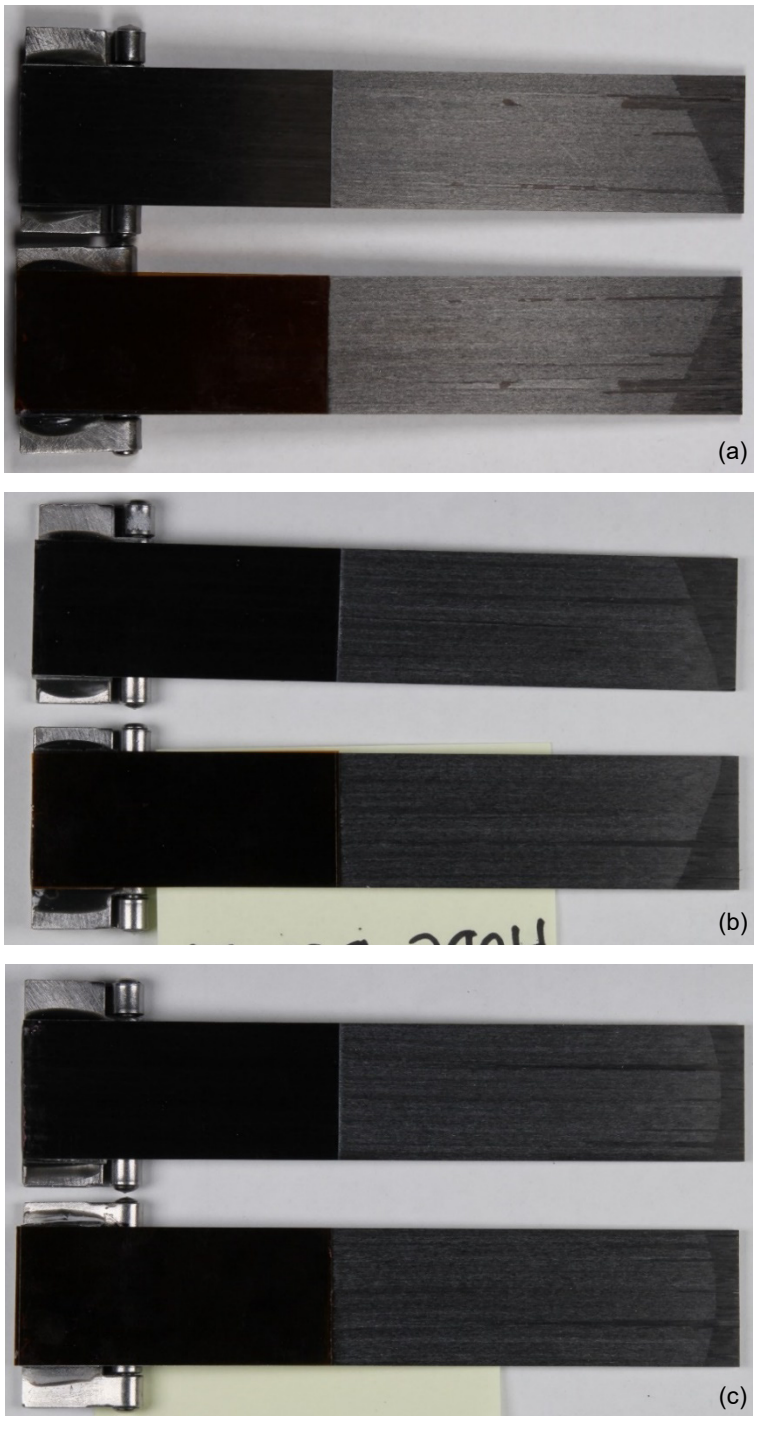
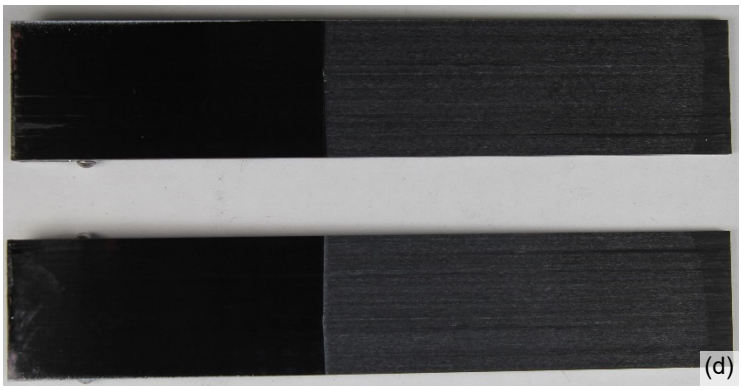


Figure 86.—DCB specimen after testing. (a) HUDC_DCB-1. (b) HUDC_DCB-2. (c) HUDC_DCB-3. (d) HUDC_DCB-5. (e) HUDC_DCB-6.



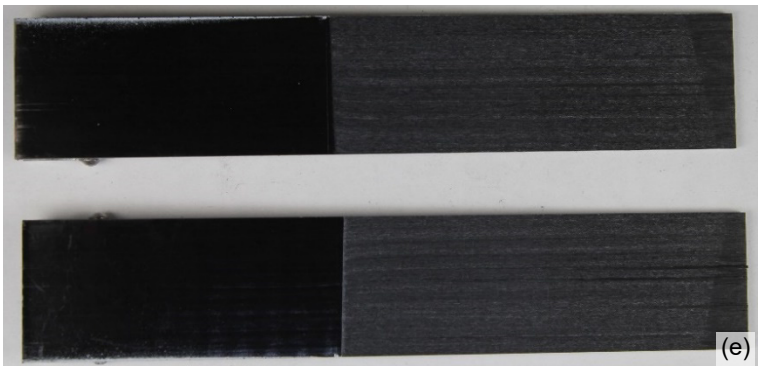


Figure 86.—Concluded.

