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Experimental Tests to Characterize the Behavior and Properties of IM7-8552 Composite

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Contents

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1.0 Overview

This document summarizes the test procedures for characterizing the quasi-static (QS), room temperature (RT) behavior of IM7/8552 unidirectional composite material. All testing reported in this document follow applicable ASTM[1] test standards as closely as possible, with any deviations reported. The overall objective is to develop a framework for the creation of MAT213 material input for use in the LS-DYNA program (LSTC, 2016). Details of the MAT213 material model and its implementation are available publicly (Goldberg et al., 2015; Harrington et al., 2016; Hoffarth et al., 2016). However, the measured properties can be utilized by most composite impact models.

The IM7/8552 composite utilized here is a unidirectional carbon fiber/epoxy resin composite system (Figure 1). The material characteristics reported by Ng and Tomblin (2013) are shown in Table 1.

2.0 Input for MAT213 Material Model and Required Material Characterization Tests

Characterization of the composite behavior requires 12 stress-strain curves as summarized in Table 2. Three different panel types were used to create the test specimens. The panels chosen to create the respective specimens are shown in Table 2. The panel dimensions are shown in Table 3. Two PT1 panels were used from which tension (1 and 2-directions), compression (1 and 2-directions), shear 1-2 plane, and off-axis tension (45°, 1-2 plane) specimens were made. The two panels are labeled PT1-1 and PT1-2.

2.1 Sample Preparation

The sample preparation was performed at Cincinnati Testing Laboratories (CTL). 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 were extracted approximately 1/8 in. oversized for all dimensions. 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 specimens) was performed using a dressed diamond wheel.

[1] https://www.astm.org

Upon completion of the machining process, each specimen was dimensionally inspected per the relevant ASTM test standards. The devices used for the inspection are those that are required by those test standards.

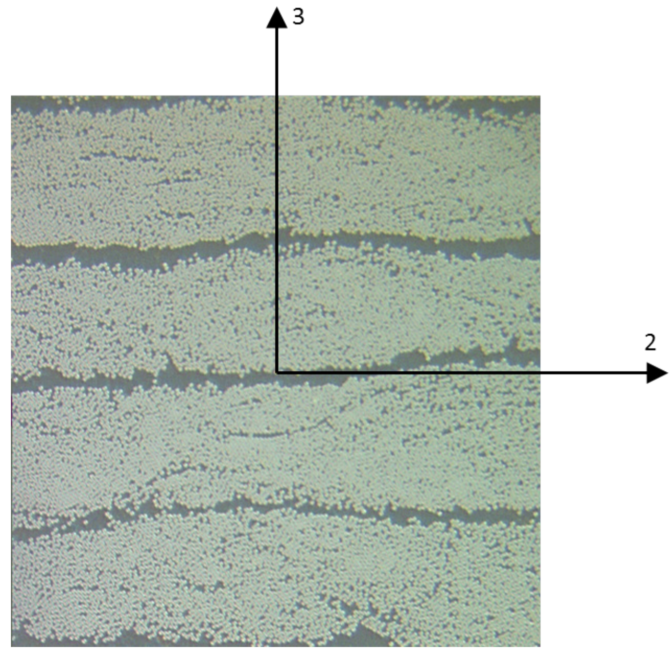

Figure 1.—Principal material directions shown in the optical microscopy image of a representative composite (the unidirectional fibers are oriented in the 1-direction).

TABLE 1.—NOMINAL COMPOSITE CHARACTERISTICS

Resin content, wt.%	35±2
Cured ply thickness, mm	0.18
Fiber areal weight, g/m^2	190

TABLE 2.—SUMMARY OF TEST SUITE

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

TABLE 3.—PANELS USED FOR TESTS

Panel type	Nominal dimensions (length by width)	Nominal thickness, mm (no. of piles)
PT1	12 by 24 in.	3.048 (16)
PT2	12 by 12 in.	22.86 (120)
PT3	12 by12 in.	4.57 (24)

2.2 Test Machines, Fixtures, Equipment and Software

All experiments are performed using three different test frames and the same camera system. Post processing of the experimental images is performed using the same software as described below.

Test Frame: The experimental procedure is performed using three different test frames—a MTS 810 test frame (Figure 2(a)), an Instron 1332 test frame (Figure 2(i)), and a MTS Exceed test frame (Figure 2(j)). Flat tension specimens are held in the frame with MTS 647.10A hydraulic grips (Figure 2(b)). The hydraulic grips are aligned by clamping a rigid, flat steel plate and allowing the heads to freely rotate into position. After aligning the hydraulic grips, the specimen is placed into the test frame. Verticality of the specimen is ensured by using a laser alignment system (Figure 2(c)). The specimen is gripped up to the end of the fiberglass tabs. Shear specimens are held in the test frame using a Wyoming Test Fixtures Iosipescu shear test fixture[2] as shown in Figure 2(d). Custom fixture for compression tests were used to test compression cubes as shown in Figure 2(e). Alignment of the specimen is ensured using 0.2 in. deep square notches machined into the center of the fixtures as shown in Figure 2(f). Flat (in-plane) compression specimens were tested using a Wyoming Test Fixtures combined loading compression fixture (CLC) as shown in Figure 2(g) and (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 is gathered using the load cell. All experiments are 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.

Digital Image Correlation (DIC) Equipment: Two Point Grey Grasshopper 3[3] cameras are used to capture images of the specimen throughout the duration of the experiment as shown in Figure 2(m). LED lamps are used to properly illuminate the specimen during the experiment. The cameras and lights are fixed to the same frame (Figure 2(n)). The frame is leveled using a bubble level in order to ensure the field of view of the cameras is both horizontal and vertical respectively. Unless otherwise noted, images are captured at five second intervals throughout the experiment using Vic-Snap 9 (CSI, 2021) for the purpose of obtaining the strain field on the surface of the specimen.

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[2] http://www.wyomingtestfixtures.com/Products/a1.html
[3] https://www.ptgrey.com/grasshopper3-gige-vision-cameras

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) 3-point bend fixture, (m) Two DIC cameras and high-speed camera, and (n) LED lighting fixture.

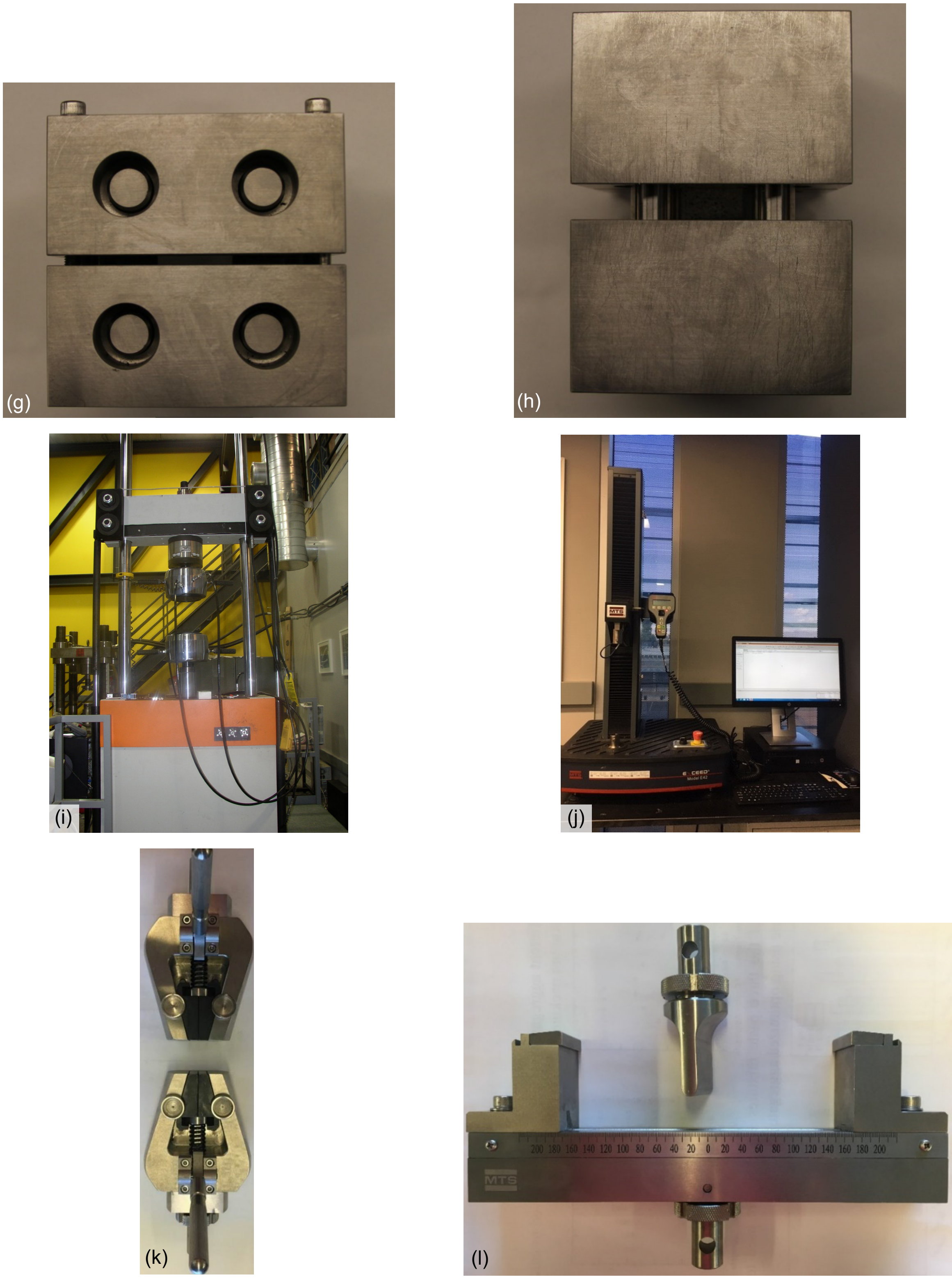

Figure 2.—Continued.

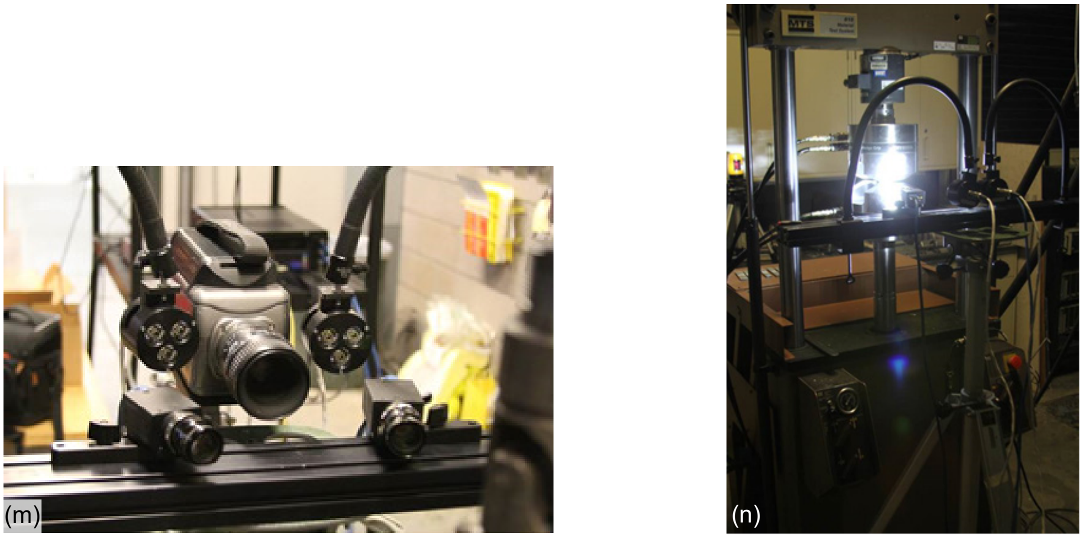

Figure 2.—Concluded.

Post Processing: The images captured during the experiment are processed for the purpose of obtaining a full strain field using Vic-3D v9 (CSI 2021). The Lagrangian definition of strain is chosen to perform the analysis. A functionality within the Vic-3D software is used to smooth the strain data using a decay filter algorithm. For the initial processing, the entire speckled region of the specimen is analyzed. After the analysis and smoothing are completed, a smaller region with constant strain is 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 are obtained and reported) is referred to as the *strain gage section* (SGS). Sample images are shown in Figure 3. The selection of the SGS is somewhat arbitrary and alternative methods have been suggested by others (Haluza et al., 2022).

Measurement Instruments: Pittsburgh 4 in. Digital Caliper[4] was used to obtain specimen dimensions that involves measuring width and thickness at 3 equally spaced intervals and using the average value for calculation of cross-sectional areas.

2.3 Typical Test Procedure

The procedure for conducting experiments is the same for each specimen unless otherwise noted. For all experiments, prior to loading the specimen, the DIC system is calibrated using Vic 3D v9 (CSI 2021). 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 were calibrated.

[4] https://go.harborfreight.com/sku/63710/

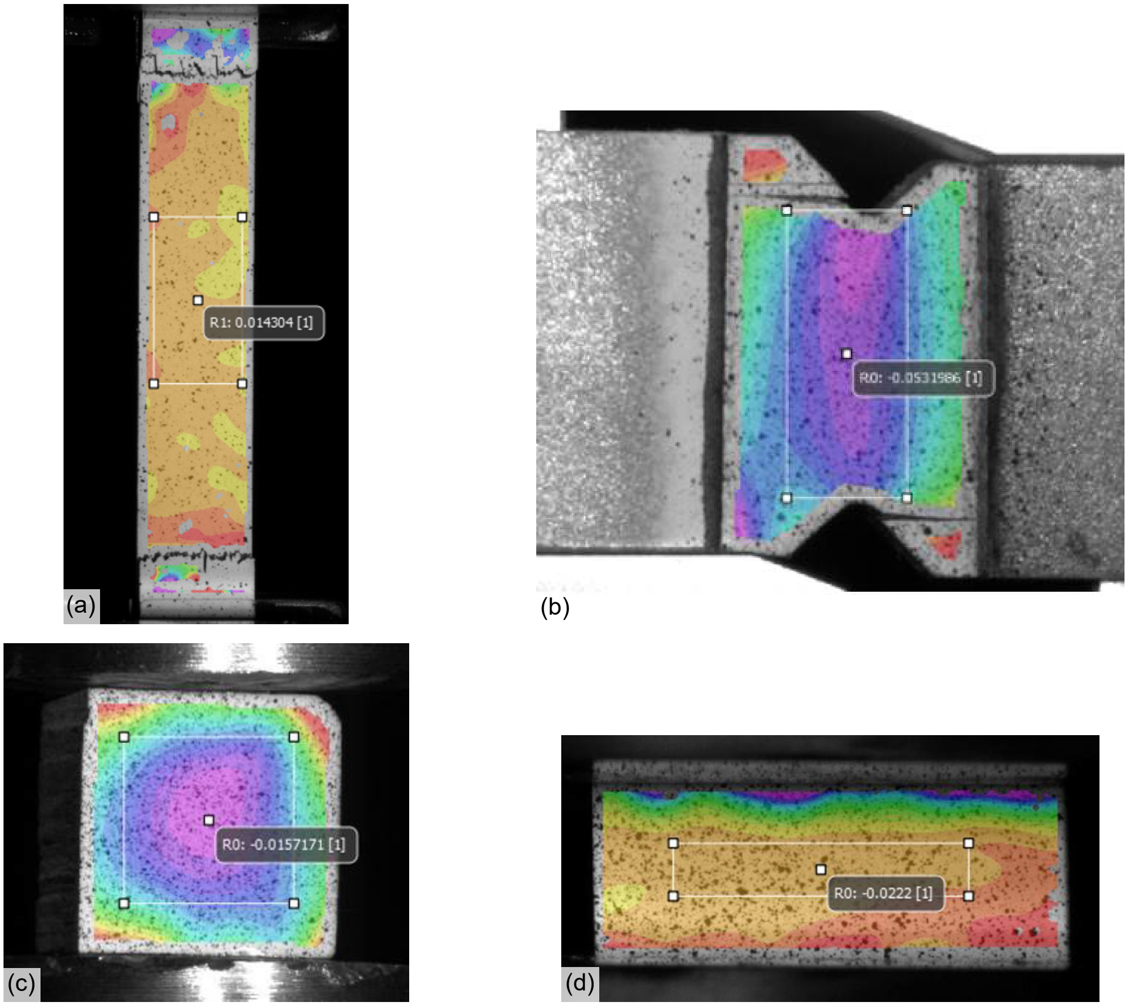

Figure 3.—Typical SGS (a) tension specimens, (b) shear specimens, (c) compression specimens (cube), and (d) compression specimens (flat panel).