TABLE 52.—SUMMARY OF DCB TEST RESULTS FOR HUDCMATERIAL USING SPRING-LOADED GRIP FIXTURE

Replicate	Loading rate, in/min	Stiffness, lb/in	Ultimate displacement, in.	Peak load, lb	Area under load-displacement curve, lb-in
HUDC_DCB-1	0.047	141.46	0.943	39.01	24.72
HUDC_DCB-2	0.047	142.27	0.929	39.46	23.83
HUDC_DCB-3	0.047	130.16	0.974	40.56	26.03
Average	-------	137.96	0.949	39.68	24.86
Standard deviation	-------	6.77	0.0229	0.80	1.11
Coefficient of variation	-------	4.9%	2.4%	2.0%	4.4%

TABLE 53.—SUMMARY OF DCB TEST RESULTS FOR HUDC MATERIAL USING MANUALLY TIGHTENED TENSION FIXTURE

Replicate	Loading rate, in/min	Stiffness, lb/in	Ultimate displacement, in.	Peak load, lb	Area under load-displacement curve, lb-in
HUDC_DCB-5	0.047	167.06	0.878	36.50	20.74
HUDC_DCB-6	0.047	178.16	0.868	36.76	20.53
Average	-------	172.61	0.873	36.63	20.63
Standard deviation	-------	7.85	0.007	0.19	0.15
Coefficient of variation	-------	4.5%	0.8%	0.5%	0.7%

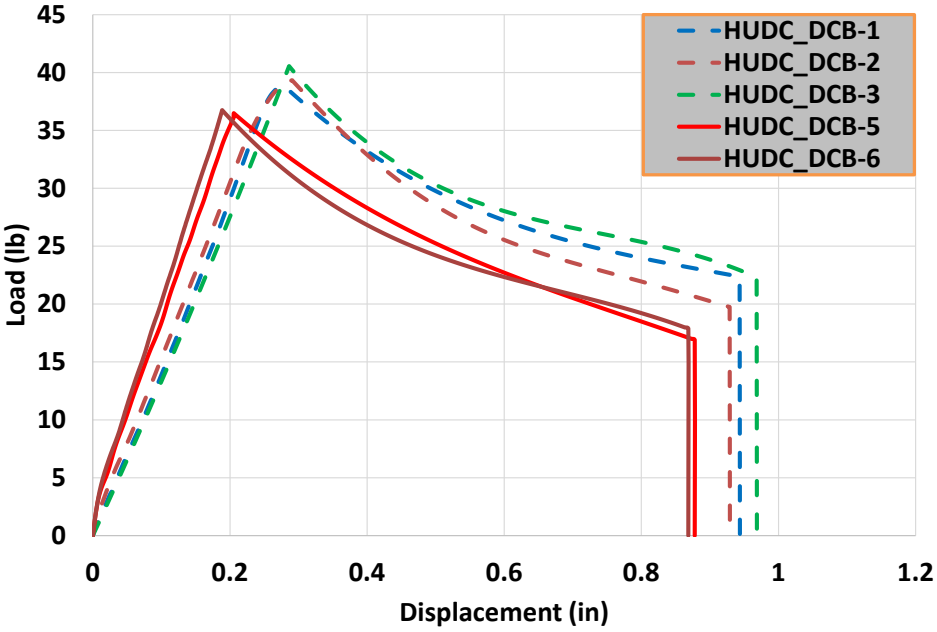


Figure 87.—DCB precrack experimental force versus displacement for HUDC material.

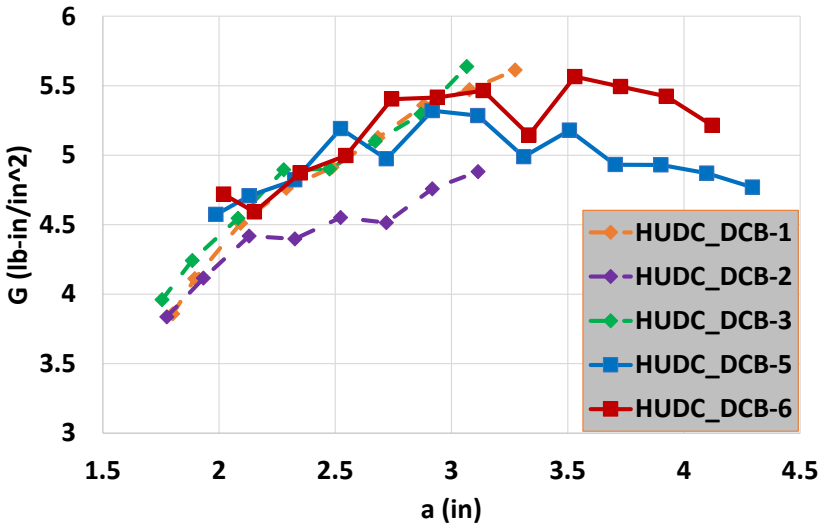


Figure 88.—Double cantilever beam R-curves for HUDC material.

3.12.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 89 and Figure 90, respectively, for the TSFC material.

Test Results: For the TSFC material, all three specimens were tested using the manually tightened tension fixture. A summary of results is reported in Table 54. Figure 91 plots the experimentally measured load against displacement that occurred at the load point. Fracture energies were calculated using the linear fracture mechanics method (Eq. (3)) at varying crack propagation lengths to generate R-curves. The resulting R-curves are presented Figure 92 for the TSFC material.

Figure 89.—DCB specimen prior to testing. (a) TSFC_DCB-2. (b) TSFC_DCB-4. (c) TSFC_DCB-6.