2.4 Post-Processing of Test Data

After the experiments are completed, force data is obtained as a function of time from the test frame's controller, and strain data is obtained as a function of time from DIC analysis. The stress in the specimen is 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 is used to calculate the cross-sectional area. The average stress is 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, is used to calculate the cross-sectional area. The average stress is calculated using the following 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 v7 in the region of interest is used in conjunction with the calculated stress to generate a true stress-strain curve for any given specimen. Several parameters are obtained from the stress strain curves of each individual specimen for the purpose of determining how consistent the data is. Table 4 describes each parameter and how they are obtained from the available data.

TABLE 4.—DESCRIPTIONS OF THE 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 which 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 post-peak 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 used when 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 QS-RT Test Details and Results

Details of each test are discussed in this section. Applicable ASTM standards are used. However, there are deviations from the standards for some tests and the deviations are noted in the report.

3.1 Test T1: In-Plane 0° Tension Test

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

Specimen Geometry: ASTM D3039 standard is applicable for this test. The specimen geometry details are shown in Figure 4. Two specimen types were considered. Figure 4(b) shows the flat 16-ply thick constant thickness specimen. Figure 4(c) shows the flat specimen that is then machined to reduce the thickness in the gage section. It should be noted that due to the high strength in the 1-direction, the specimens with the reduced thickness are necessary to obtain a full stress-strain curve until the specimen fails. Shaded regions indicate where fiberglass tabs are bonded to the specimen.

The average specimen dimensions in the gage section are shown in Table 5 for the five tested replicates.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 5. Figure 6 shows the specimens after testing. The specimens exhibited longitudinal cracks in the matrix between the fibers at failure.

Test Results: The summary of the results from the tests is shown in Table 6. IM7T1-1 and IM7T1-3 tests (corresponding to the constant thickness specimens) were not carried out till failure because the attached fiberglass tabs debonded (Figure 6(a) and (b)) before the specimen failed. Therefore, the stress strain curve for these two replicates are plotted up to maximum stress achieved during the experiment.

Figure 7 shows the individual stress-strain curves for each of the specimens.

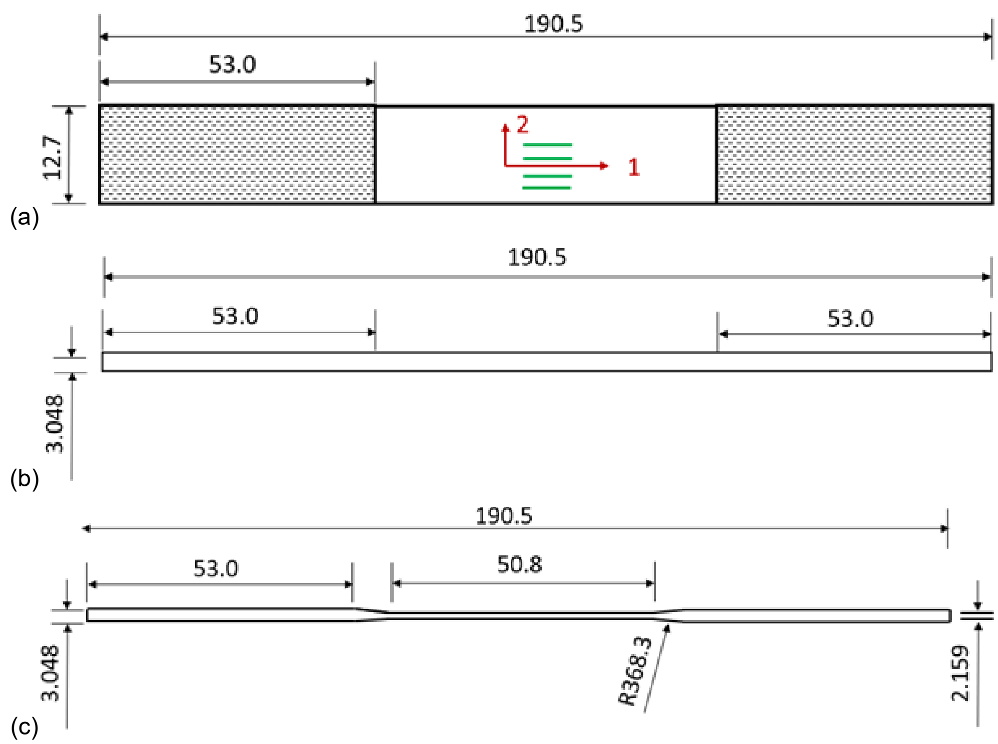

Figure 4.—Typical specimen geometry and layout (a) plan view, (b) flat specimen elevation view, and (c) reduced thickness in the gage section elevation view (all dimensions in mm).

TABLE 5.—ONE-DIRECTION TENSION TEST SPECIMEN DIMENSIONS

Replicate ID	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7T1-1	0.503	0.111	0.056
IM7T1-3	0.503	0.116	0.058
IM7T1-4	0.503	0.088	0.043
IM7T1-5	0.503	0.087	0.043
IM7T1-6	0.502	0.086	0.043

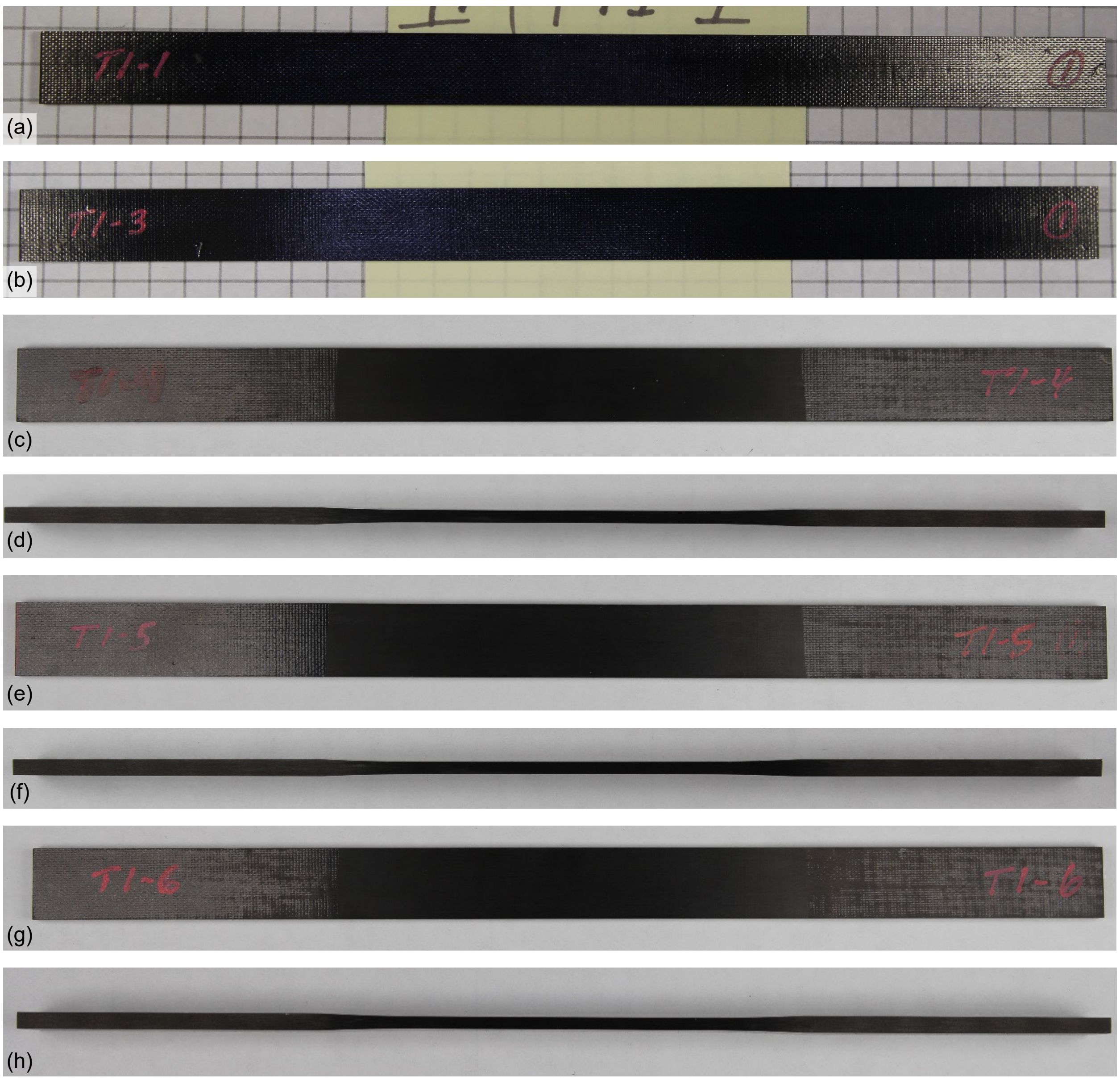

Figure 5.—One-direction tension specimens before testing (a) IM7T1-1, (b) IM7T1-3, (c) IM7T1-4 (plan view), (d) IM7T1-4 (elevation), (e) IM7T1-5 (plan view), (f) IM7T1-5 (elevation), (g) IM7T1-6 (plan view), and (h) IM7T1-6 (elevation).

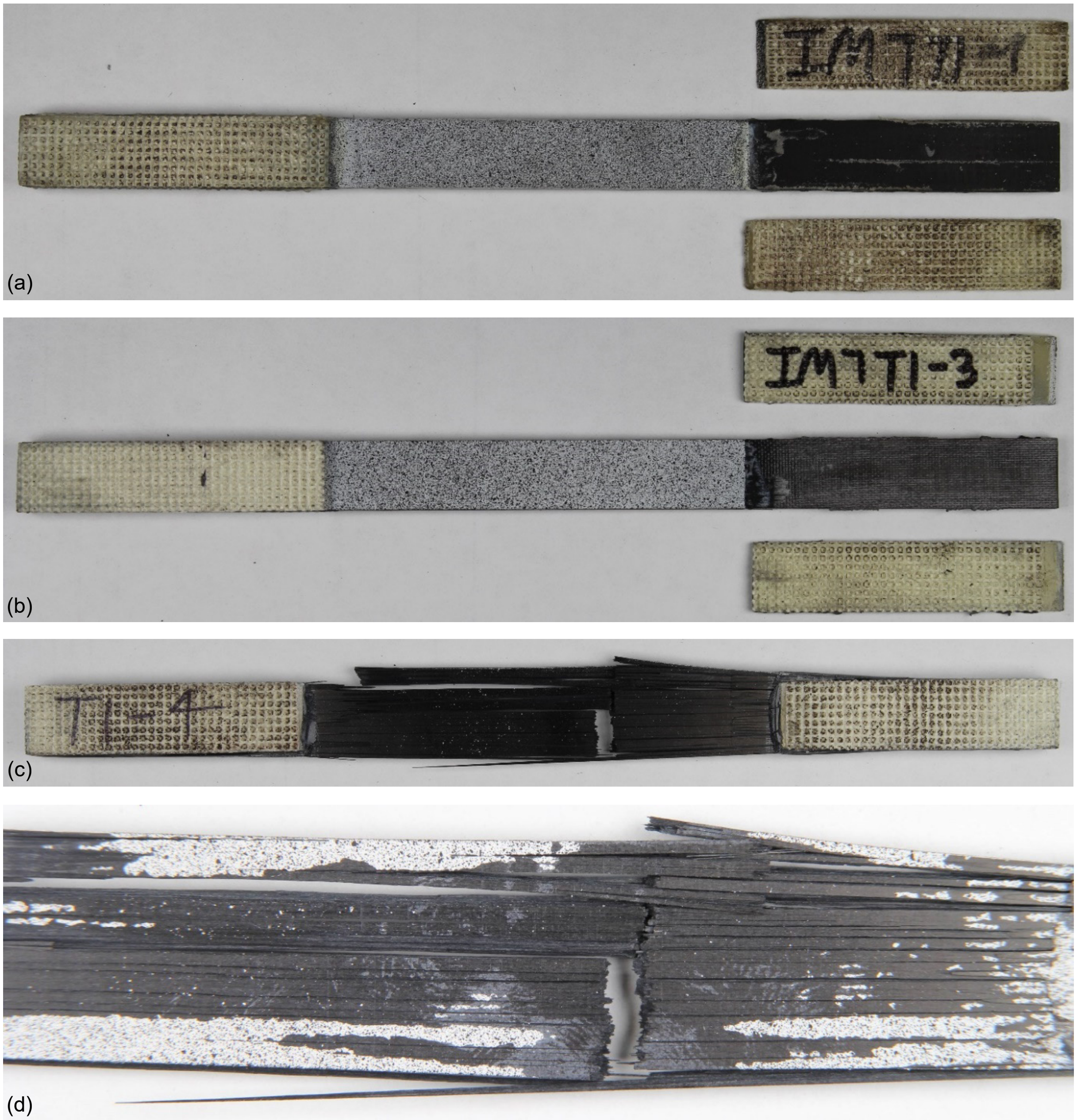

Figure 6.—One-direction tension specimens after testing (a) IM7T1-1, (b) IM7T1-3, (c) IM7T1-4, (d) IM7T1-4 (close-up), (e) IM7T1-5, (f) IM7T1-5 (close-up), (g) IM7T1-6, and (h) IM7T1-6 (close-up).

Figure 6.—Concluded.

TABLE 6.—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
IM7T1-1	0.002	1.11×10^{-5}	24,817,318	0.3423	----------	----------
IM7T1-3	0.002	1.11×10^{-5}	22,744,684	0.3347	----------	----------
IM7T1-4	0.002	1.11×10^{-5}	22,848,270	0.3170	0.01690	407,499
IM7T1-5	0.002	1.11×10^{-5}	23,220,874	0.3366	0.01569	378,402
IM7T1-6	0.002	1.11×10^{-5}	23,246,299	0.3168	0.01604	391,111
Average	--------	------------	23,105,148	0.3235	0.01621	392,337
Standard deviation	--------	------------	222,826	0.0114	0.00062	14,587
Coefficient of variation	--------	------------	1.0%	3.5%	3.8%	3.7%

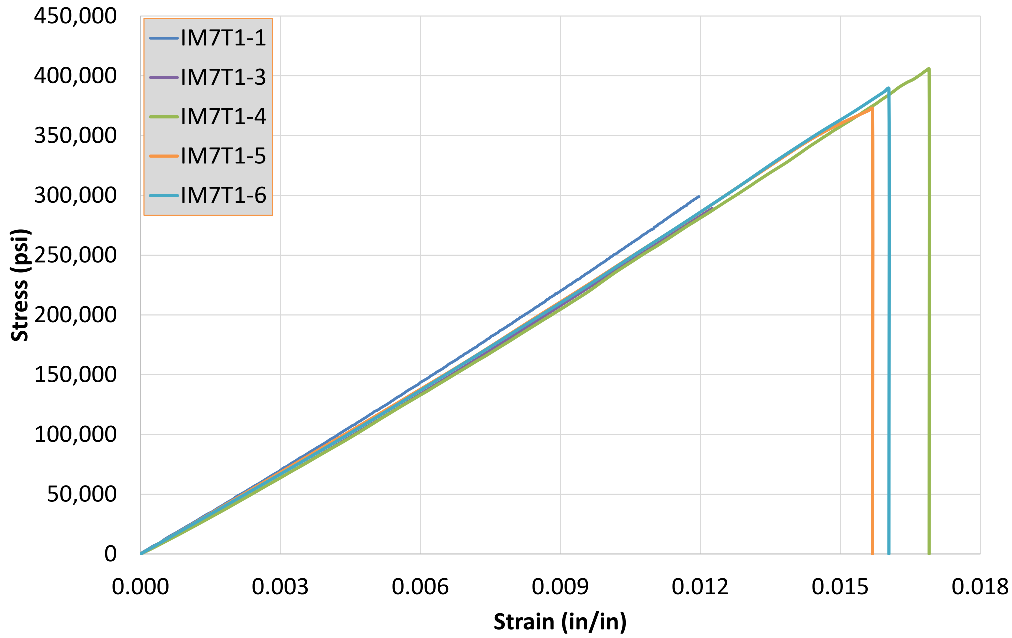

Figure 7.—One-direction tension stress-strain curves.

3.2 Test T2: In-Plane 90° Tension Test

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

Specimen Geometry: The specimen dimensions and layout are shown in Figure 8. The specimen geometry shown in Figure 8 is taken from ASTM D3039. Shaded regions indicate where the fiberglass tabs are bonded to the specimen.

The average specimen dimensions in the gage section are shown in Table 7 for the three tested replicates.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 9. The specimens exhibited brittle cracking in the matrix near the grip before the tests were terminated and at failure. Figure 10 shows the specimens after testing. The highlighted red box shows where the specimen has fractured.

Test Results: The summary of the results from the tests is shown in Table 8.

Figure 11 shows the individual stress-strain curves for each of the specimens.

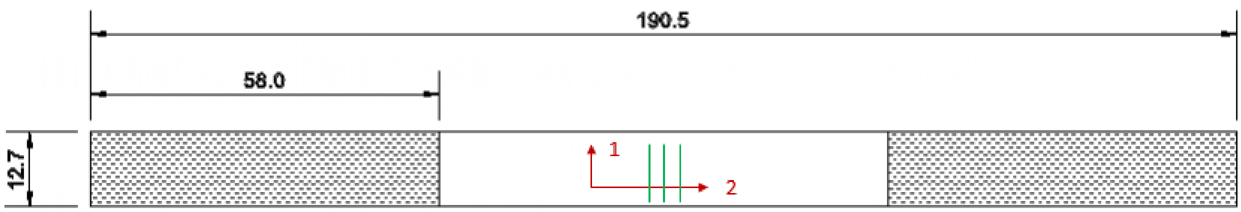

Figure 8.—Typical specimen geometry and layout (dimensions in mm).

TABLE 7.—TWO-DIRECTION TENSION TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7T2-1	0.503	0.116	0.058
IM7T2-2	0.501	0.116	0.058
IM7T2-4	0.502	0.116	0.058

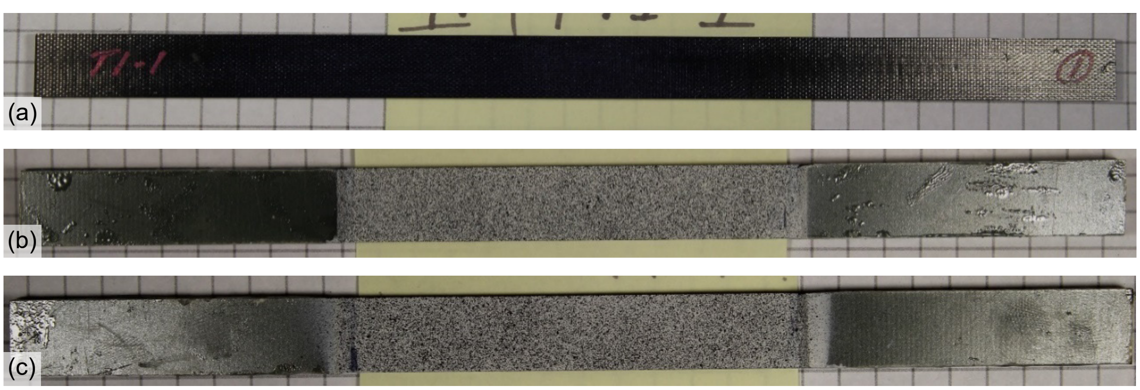

Figure 9.—Two-direction tension specimens before testing (a) IM7T2-1, (b) IM7T2-2, and (c) IM7T2-4.

Figure 10.—Two-direction tension specimens after testing (a) IM7T2-1, (b) IM7T2-2, and (c) IM7T2-4.

TABLE 8.—SUMMARY OF 2-DIRECTION TENSION TEST RESULTS

Replicate	Loading rate, in./min	Strain rate, 1/s	E_{22}, psi	Poisson's ratio, ν_{21}	Ultimate strain	Peak stress, psi
IM7T2-1	0.0025	1.39×10^{-5}	1,292,255	0.0201	0.01071	12,087
IM7T2-2	0.0025	1.39×10^{-5}	1,302,960	0.0215	0.01021	11,901
IM7T2-4	0.0025	1.39×10^{-5}	1,302,796	0.0208	0.00976	11,238
Average	---------	-----------	1,299,337	0.0208	0.01023	11,742
Standard deviation	---------	-----------	6,134	0.0007	0.00048	446
Coefficient of variation	---------	-----------	0.5%	3.4%	4.7%	3.8%

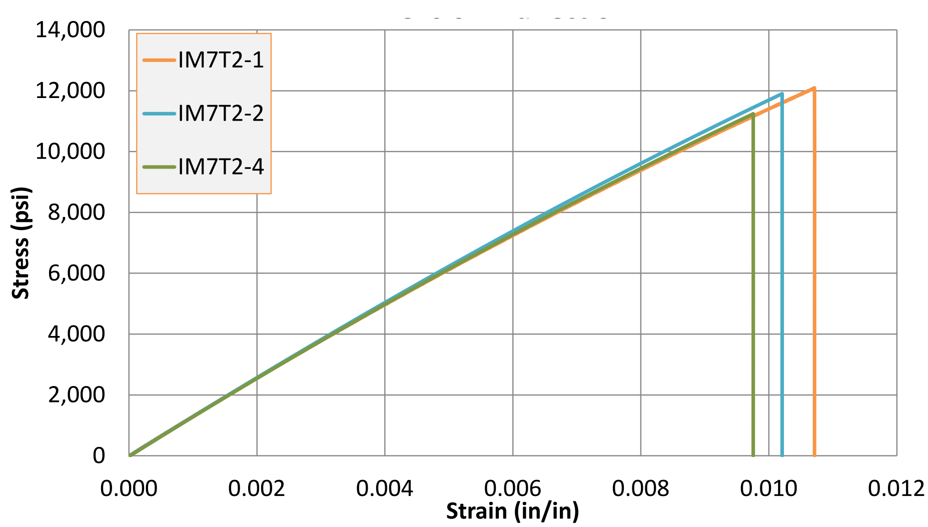

Figure 11.—Two-direction tension stress-strain curves.

3.3 Test T3: Out-of-Plane Tension Test

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 12. ASTM standard could not be followed when creating the specimens because the specimen geometry is dictated by the thickness of the test panel. Only one principal plane 1-3 is considered when gathering strain data during this test.

The average specimen dimensions in the gage section are shown in Table 9 for the three tested replicates.

Specimen Preparation: The maximum length of the specimen is dictated by the thickness of the 120-ply panel. Sufficiently long specimens are needed to properly secure the specimen 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 13 shows the rendering of the fiberglass tabbing system. Approximately one-third of either end of the specimen is then placed inside the pocket and is bonded to the fiberglass tabs using 3M DP460 Scotch Weld toughened two-part epoxy.

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.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 14. The specimens exhibited brittle failure of the matrix in the middle of the gage section for specimen IM7T1-3 and near the grip area for other two specimens. Figure 15 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 10.

Figure 16 shows the individual stress-strain curves for each of the specimens.

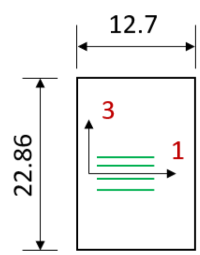

Figure 12.—Typical specimen geometry and layout (dimensions in mm).

TABLE 9.—THREE-DIRECTION TENSION TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7T13-3	0.371	0.061	0.023
IM7T13-4	0.371	0.060	0.022
IM7T13-5	0.371	0.057	0.021

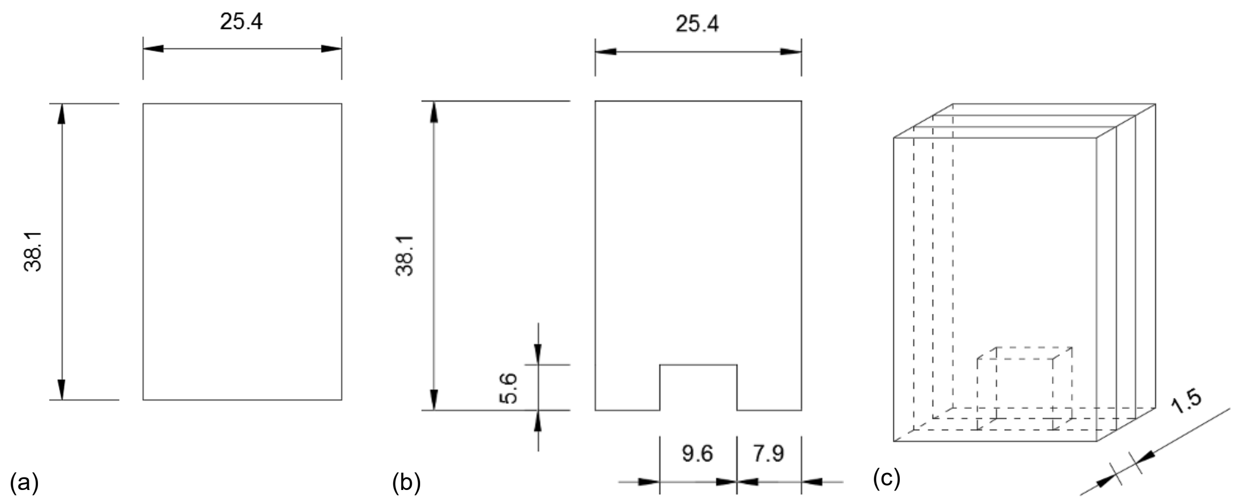

Figure 13.—Fiberglass tab layup geometry (a) outer layers, (b) center layer, and (c) overall layup (dimensions in mm).

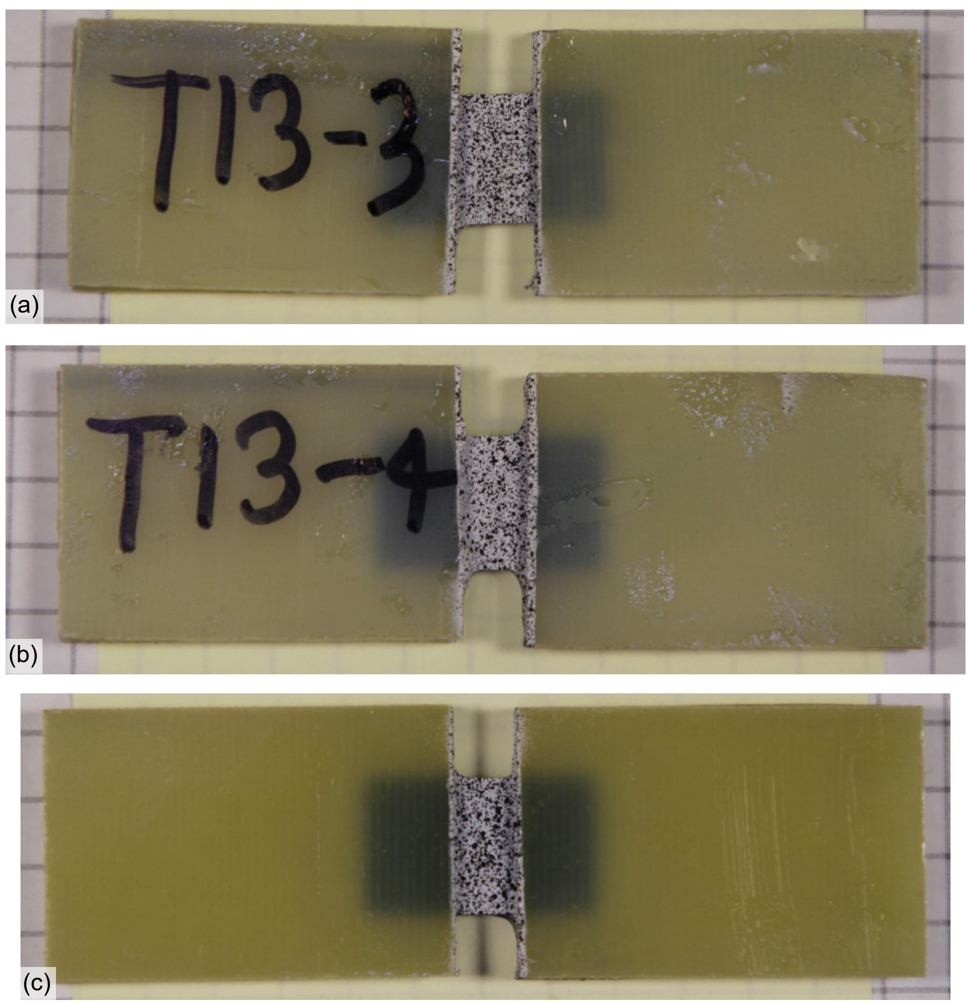

Figure 14.—Three-direction tension specimens prior to testing (a) IM7T13-3, (b) IM7T13-4, and (c) IM7T13-5.

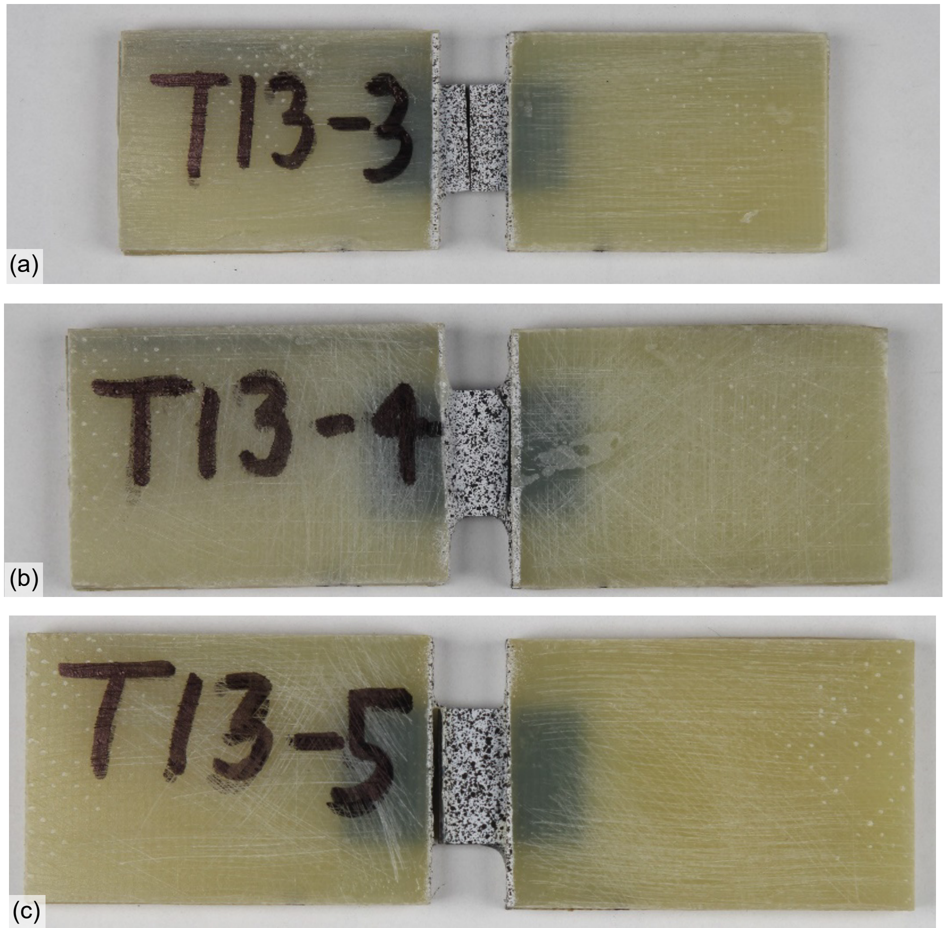

Figure 15.—Three-direction tension specimens after testing (a) IM7T13-3, (b) IM7T13-4, and (c) IM7T13-5.