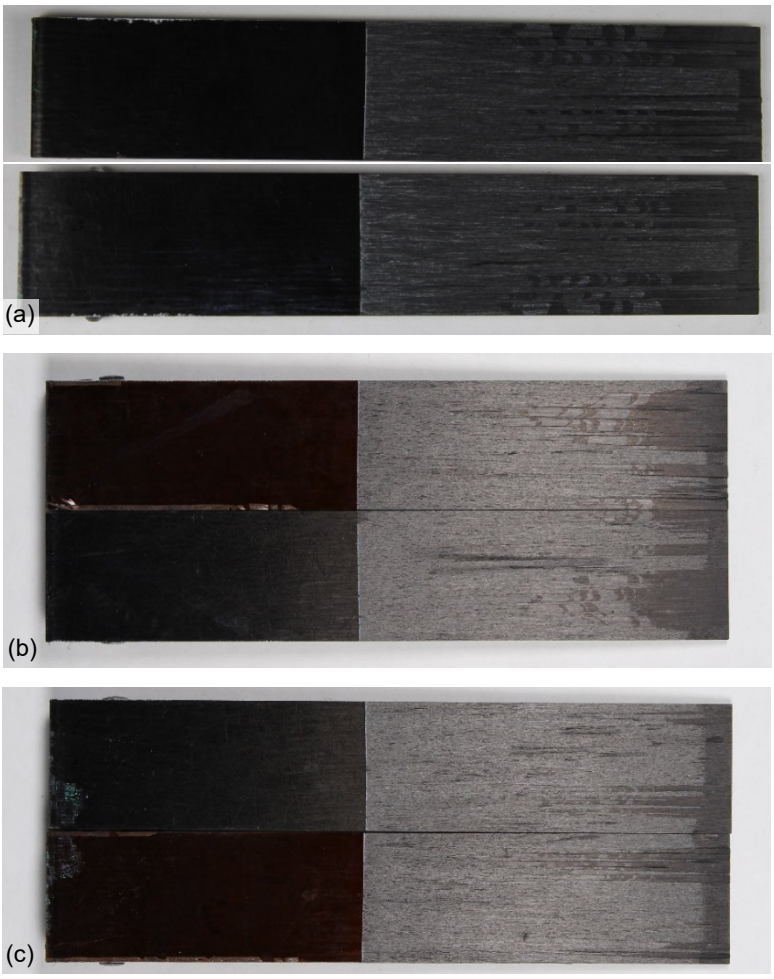


Figure 90.—DCB specimens after testing. (a) TSFC_DCB-2. (b) TSFC_DCB-4. (c) TSFC_DCB-6.

TABLE 54.—SUMMARY OF DCB TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Stiffness, lb/in	Ultimate displacement, in.	Peak load, lb	Area under load-displacement curve, lb-in
TSFC_DCB-2	0.047	85.37	1.711	35.22	41.58
TSFC_DCB-4	0.047	75.22	1.734	33.25	40.82
TSFC_DCB-6	0.047	82.78	1.640	36.48	40.86
Average	-	81.12	1.695	34.98	41.09
Standard deviation	-	5.27	0.0489	1.63	0.42
Coefficient of variation	-	6.5%	2.9%	4.6%	1.0%

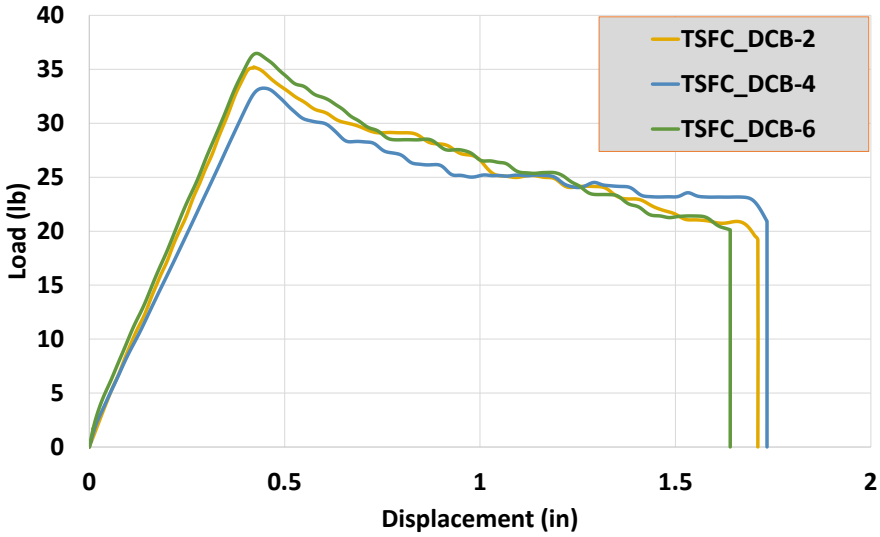


Figure 91.—DCB precrack experimental force versus displacement for TSFC material.

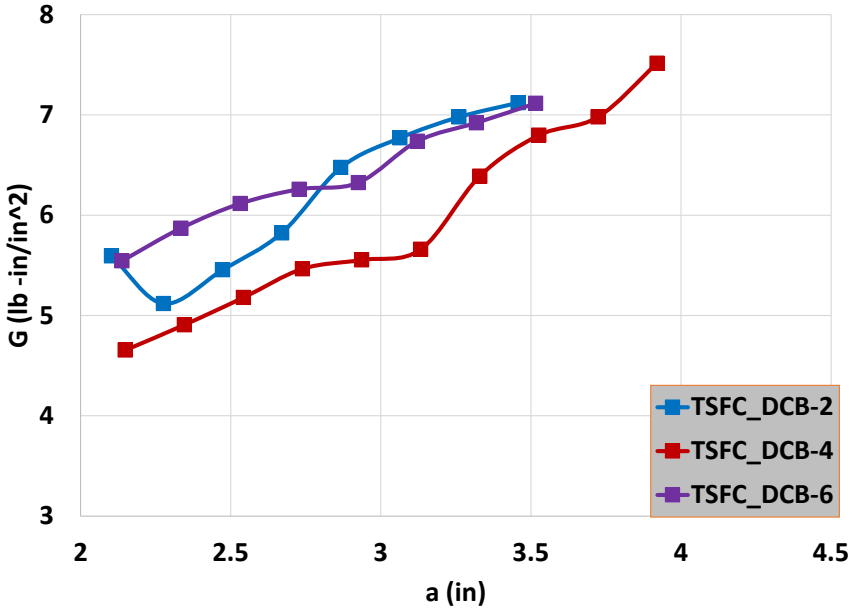


Figure 92.—Double cantilever beam R-curves for TSFC material.