TABLE 10.—SUMMARY OF 3-DIRECTION TENSION TEST RESULTS

Replicate	Loading rate, in./min	Strain rate, 1/s	E_{33}, psi	Poisson's ratio, ν_{31}	Failure strain	Peak stress, psi
IM7T13-3	0.001	1.85×10^{-5}	1,101,488	0.0231	0.0086	8,379
IM7T13-4	0.001	1.85×10^{-5}	1,047,414	0.0323	0.0077	7,887
IM7T13-5	0.001	1.85×10^{-5}	1,121,080	0.0229	0.0068	7,273
Average	-------	-----------	1,089,994	0.026	0.0077	7,846
Standard deviation	-------	-----------	31,153	0.004	0.0007	453
Coefficient of variation	-------	-----------	2.9%	16.8%	9.3%	5.8%

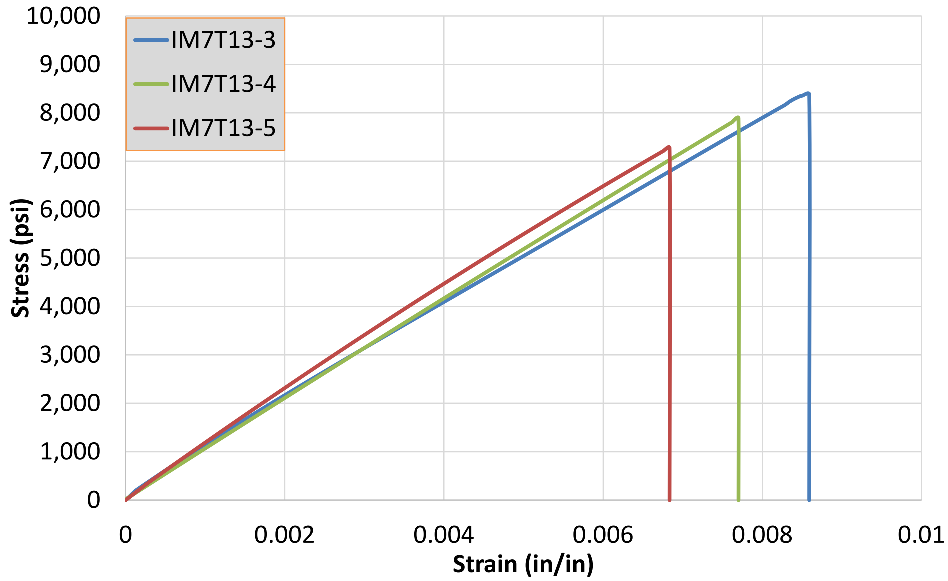

Figure 16.—Three-direction tension stress-strain curves.

3.4 Test T4: In-Plane 0° Compression Test

This test is used to generate the compressive stress-strain curve in the 1-direction. 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 17. The geometry shown is in accordance with the guidelines set forth by ASTM D6641.

The average specimen dimensions in the gage section are shown in Table 11 for the three tested replicates.

Specimen Photographs: The photographs of the specimen before the tests are shown in Figure 18. The specimens exhibited brittle failure by end-crushing and longitudinal matrix splitting in gage area. Figure 19 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 12.

Figure 20 shows the individual stress-strain curves for each of the specimens.

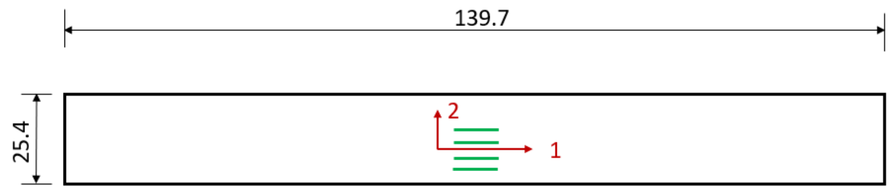

Figure 17.—Typical specimen geometry and layout (dimensions in mm).

TABLE 11.—ONE-DIRECTION COMPRESSION TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7C1-1	1.000	0.120	0.120
IM7C1-3	0.989	0.117	0.117
IM7C1-4	0.999	0.117	0.116

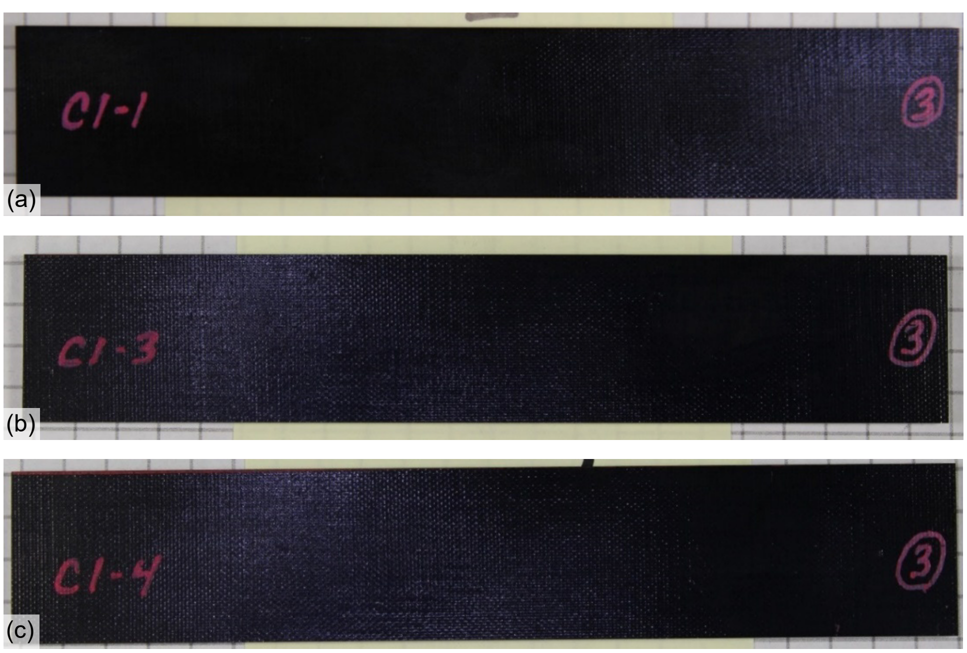

Figure 18.—One-direction compression specimens prior testing (a) IM7C1-1, (b) IM7C1-3, and (c) IM7C1-4.

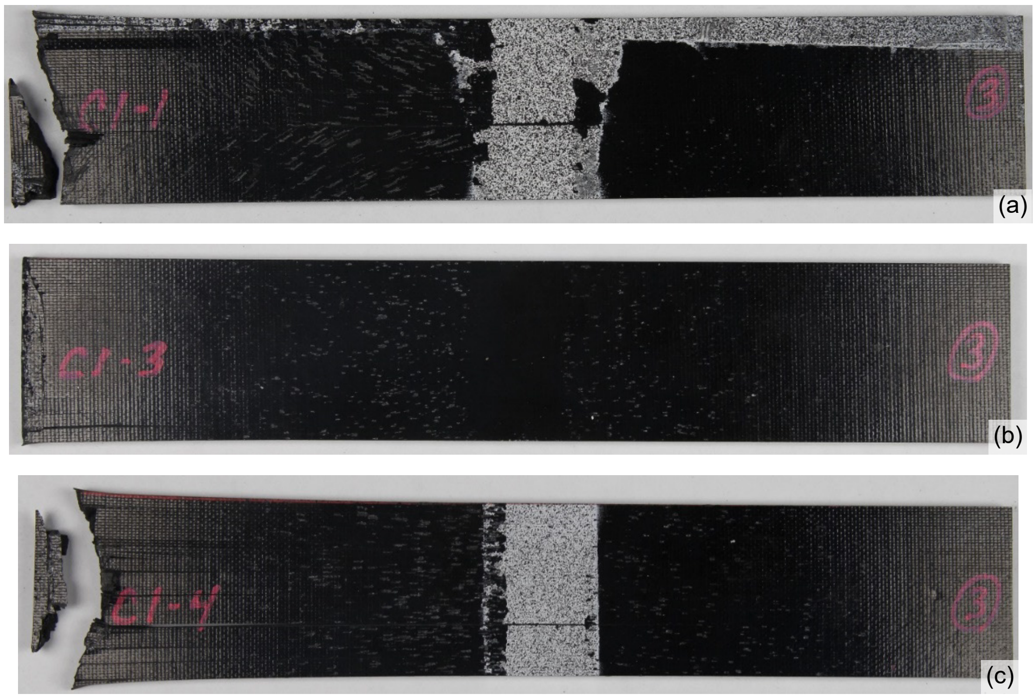

Figure 19.—One-direction compression specimens after testing (a) IM7C1-1, (b) IM7C1-3, and (c) IM7C1-4.

TABLE 12.—SUMMARY OF 1-DIRECTION COMPRESSION TEST RESULTS

Replicate	Loading rate, in./min	Strain rate, 1/s	E_{11}, psi	Ultimate strain	Peak stress, psi
IM7C1-1	0.01	3.03×10^{-5}	19,206,644	0.00638	113,158
IM7C1-3	0.01	3.03×10^{-5}	19,926,195	0.00663	123,618
IM7C1-4	0.01	3.03×10^{-5}	19,220,074	0.00621	113,455
Average	-----	------------	19,450,971	0.00641	116,744
Standard deviation	-----	------------	336,079	0.00017	4,862
Coefficient of variation	-----	------------	1.73%	2.71%	4.17%

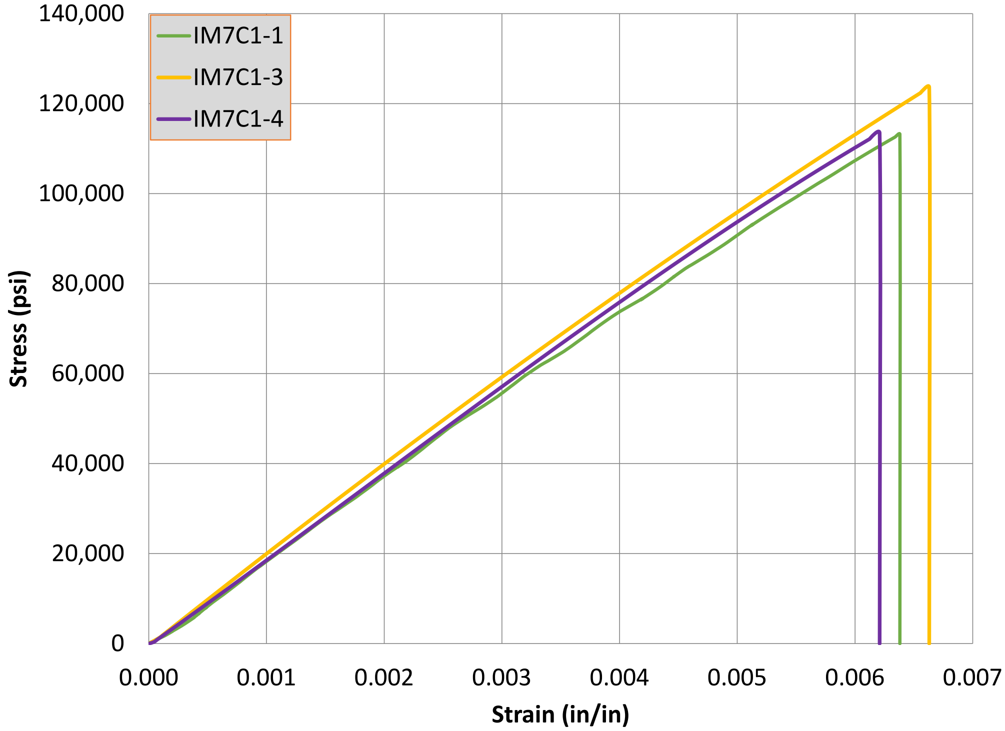

Figure 20.—One-direction compression stress-strain curves.

3.5 Test T5: In-Plane 90° Compression Test

This test is used to generate the compressive stress-strain curve in the in the 2-direction. 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 21. The geometry shown is in accordance with the guidelines set forth by ASTM D3410.

The average specimen dimensions in the gage section are shown in Table 13 for the three tested replicates.

Specimen Photographs: The photographs of the specimen before the tests are shown in Figure 22. The specimens exhibited crushing of the matrix in the middle of the gage section tagged as the BGM[5] mode of failure in the ASTM standard. Figure 23 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 14.

Figure 24 shows the individual stress-strain curves for each of the specimens.

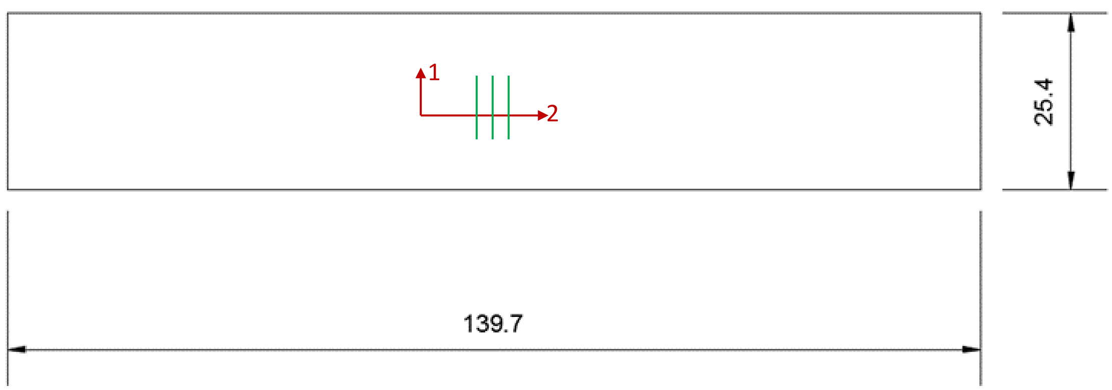

Figure 21.—Typical specimen geometry and layout (all dimensions in mm).

TABLE 13.—TWO-DIRECTION COMPRESSION TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7C2-2	0.999	0.117	0.117
IM7C2-4	0.999	0.119	0.119
IM7C2-5	0.998	0.118	0.118

[5] BGM: B- Brooming, G- Gage, M- Middle

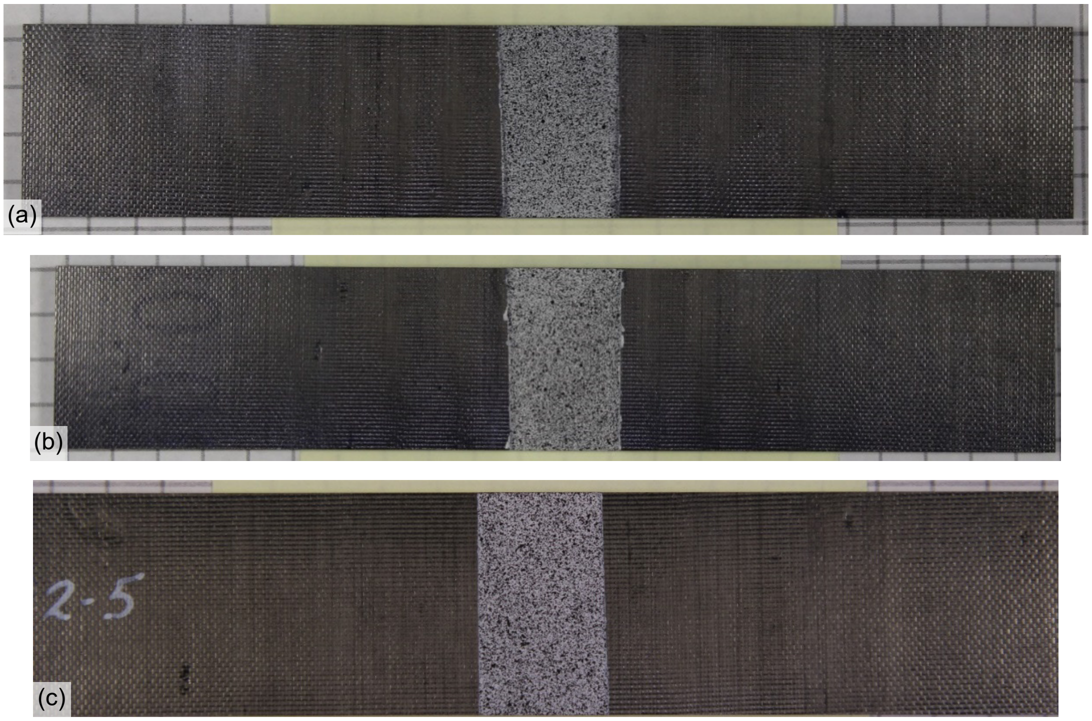

Figure 22.—Two-direction compression specimens prior testing (a) IM7C2-2, (b) IM7C2-4, and (c) IM7C2-5.

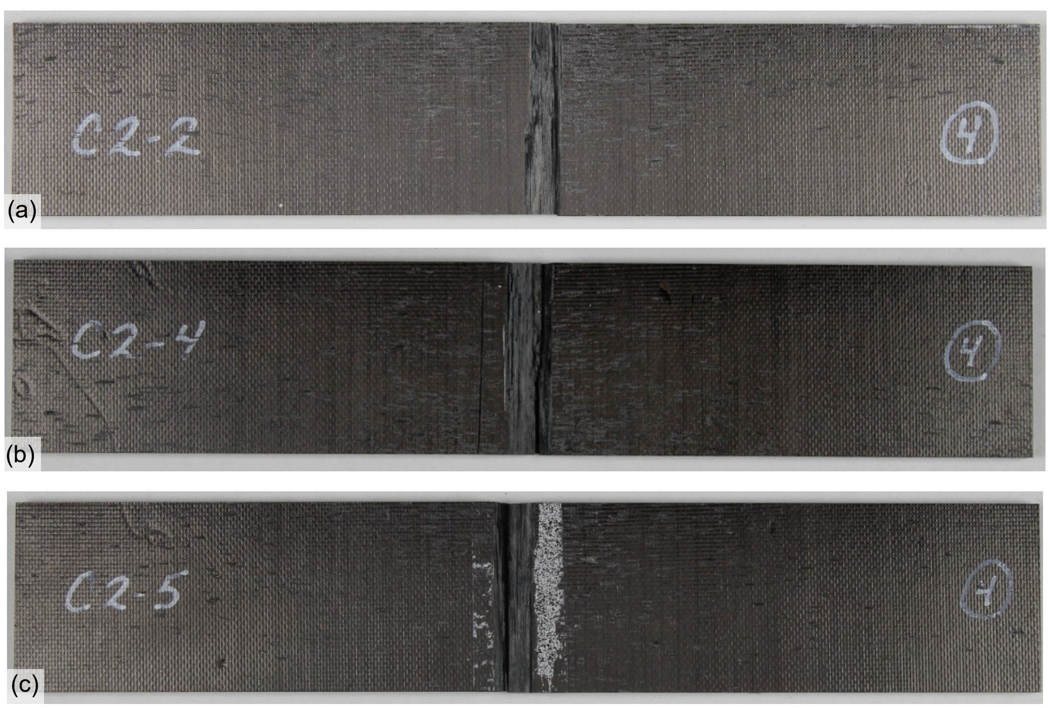

Figure 23.—Two-direction compression specimens after testing (a) IM7C2-2, (b) IM7C2-4, and (c) IM7C2-5.

TABLE 14.—SUMMARY OF 2-DIRECTION COMPRESSION TEST RESULTS

Replicate	Loading rate, in./min	Strain rate, 1/s	E_{22}, psi	Ultimate strain	Peak stress, psi
IM7C2-2	0.01	3.03×10^{-5}	1,367,640	0.03792	34,715
IM7C2-4	0.01	3.03×10^{-5}	1,293,081	0.03964	34,893
IM7C2-5	0.01	3.03×10^{-5}	1,344,136	0.03862	34,616
Average	-----	------------	1,334,952	0.03873	34,741
Standard deviation	-----	------------	31,123	0.00071	115
Coefficient of variation	-----	------------	2.33%	1.82%	0.33%

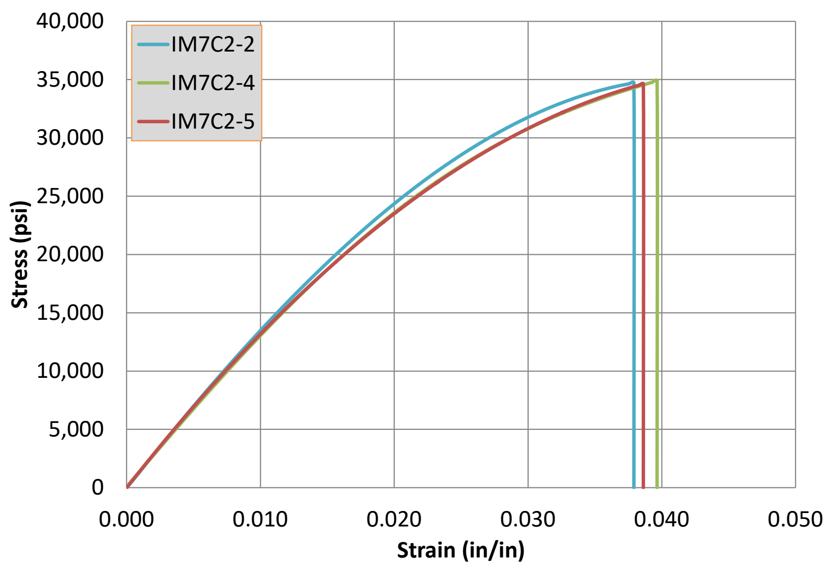

Figure 24.—Two-direction compression stress-strain curves.

3.6 Test T6: Out-of-Plane Compression Test

This test is used to generate the compressive stress-strain curves in the through thickness or 3-direction. 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 25. The geometry shown is a modified version of the geometry set forth by ASTM D7291. 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 1-3 is considered when gathering strain data during any given test.

The average specimen dimensions in the gage section are shown in Table 15 for the three tested replicates.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 26. The specimens exhibited brittle failure of the matrix in the 1-3 plane before the tests were terminated. Figure 27 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 16.

Figure 28 shows the individual stress-strain curves for each of the specimens.

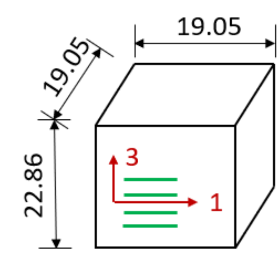

Figure 25.—Typical specimen geometry and layout 1-3 plane speckled (all dimensions in mm).

TABLE 15.—THREE-DIRECTION COMPRESSION TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7C3-2	0.751	0.751	0.564
IM7C3-3	0.751	0.751	0.565
IM7C3-4	0.751	0.751	0.564

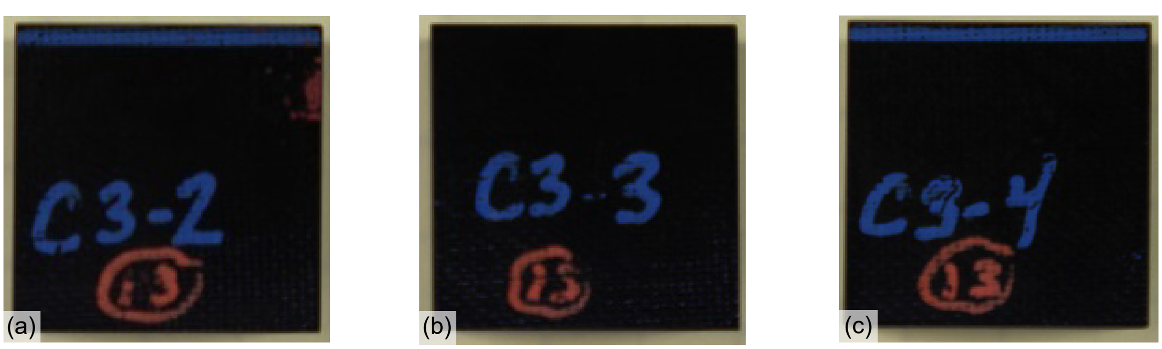

Figure 26.—Three-direction compression specimens prior to testing (a) IM7C3-2, (b) IM7C3-3, and (c) IM7C3-4.

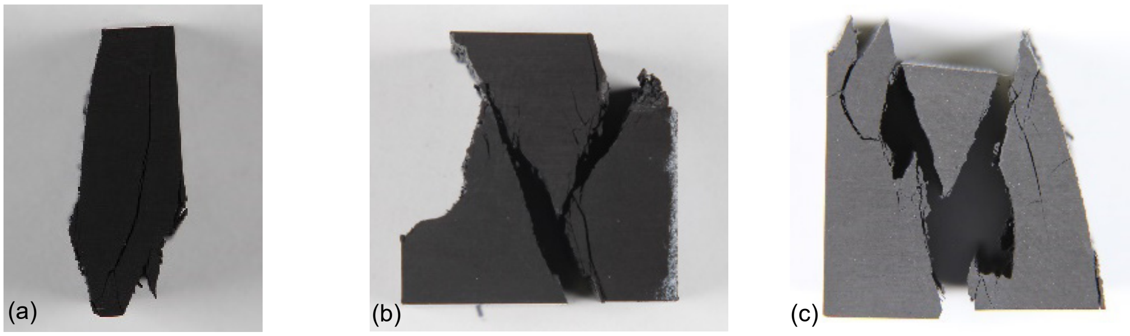

Figure 27.—Three-direction compression specimens after testing (a) IM7C3-2, (b) IM7C3-3, and (c) IM7C3-4.

TABLE 16.—SUMMARY OF THE 3-DIRECTION COMPRESSION TEST RESULTS

Replicate	Loading rate, in./min	Strain rate, 1/s	E_{33}, psi	Ultimate strain	Peak stress, psi
IM7C3-2	0.01	1.855×10^{-5}	1,410,172	0.029098	33,649
IM7C3-3	0.01	1.855×10^{-5}	1,459,211	0.032609	37,063
IM7C3-4	0.01	1.855×10^{-5}	1,510,433	0.031392	35,663
Average	----	------------	1,459,939	0.03103	35,458
Standard deviation	----	------------	40,935	0.00146	1,401
Coefficient of variation	----	------------	2.80%	4.69%	3.95%

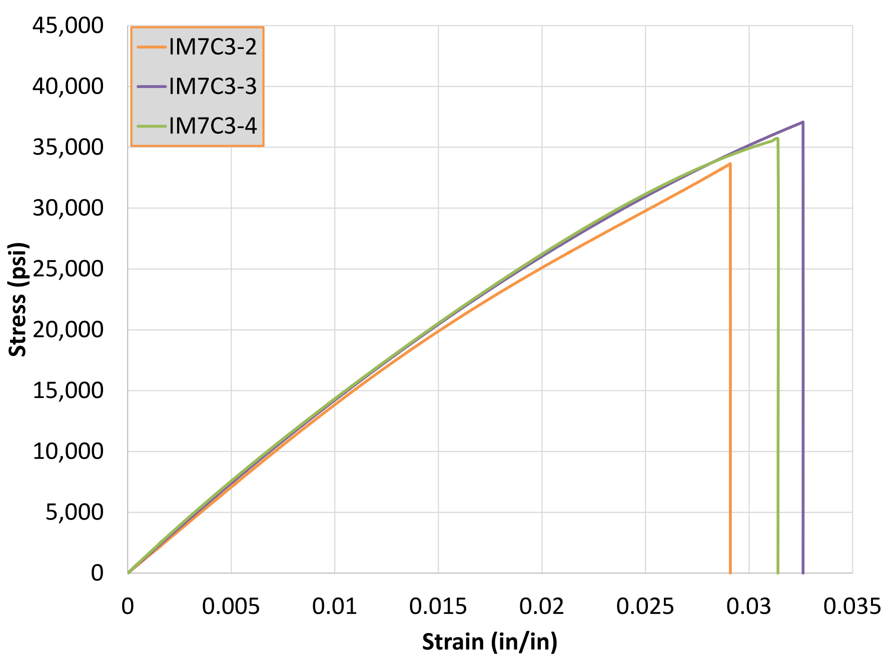

Figure 28.—Three-direction compression stress-strain curves.

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

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

Specimen Geometry: The specimen dimensions and layout are shown in Figure 29. The geometry shown is in accordance with the guidelines set forth by ASTM D5379/D5379M-12. Shaded regions indicate where fiberglass tabs are bonded to the specimen.

The average specimen dimensions in the gage section are shown in Table 17 for the three tested replicates. The ligament height is defined as the distance between the notches.

Figure 30 shows the modes of failure observed in the shear specimens, which are similar to those deemed acceptable by the ASTM standard.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 31. The specimens exhibited HGN[6] failure as shown in Figure 32. Figure 33 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 18. The shear modulus reported in Table 18 is in terms of engineering shear strain not tensorial shear strain.

Figure 34 shows the individual stress-strain curves for each of the specimens. ASTM standard states that the ultimate engineering shear strain should be less than 0.05 (0.025 ultimate tensorial shear strain). Therefore, the stress strain curves in Figure 34 are terminated at 0.025 tensorial shear strain. Note that these tests were carried out beyond 0.05 engineering strain but not to failure.

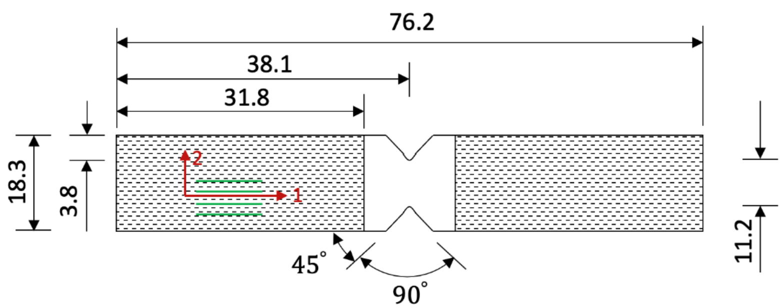

Figure 29.—Typical specimen geometry.