3.13 Test T14: ENF Test

Experimental Setup: The ASTM procedure was followed for both the NPC and PC conditions. For each condition, two calibration cycles were performed and followed by a fracture cycle. The compliance of the specimen for each cycle was computed as the linear portion of the relationship between the load and displacement. A constant span between the support rollers was used across all cycles to ensure that the change in compliance was only a function of the crack length. The three cycles combined were used in the compliance calibration process to find a linear least-squares regression on the relationship between the compliance of each cycle and the crack length of each cycle. A loading rate of 0.6 mm/min was used for each cycle. The experimental procedure was performed using an MTS Exceed® test frame (Figure 2(j)) with a 3-point bend fixture (Figure 2(l)).Assessment of the crack front along the width of the sample could not be accurately measured, therefore, fracture toughness values could not be validated and are not reported. Additionally, mode 2 energy release rate, G2C, was calculated using the J-integral method, which requires the shear crack tip displacement as an input. However, the available software lacks the capability to directly measure shear crack tip displacement. Estimation of the shear crack tip displacement using DIC images resulted in significant variations across replicates, leading to inconsistent G2C values. This was due to the sensitivity of calculated G2C values associated with errors in DIC-measured displacement data near the crack tip.

Specimen Geometry: ASTM D7905, Standard Test Method for Determination of the Mode II Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites (Ref. 15), is applicable for this test. The specimen geometry and layout are shown in Figure 93. The average specimen dimensions for HUDC and TSFC are shown in Table 55 and Table 56, respectively, for the three tested replicates.

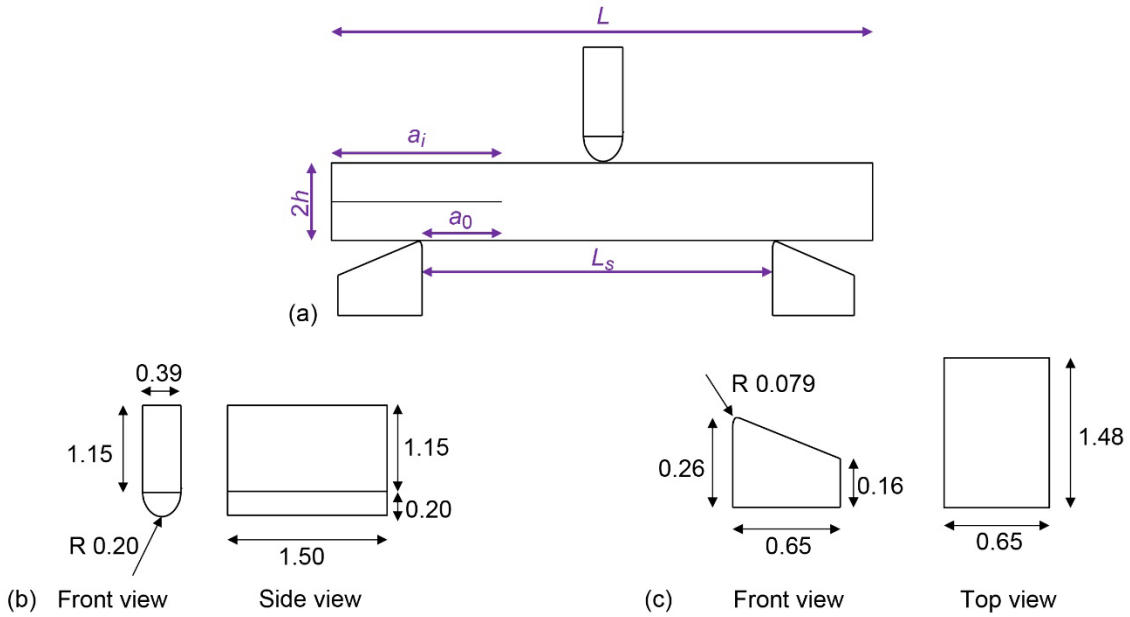


Figure 93.—Typical ENF specimen geometry and fixture layout. (a) Geometry. (b) Loading fixture. (c) Support fixture.

TABLE 55.—ENF TEST SPECIMEN DIMENSIONS FOR HUDC MATERIAL

Replicate ID	a_i, in. NPC	a_i, in. PC	a_0, in. NPC and PC	h, in.	[a]b, in.	L_s, in.	L, in.
HUDC_ENF-1	2.286	2.651	1.181	0.088	1.004	3.941	6.5
HUDC_ENF-3	2.274	2.710	1.181	0.087	1.003	3.941	6.5
HUDC_ENF-4	2.285	2.593	1.181	0.086	1.003	3.941	6.5
Average	2.281	2.651	1.181	0.087	1.003	3.941	6.5
Standard deviation	0.0067	0.0583	0	0.0009	0.0006	0	0
Coefficient of variation	0.3%	2.2%	0.0%	1.0%	0.1%	0.0%	0.0%

[a]Width of specimen.