TABLE 17.—ONE-TWO PLANE SHEAR TEST SPECIMEN DIMENSIONS

Replicate	Ligament height, in.	Thickness, in.	Cross sectional area, in^2
IM7S12-1	0.495	0.112	0.055
IM7S12-3	0.496	0.116	0.058
IM7S12-4	0.497	0.114	0.057

[6] HGN: H- Horizontal cracking, G- Gage section, N- between the notches

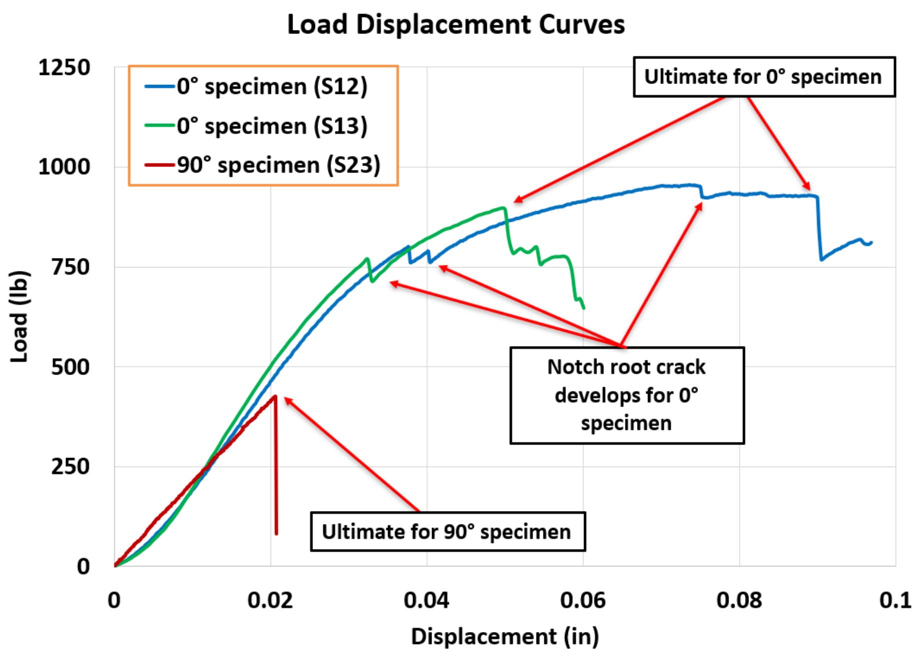

Figure 30.—Shear failure modes.

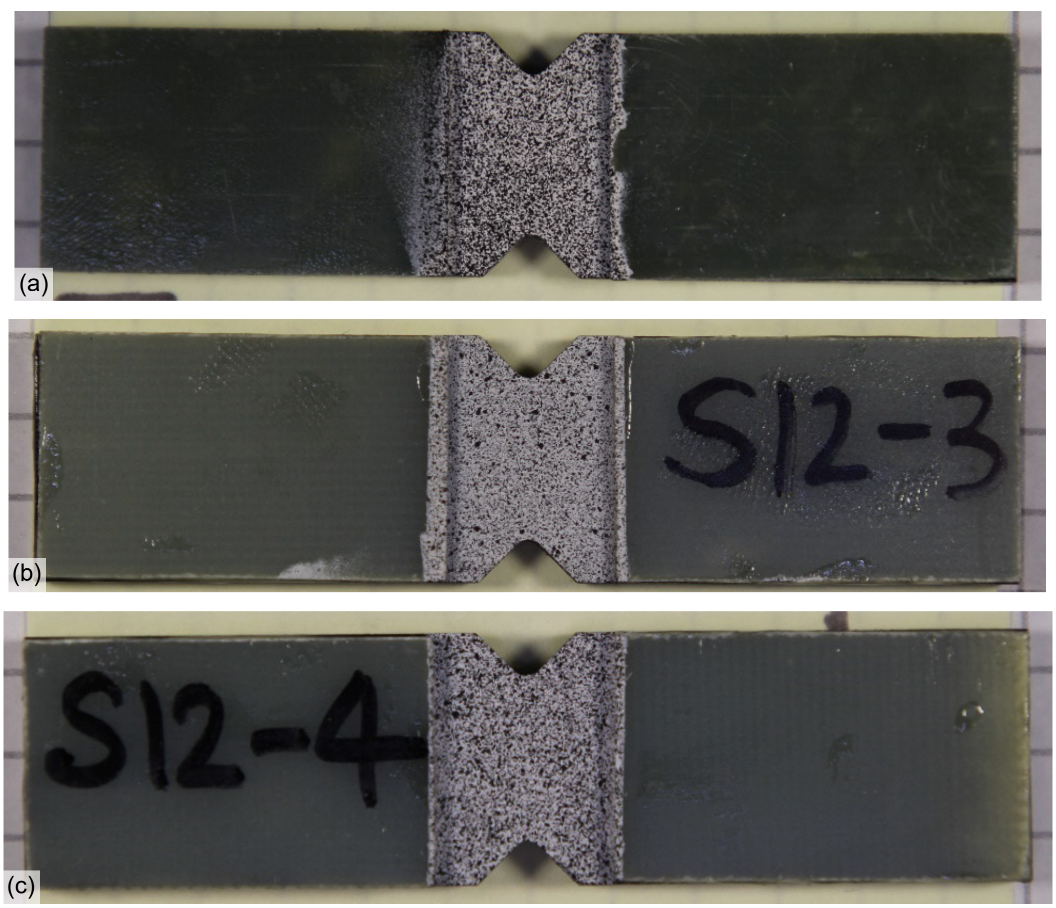

Figure 31.—One-two plane shear specimens prior to testing (a) IM7S12-1, (b) IM7S12-3, and (c) IM7S12-4.

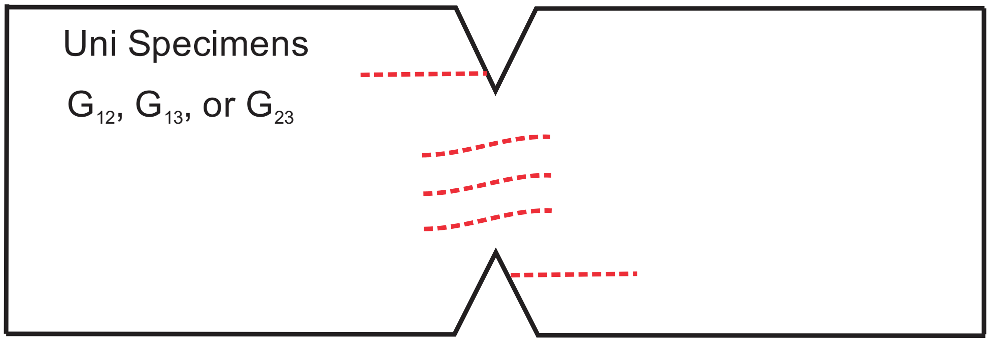

Figure 32.—Horizontal cracking in gage section between the notches (HGN) failure mode.

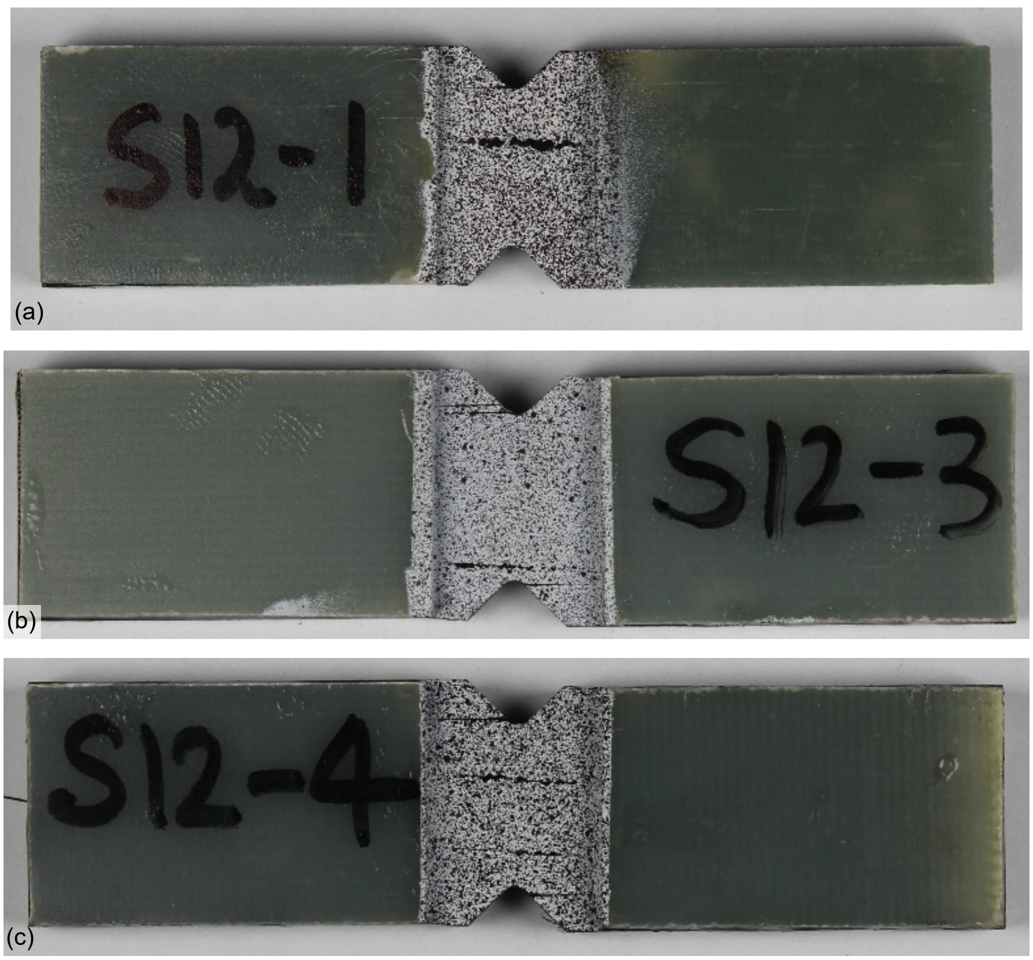

Figure 33.—One-two plane shear specimens after testing (a) IM7S12-1, (b) IM7S12-3, and (c) IM7S12-4.

TABLE 18.—SUMMARY OF THE 1-2 PLANE SHEAR TEST RESULTS

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
IM7S12-1	0.0025	0.00010	5.203×10^{-5}	622,253	0.05000	0.02500	15,089
IM7S12-3	0.0025	0.00010	5.203×10^{-5}	666,537	0.05000	0.02500	14,202
IM7S12-4	0.0025	0.00010	5.203×10^{-5}	663,345	0.05000	0.02500	14,184
Average	--------	----------	-------------	650,712	0.05000	0.02500	14,492
Standard deviation	--------	----------	-------------	24,698	0.00000	0.00000	517
Coefficient of variation	--------	----------	-------------	3.80%	0.00%	0.00%	3.569%

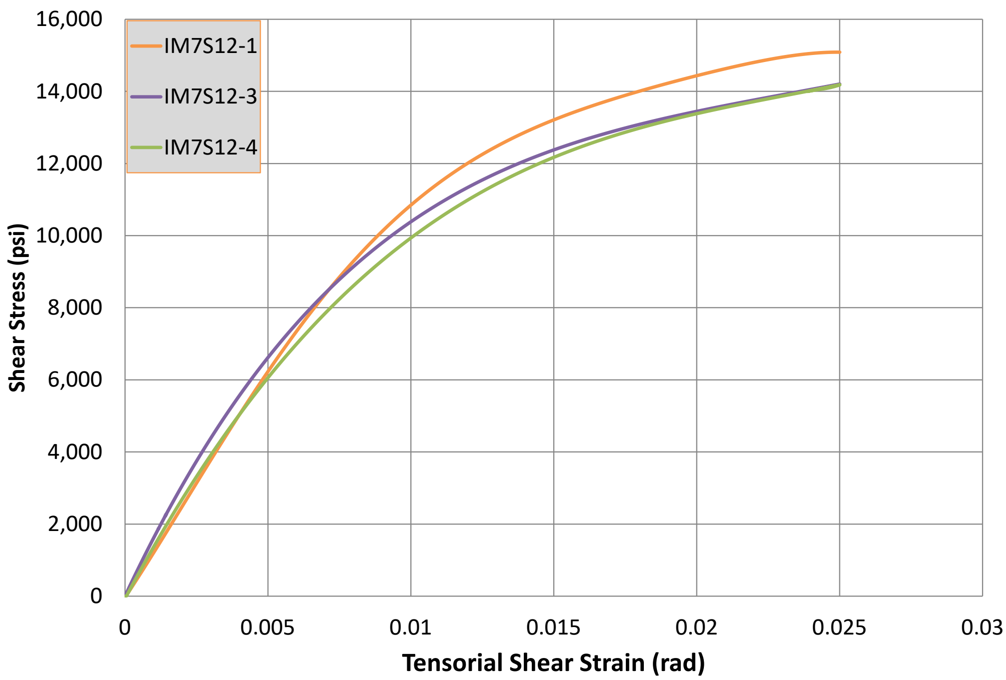

Figure 34.—One-two plane shear stress-tensorial strain curves.

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

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

Specimen Geometry: The specimen dimensions and layout are shown in Figure 35. The geometry shown is in accordance with the guidelines set forth by ASTM D5379/D5379M-12. Shaded regions indicate where fiberglass tabs are bonded to the specimen.

The average specimen dimensions between the notches are shown in Table 19 for the three tested replicates. The ligament height is defined as the distance between the notches.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 36. The specimens exhibited angle cracking adjacent to the notch region and referred as ANA[7] failure modes in ASTM Standard D5379. Figure 37 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 20. The shear modulus reported in Table 20 is in terms of engineering shear strain.

Figure 38 shows the individual stress-strain curves for each of the specimens.

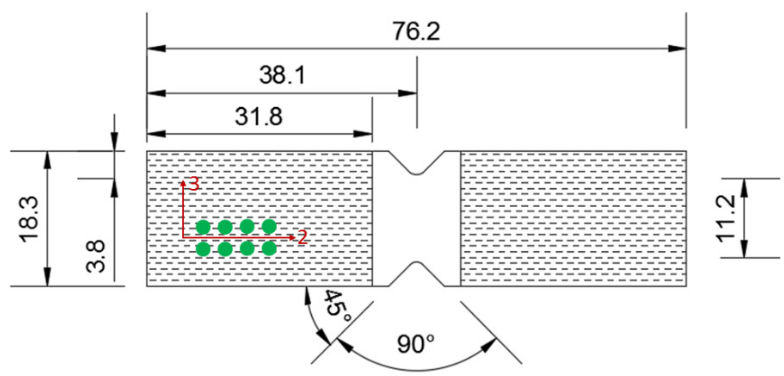

Figure 35.—Typical specimen geometry and layout.