TABLE 56.—ENF TEST SPECIMEN DIMENSIONS FOR TSFC MATERIAL

Replicate ID	a_i, in. NPC	a_i, in. PC	a_0, in. NPC and PC	h, in.	[a]b, in.	L_s, in.	L, in.
TSFC_ENF-1	2.485	3.062	1.181	0.078	1.002	3.941	6.5
TSFC_ENF-2	2.472	3.000	1.181	0.076	1.011	3.941	6.5
TSFC_ENF-3	2.485	3.342	1.181	0.075	1.002	3.941	6.5
Average	2.480	3.135	1.181	0.076	1.005	3.941	6.5
Standard deviation	0.0076	0.1821	0.0000	0.0014	0.0049	0.00	0.00
Coefficient of variation	0.3%	5.8%	0.0%	1.8%	0.5%	0.0%	0.0%

[a]Width of specimen.

3.13.1 HUDC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 94 and Figure 95, respectively, for the HUDC material.

Test Results: A summary of results from the tests on the HUDC material is reported in Table 57. In Figure 96, the experimentally measured load is plotted against displacement that occurred at the load point.

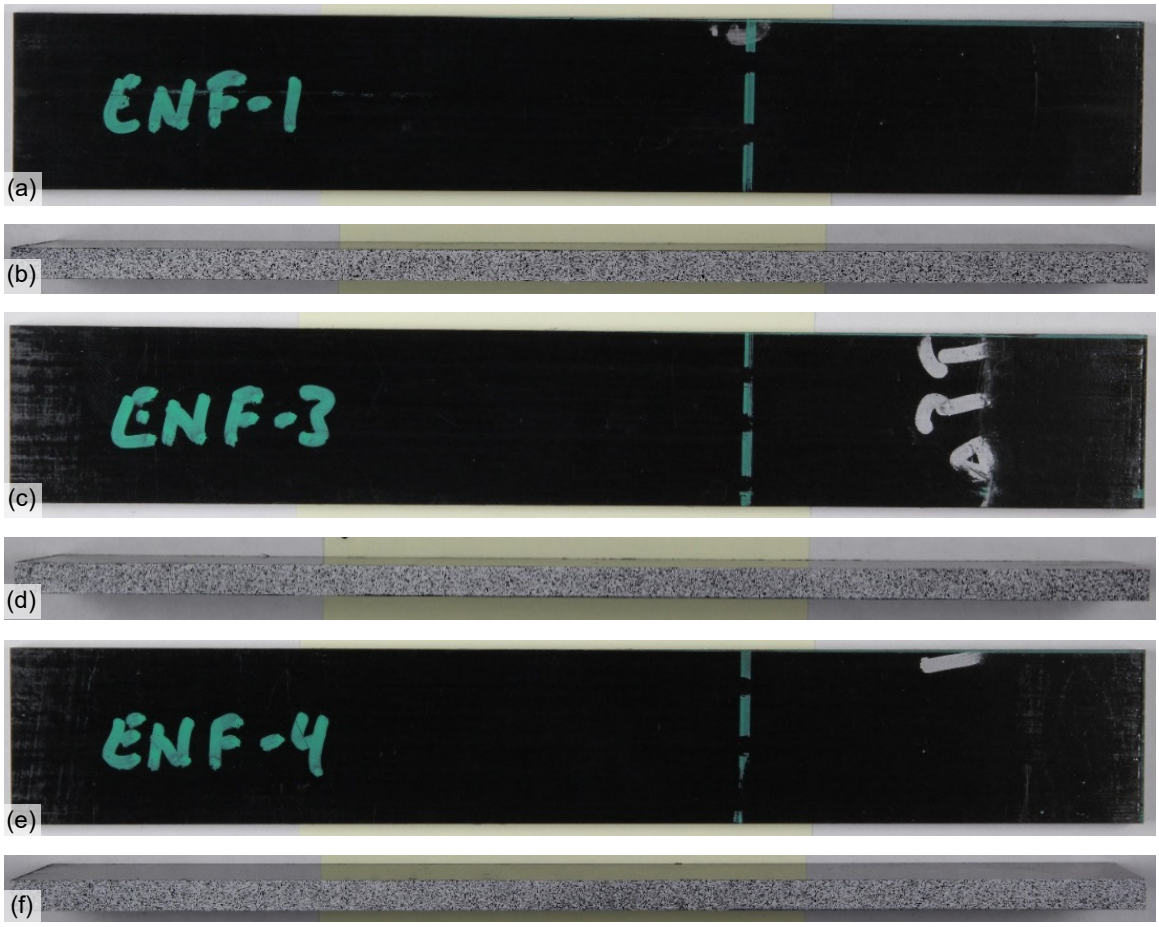


Figure 94.—Image of ENF specimen prior to testing (top surface showing specimen width; side of specimen showing thickness). (a) HUDC_ENF-1 (plan view). (b) HUDC_ENF-1 (elevation). (c) HUDC_ENF-3 (plan view). (d) HUDC_ENF-3 (elevation). (e) HUDC_ENF-4 (plan view). (f) HUDC_ENF-4 (elevation).