TABLE 19.—TWO-THREE PLANE SHEAR TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7S23-3	0.495	0.118	0.058
IM7S23-4	0.497	0.122	0.060
IM7S23-5	0.494	0.119	0.059

[7] ANA: A-Angled cracking, N- Notch region, A-Adjacent to notches

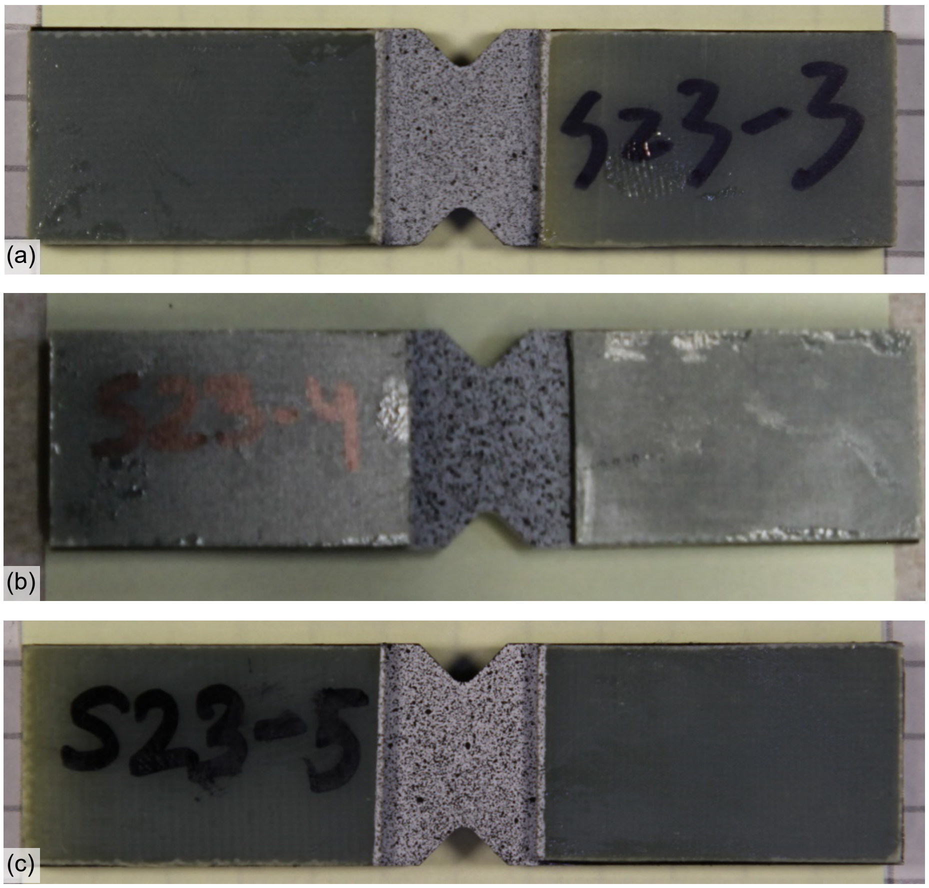

Figure 36.—Two-three plane shear specimens prior to testing (a) IM7S23-3, (b) IM7S23-4, and (c) IM7S23-5.

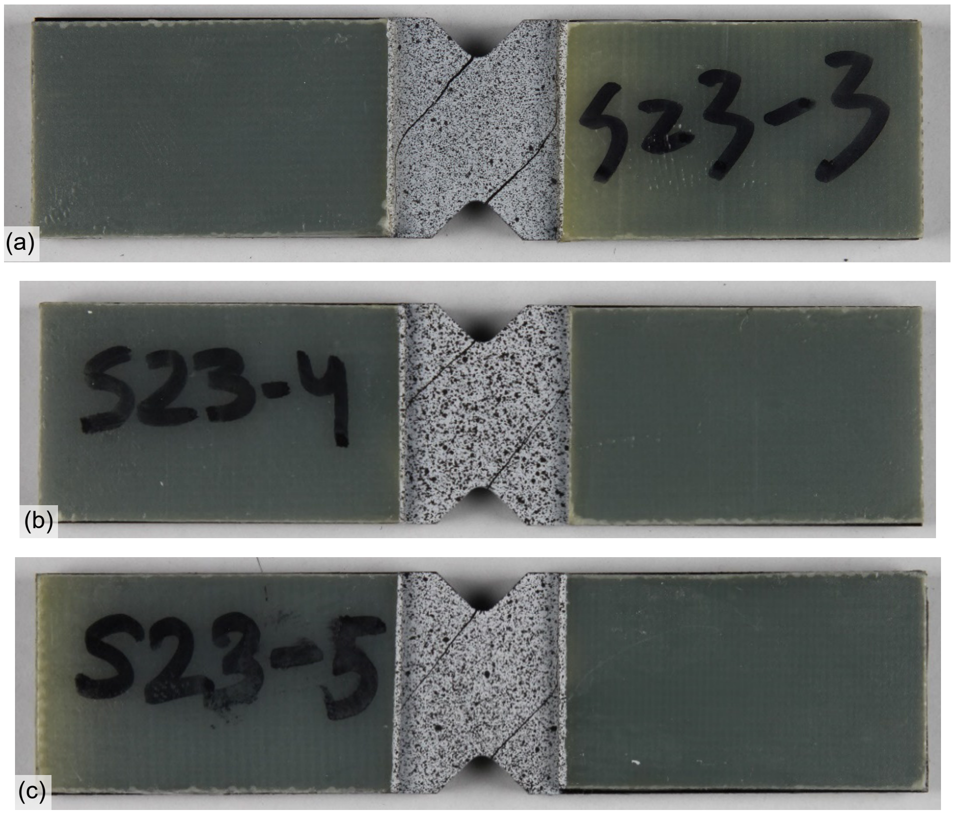

Figure 37.—Two-three plane shear specimens after testing (a) IM7S23-3, (b) IM7S23-4, and (c) IM7S23-5.

TABLE 20.—SUMMARY OF THE 2-3 PLANE SHEAR TEST RESULTS

Replicate	Loading rate, in./min	Engineering strain rate, 1/s	Tensorial strain rate	G_{23}, psi	Ultimate strain	Tensorial ultimate strain	Peak stress, psi
IM7S23-3	0.001	4.167×10^{-5}	2.083×10^{-5}	424,906	0.02066	0.01033	7,996
IM7S23-4	0.001	4.167×10^{-5}	2.083×10^{-5}	414,190	0.01901	0.00950	6,973
IM7S23-5	0.001	4.167×10^{-5}	2.083×10^{-5}	404,991	0.01934	0.00967	7,260
Average	------	-------------	-------------	414,695	0.01967	0.00984	7,410
Standard Deviation	------	-------------	-------------	9,967	0.00087	0.00044	528
Coefficient of Variation	------	-------------	-------------	2.4%	4.4%	4.4%	7.1%

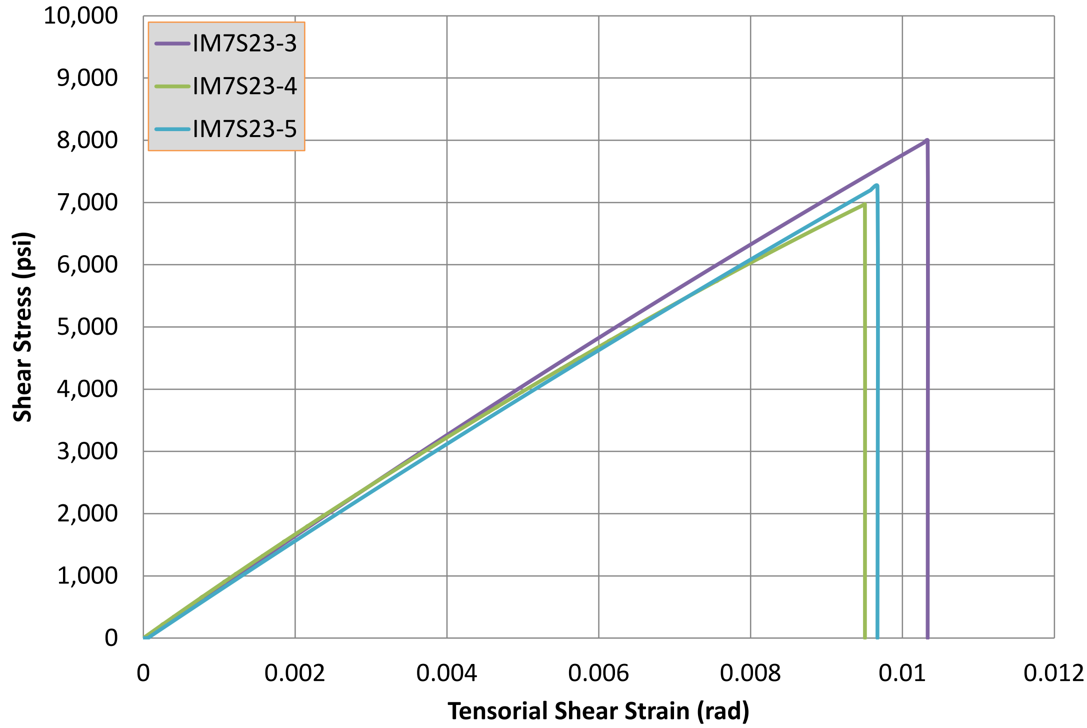

Figure 38.—Two-three plane shear stress-tensorial strain curves.

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

This test is used to generate the shear stress-strain curve in the 1-3 plane. 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 39. The geometry shown is in accordance with the guidelines set forth by ASTM D5379/D5379M-12. Shaded regions indicate where fiberglass tabs are bonded to the specimen.

The average specimen dimensions between the notches are shown in Table 21 for the three tested replicates. The ligament height is defined as the distance between the notches.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 40. The specimens exhibited HGN failure, shown in Figure 32. Figure 41 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 22. The shear modulus reported in Table 22 is in terms of engineering shear strain not tensorial shear strain.

Figure 42 shows the individual stress-strain curves for each of the specimens. Stress strain curves are terminated at 0.025 tensorial shear strain and these tests were carried out beyond 0.05 engineering strain but not to failure similar to the shear tests in 1-2 plane.

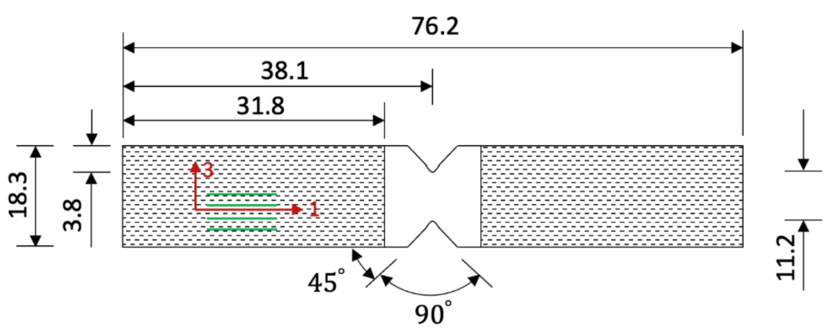

Figure 39.—Typical specimen geometry and layout

TABLE 21.—TWO-THREE PLANE SHEAR TEST SPECIMEN DIMENSIONS

Replicate	Ligament height, in.	Thickness, in.	Cross sectional area, in^2
IM7S13-2	0.497	0.120	0.059
IM7S13-3	0.498	0.120	0.060
IM7S13-4	0.498	0.120	0.060

Figure 40.—One-three plane shear specimens prior to testing (a) IM7S13-2, (b) IM7S13-3, and (c) IM7S13-4.

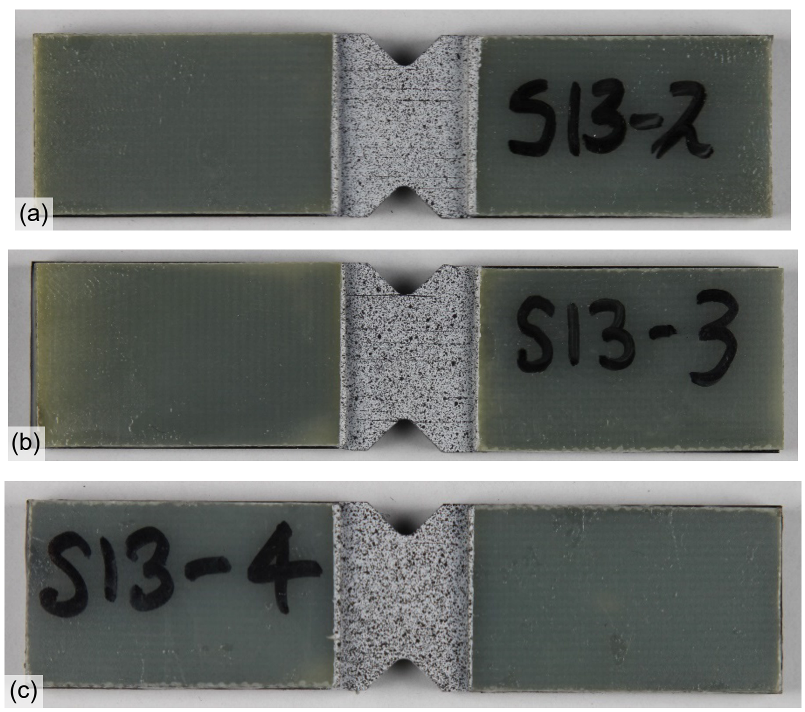

Figure 41.—One-three plane shear specimens after testing (a) IM7S13-2, (b) IM7S13-3, and (c) IM7S13-4.

TABLE 22.—SUMMARY OF 1-3 PLANE SHEAR TEST RESULTS

Replicate	Loading rate, in./min	Engineering strain rate, 1/s	Tensorial strain rate	G_{13}, psi	Ultimate strain	Tensorial ultimate strain	Peak stress, psi
IM7S13-2	0.01	4.167×10^{-5}	2.083×10^{-5}	785,869	0.05000	0.02500	15,042
IM7S13-3	0.01	4.167×10^{-5}	2.083×10^{-5}	731,460	0.05000	0.02449	15,015
IM7S13-4	0.01	4.167×10^{-5}	2.083×10^{-5}	774,463	0.04899	0.02500	15,037
Average	-----	-------------	-------------	763,931	0.04966	0.02475	15,031
Standard deviation	-----	-------------	-------------	28,693	0.00058	0.00036	14
Coefficient of variation	-----	-------------	-------------	3.8%	1.2%	1.4%	0.1%

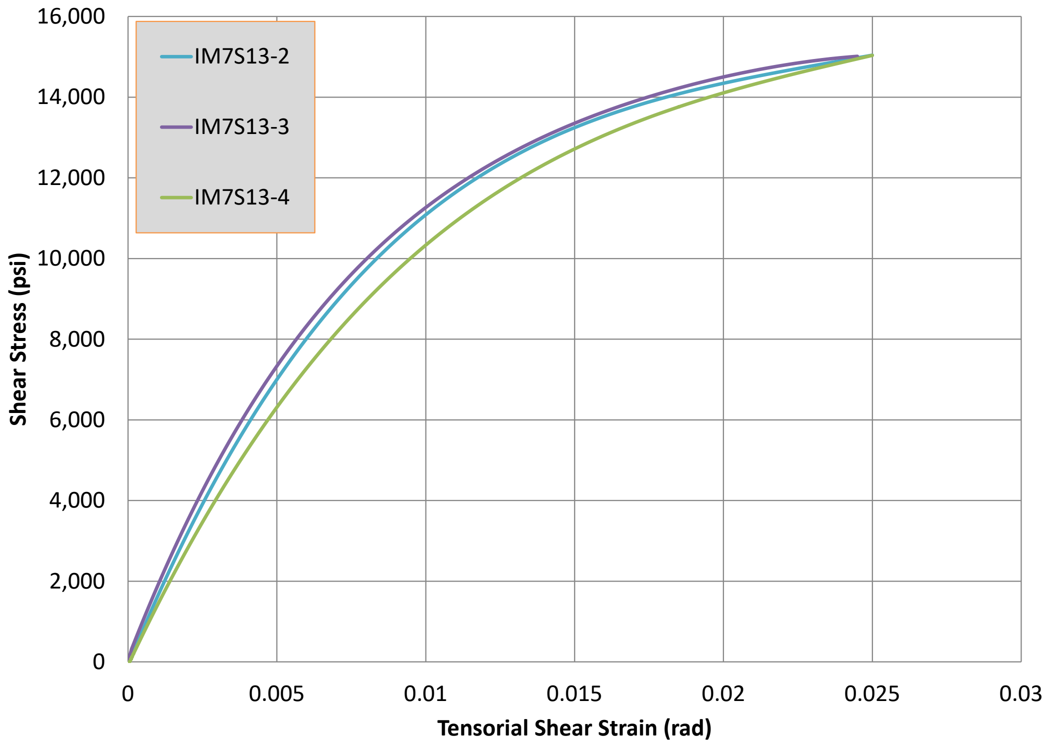

Figure 42.—One-three plane shear stress-tensorial strain curves.

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

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

Specimen Geometry: The specimen dimensions and layout are shown in Figure 43. The specimen geometry shown in Figure 43 is taken from ASTM D3039. Shaded regions indicate where the fiberglass tabs are bonded to the specimen.