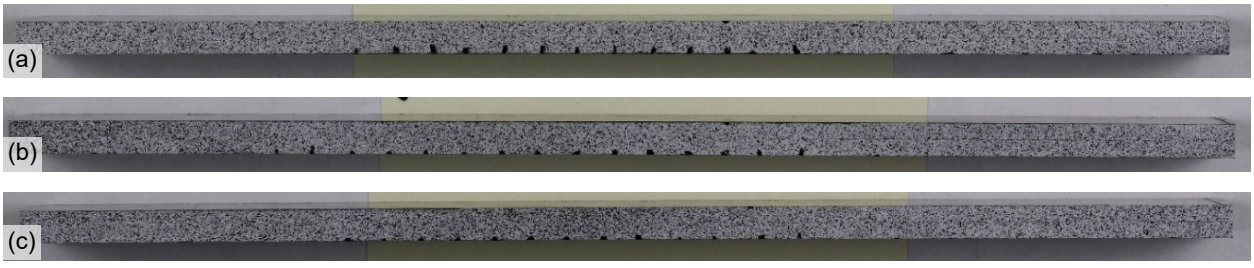


Figure 95.—ENF specimen after testing. (a) HUDC_ENF-1. (b) HUDC_ENF-3. (c) HUDC_ENF-4.

TABLE 57.—SUMMARY OF ENF TEST RESULTS FOR HUDC MATERIAL

Replicate	Loading rate, in/min	Stiffness, lb/in.	Ultimate displacement, in.	Peak load, lb	Area under load-displacement curve, lb-in.
HUDC_ENF-1	0.024	3,492.4	0.115	334.6	20.94
HUDC_ENF-3	0.024	3,551.3	0.119	351.7	23.75
HUDC_ENF-4	0.024	3,202.8	0.113	320.4	19.82
Average	-------	3,415.5	0.116	335.5	21.50
Standard deviation	-------	186.52	0.0030	15.65	2.03
Coefficient of variation	-------	5.5%	2.6%	4.7%	9.4%

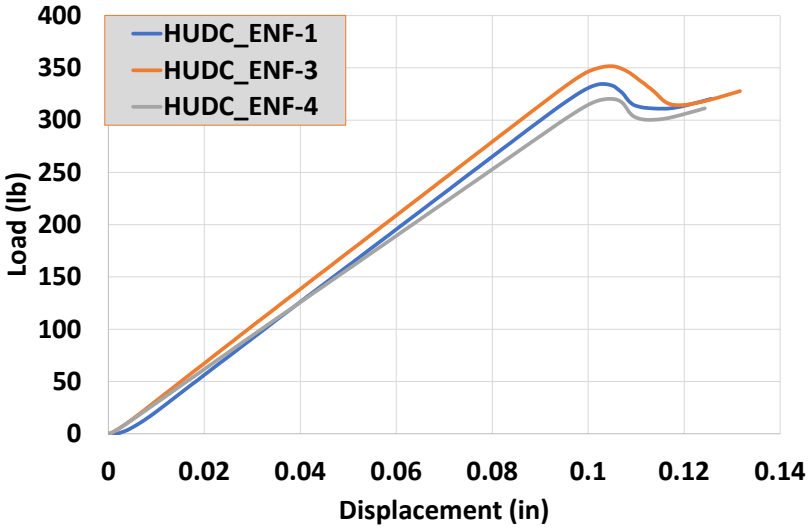


Figure 96.—ENF precracked load versus displacement for HUDC material.

3.13.2 TSFC Results

Specimen Photographs: Photographs of the specimens before and after testing are shown in Figure 97 and Figure 98, respectively, for the TSFC material.

Test Results: A summary of results from the tests on the TSFC material is reported in Table 58. In Figure 99, the experimentally measured load is plotted against displacement that occurred at the load point.

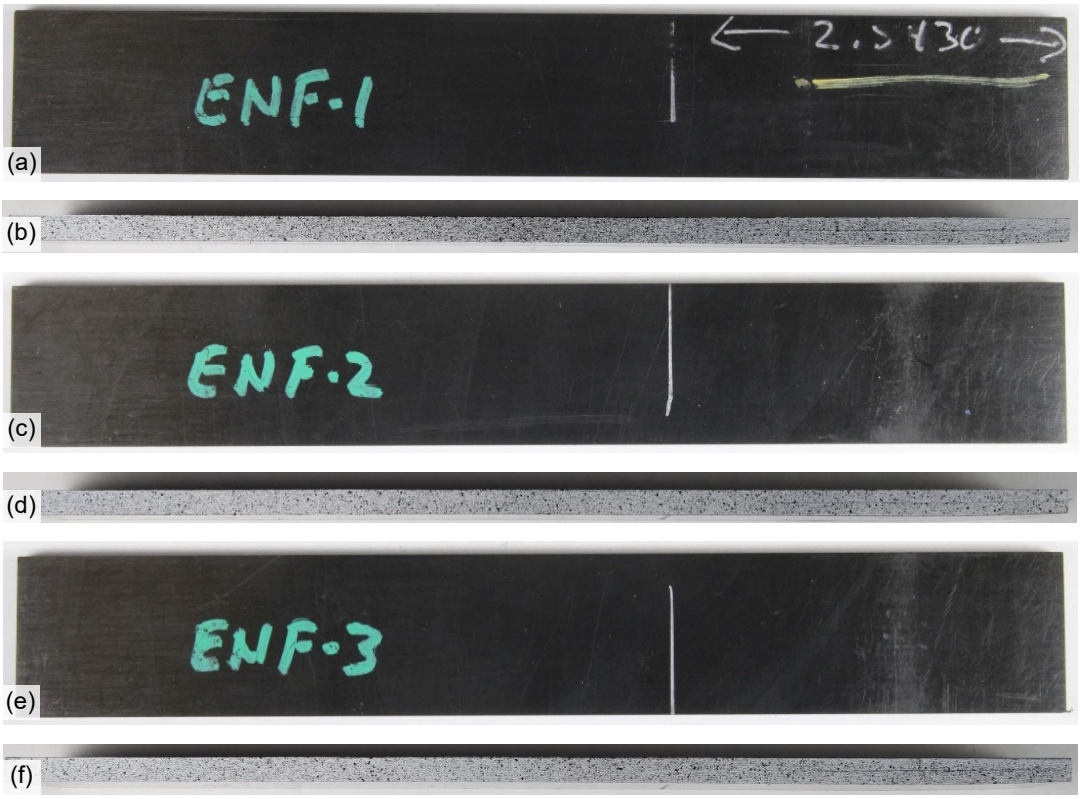


Figure 97.—ENF specimen prior to testing (top surface showing specimen width; side of specimen showing thickness). (a) TSFC_ENF-1 (plan view). (b) TSFC_ENF-1 (elevation). (c) TSFC_ENF-2 (plan view). (d) TSFC_ENF-2 (elevation). (e) TSFC_ENF-3 (plan view). (f) TSFC_ENF-3 (elevation).

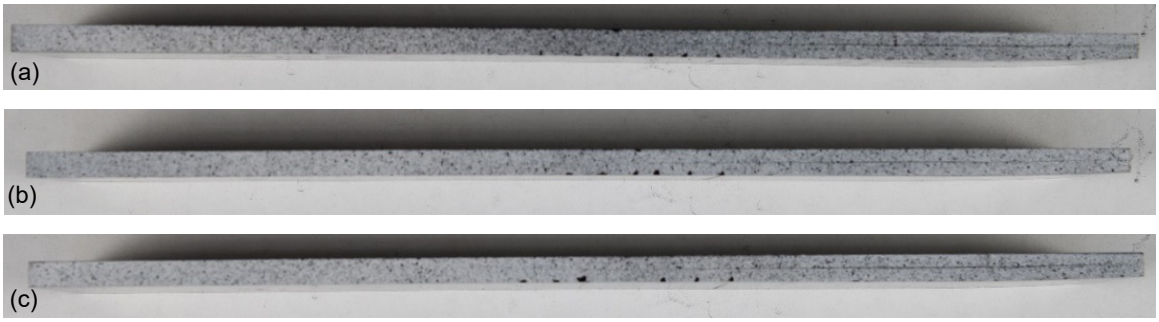


Figure 98.—ENF specimen after testing. (a) TSFC_ENF-1. (b) TSFC_ENF-2. (c) TSFC_ENF-3.

TABLE 58.—SUMMARY OF ENF TEST RESULTS FOR TSFC MATERIAL

Replicate	Loading rate, in/min	Stiffness, lb/in	Ultimate displacement, in	Peak load, lb	Area under load-displacement curve, lb-in
TSFC_ENF-1	0.024	2,589.6	0.115	294.9	15.51
TSFC_ENF-2	0.024	2,566.4	0.119	297.2	17.29
TSFC_ENF-3	0.024	2,508.8	0.113	278.6	15.30
Average	-------	2,554.9	0.116	290.2	16.03
Standard deviation	-------	41.62	0.0030	10.13	1.09
Coefficient of variation	-------	1.6%	2.6%	3.5%	6.8%

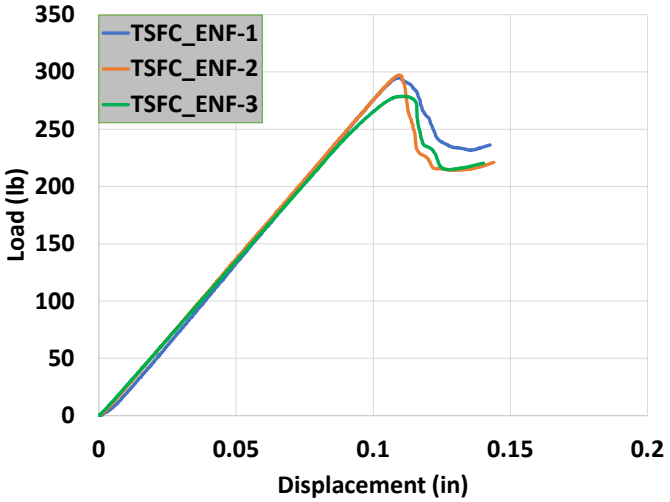


Figure 99.—ENF precracked load versus displacement for TSFC material.

4.0 Test T15: Specific Gravity Test

The mass density of the material was found in accordance with ASTM D792-13, Standard Test Methods for Density and Specific Gravity (Relative Density) of Plastics by Displacement (Ref. 16). First, the mass of the specimens in air was found using a scale. Second, a beaker was filled with water and the specimens were immersed in the liquid using a wire to suspend the specimen in the liquid and to prevent the specimen from contacting the beaker. The apparent mass of the specimen and the submerged portion of the wire in water were recorded. Third, the wire was submerged up to the same point as in the second step and its apparent mass in water was recorded. Using all three measurements, the specific gravity of the material was determined using Equation (4),

$$S_g = \frac{a}{a + w - b} \tag{4}$$

where
S_g = specific gravity
a = apparent mass of specimen in air
b = apparent mass of completely immersed specimen and partially immersed wire in liquid
w = apparent mass of partially immersed wire in liquid

The samples used in the experiment were taken from the edge of the panels. The process was calibrated and verified by first using aluminum. The specific gravity obtained using aluminum was 2.70, which is within the reported range.

Mass measurements were made using an AWS® (American Weigh Wholesale, Inc.) AL201S Analytical Balance, which has a resolution of 0.1 mg. The stand and beaker shown in Figure 100 are part of a specific gravity kit obtained from Mineralab® (Huish Enterprises, LLC).

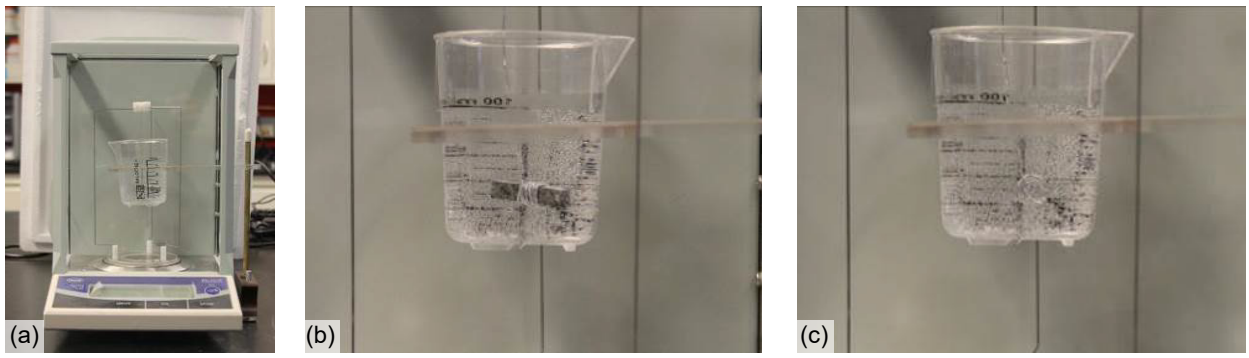


Figure 100.—Specific gravity test. (a) Overall test setup. (b) Specimen and wire submerged in water. (c) Wire submerged in water.

4.1.1 HUDC Results

Test Results: Using the mass measurements, the specific gravity was multiplied by the mass density of water to determine the mass density of each specimen, as shown in Table 59 for the HUDC material system. A 123-ply panel with a 0.90-in (22.9-mm) nominal thickness was used for specific gravity measurements.

4.1.2 TSFC Results

Test Results: Using the mass measurements, the specific gravity was multiplied by the mass density of water to determine the mass density of each specimen, as shown in Table 60 for the TSFC material system. A 180-ply panel with a 0.90-in (22.9-mm) nominal thickness was used for specific gravity measurements.

TABLE 59.—SPECIFIC GRAVITY MEASUREMENTS FOR HUDC MATERIAL

Replicate	Mass: specimen in air, g	Mass: wire + specimen submerged, g	Mass: wire submerged, g	Specific gravity
HUDC_SG-1	3.1973	1.839	0.683	1.566
HUDC_SG-2	3.1897	1.837	0.683	1.567
HUDC_SG-3	3.1800	1.839	0.683	1.569
Average	-------	-------	------	1.567
Standard deviation	-------	-------	------	0.0012

TABLE 60.—SPECIFIC GRAVITY MEASUREMENTS FOR TSFC MATERIAL

Replicate	Mass: specimen in air, g	Mass: wire + specimen submerged, g	Mass: wire submerged, g	Specific gravity
TSFC_SG-1	2.1753	1.4523	0.69	1.5395
TSFC_SG-2	2.1777	1.4500	0.69	1.5361
TSFC_SG-3	2.1690	1.4460	0.69	1.5350
Average	--------	--------	-----	1.5369
Standard deviation	--------	--------	-----	0.0019

5.0 Concluding Remarks

This report presented laboratory testing details and data analysis results for two unidirectional composite material systems: (1) HUDC (HexPly® unidirectional composite), a continuous fiber (CF) unidirectional carbon fiber polymer composite system, and (2) the discontinuous short fiber composite system known as TSFC (Tailorable Universal Feedstock for Forming (TuFF) short fiber composite). Tests were conducted at room temperature and at quasistatic loading conditions, and data were obtained from analysis of the laboratory tests for the HUDC and TSFC unidirectional composites. Stress-strain curves from 11 different tests were obtained and presented. In addition, the mass density and volume fraction of both composites were obtained.

In summary, comparison of the mechanical properties of the TuFF fiber composite to those of the CF composite indicated that the TuFF material system has nearly equivalent (less than 15% difference) elastic moduli in all three principal material directions. Similarly, the TuFF fiber composite's strengths under both tension and compression in the fiber direction, as well as the in-plane shear moduli, showed nearly equivalent values as compared to the CF composite. Improved transverse strength, in-plane shear strength, and both out-of-plane shear moduli were seen in the TuFF material. The TuFF material system, however, showed a significant reduction (~40%) in through-thickness tensile strength as compared to the CF material system.

Appendix

TABLE A.1.—COMPOSITE MECHANICAL PROPERTY SUMMARY
USING AVERAGE VALUES FROM EXPERIMENTAL TESTS

	Continuous fiber	TuFF
Ply Properties		
Ply thickness, in.	0.0073	0.0048
Specific gravity	1.567	1.537
Young's modulus, Msi		
E_{11T}	23.303	19.991
E_{22T}	1.319	1.352
E_{33T}	1.300	1.199
E_{11C}	21.934	19.504
E_{22C}	1.268	1.306
E_{33C}	1.482	1.307
Shear modulus, Msi		
G_{12}	0.927	0.803
G_{23}	0.548	0.747
G_{13}	1.594	1.946
Poisson's ratio		
ν_{12}	0.3457	0.3693
ν_{21}	0.0289	0.0311
ν_{32}	0.3476	0.4092
ν_{31}	0.0191	0.015
Strength, ksi		
Longitudinal tensile strength, σ^{UT1}	400.17	360.05
Longitudinal compressive strength, σ^{UC1}	112.93	121.58
Transverse tensile strength, σ^{UT2}	12.61	16.18
Transverse compressive strength, σ^{UC2}	31.44	28.99
Through-thickness tensile strength, σ^{UT3}	6.36	4.05
Through-thickness compressive strength, σ^{UC3}	32.78	36.68
Longitudinal shear 5% strength, τ^{U12}	12.10	16.76
Transverse shear 5% strength, τ^{U13}	14.43	14.16
Through-thickness shear ult. strength, τ^{U23}	7.07	7.06
Failure/Energy Evolution		
Initiation mode I fracture energy	4.65[a]	5.26

[a]Average of HUDC_DCB-5 and DCB-6.

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