The average specimen dimensions in the gage section are shown in Table 23 for the three tested replicates.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 44. Figure 45 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 24.

Figure 46 shows the individual stress-strain curves for each of the specimens.

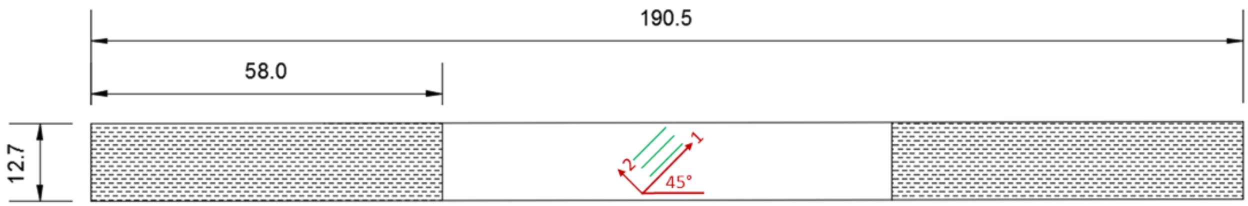

Figure 43.—Specimen geometry and layout (a) ASTM geometry, and (b) alternative geometry.

TABLE 23.—ONE-TWO PLANE 45° OFF-AXIS
TENSION TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7O12-1	0.503	0.116	0.058
IM7O12-4	0.502	0.116	0.058
IM7O12-5	0.502	0.116	0.058

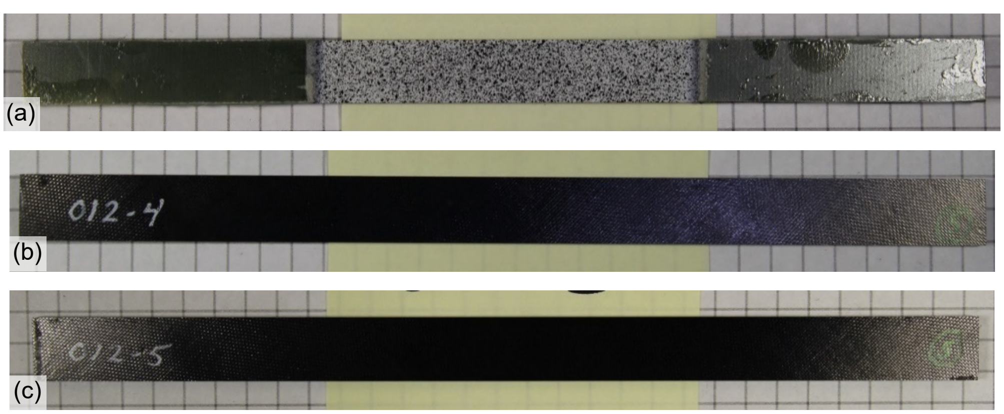

Figure 44.—One-two plane 45° off-axis tension specimens prior to testing (a) IM7O12-1, (b) IM7O12-4, and (c) IM7O12-5.

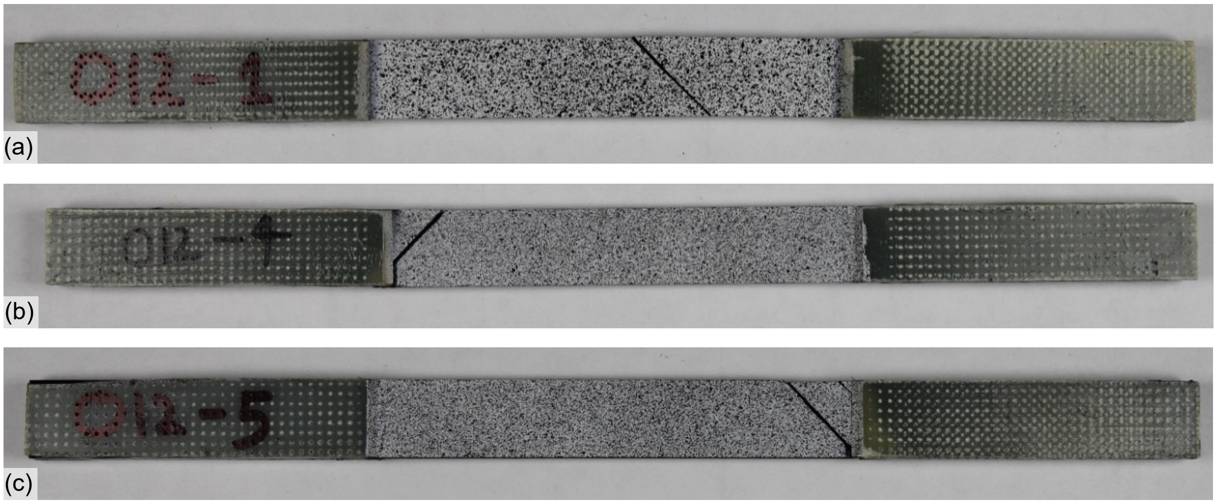

Figure 45.—One-two plane 45° off-axis tension specimens after testing (a) IM7O12-1, (b) IM7O12-4, and (c) IM7O12-5.

TABLE 24.—SUMMARY OF 1-2 PLANE 45° OFF-AXIS TENSION TEST RESULTS

Replicate	Loading rate, in./min	Strain rate, 1/s	Modulus, psi	Ultimate strain	Peak stress, psi
IM7O12-1	0.02	8.00×10^{-5}	1,862,433	0.01396	18,239
IM7O12-4	0.02	8.00×10^{-5}	1,822,120	0.01389	18,047
IM7O12-5	0.02	8.00×10^{-5}	1,824,193	0.01403	18,077
Average	-----	-----------	1,836,249	0.01396	18,121
Standard deviation	-----	-----------	22,700	0.00007	103
Coefficient of variation	-----	-----------	1.236%	0.490%	0.571%

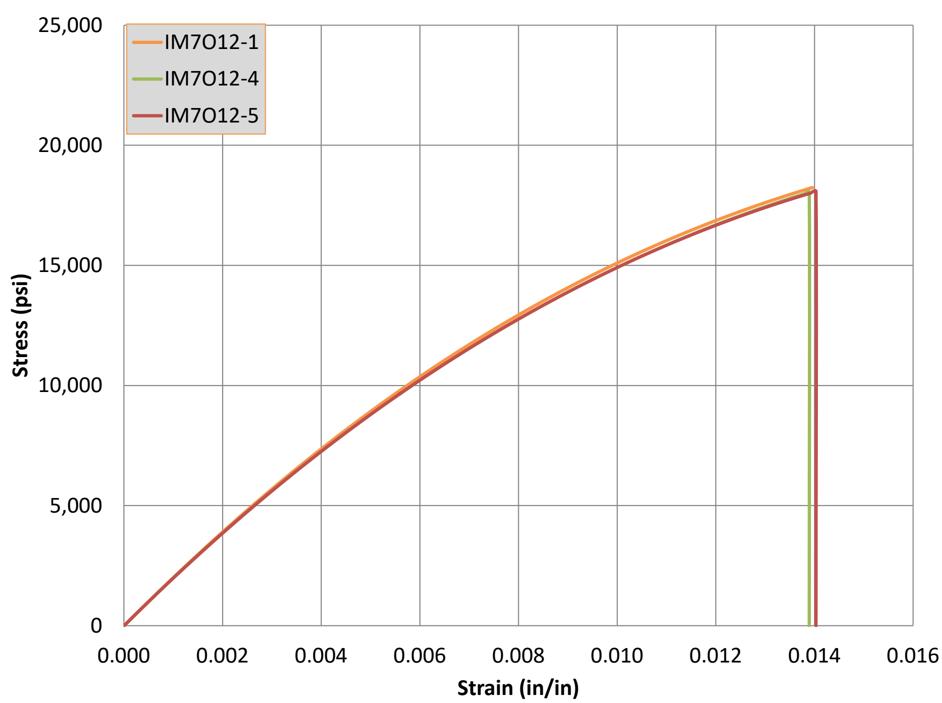

Figure 46.—One-two plane 45° off-axis tension stress-strain curves.

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

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

Specimen Geometry: The specimen dimensions and layout are shown in Figure 47. The geometry shown is a modified version of the geometry set forth by ASTM D7291. 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 are shown in Table 25 for the three tested replicates.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 48. The specimens exhibited brittle failure of the matrix in the 2-3 plane before the tests were terminated. Figure 49 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 26.

Figure 50 shows the individual stress-strain curves for each of the specimens.

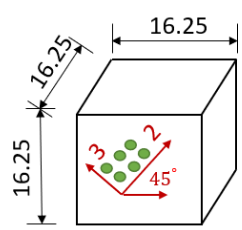

Figure 47.—Specimen geometry and layout.

TABLE 25.—TWO-THREE PLANE 45° OFF-AXIS COMPRESSION TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7O23-1	0.594	0.591	0.348
IM7O23-3	0.582	0.581	0.338
IM7O23-4	0.591	0.582	0.345

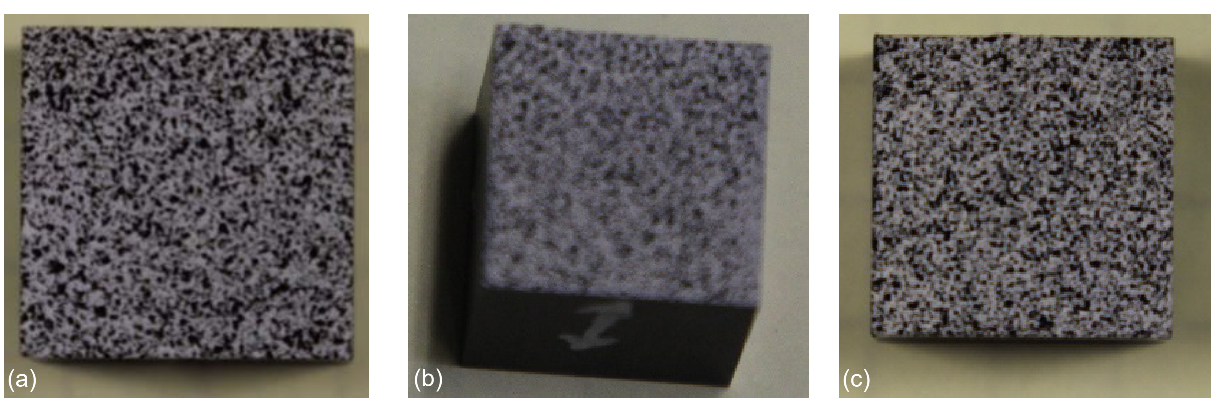

Figure 48.—Two-three plane 45° off-axis compression test specimens prior to testing (a) IM7O23-1, (b) IM7O23-3, and (c) IM7O23-4.

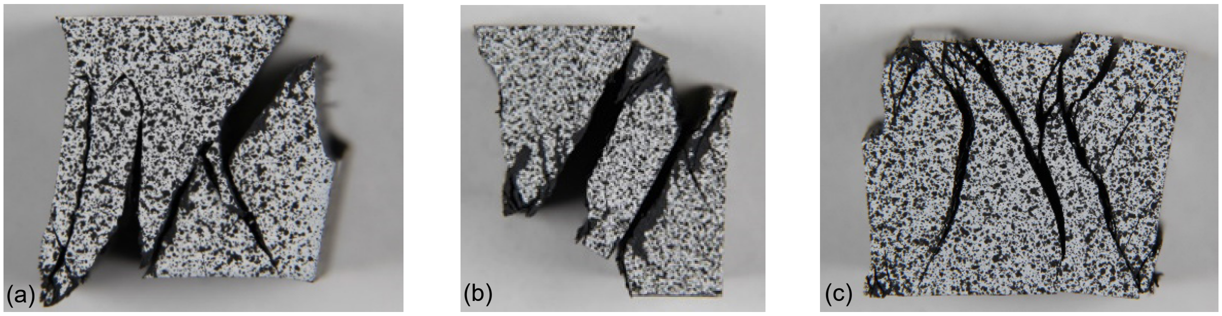

Figure 49.—Two-three plane 45° off-axis compression test specimens after testing (a) IM7O23-1, (b) IM7O23-3, and (c) IM7O23-4.

TABLE 26.—SUMMARY OF 2-3 PLANE 45° OFF-AXIS COMPRESSION TEST RESULTS

Replicate	Loading rate, in./min	Strain rate, 1/s	Modulus, psi	Ultimate strain	Peak stress, psi
IM7O23-1	0.005	9.256×10^{-5}	1,269,974	0.04203	37,328
IM7O23-3	0.005	9.256×10^{-5}	1,251,806	0.03827	36,970
IM7O23-4	0.005	9.256×10^{-5}	1,179,638	0.04002	37,015
Average	-------	-------------	1,233,806	0.04011	37,104
Standard deviation	-------	-------------	47,782	0.00188	195
Coefficient of variation	-------	-------------	3.9%	4.7%	0.5%

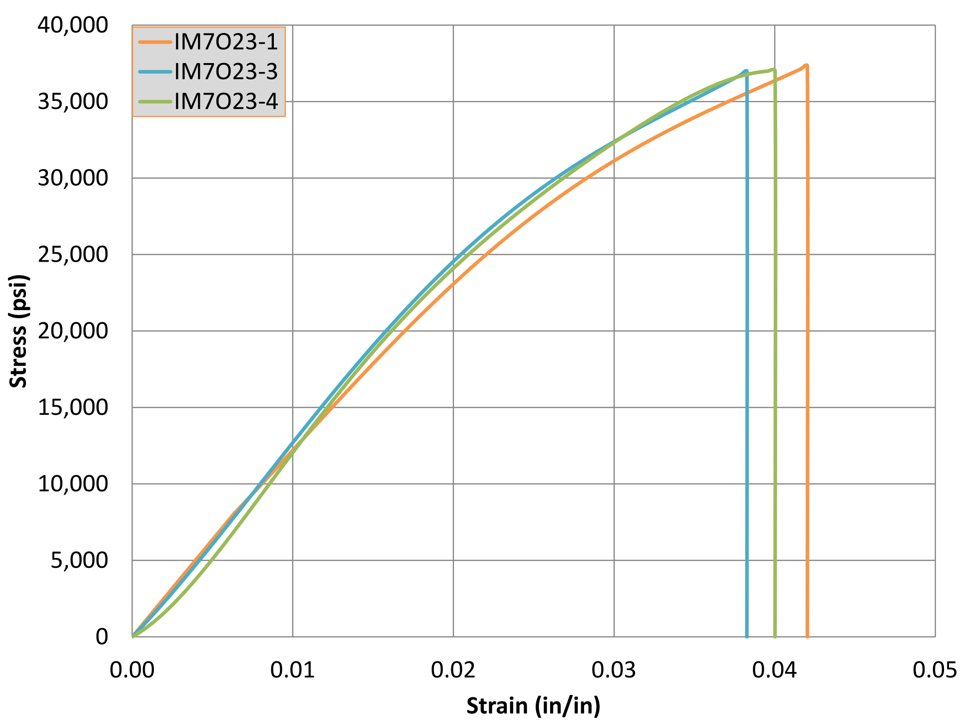

Figure 50.—Two-three plane 45° off-axis compression stress-strain curves.

3.12 Test T12: Off-Axis Compression Test 45° in the 1-3 Plane

This test is used to generate the 45° off-axis compression stress-strain curve in the 1-3 plane. MTS 810 test frame (Figure 2(a)) was used to perform these tests.

Specimen Geometry: The specimen dimensions and layout are shown in Figure 51. The geometry shown is a modified version of the geometry set forth by ASTM D7291. 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 are shown in Table 27 for the three tested replicates.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 52. Figure 53 shows the specimens after testing.

Test Results: The summary of the results from the tests is shown in Table 28.

Figure 54 shows the individual stress-strain curves for each of the specimens.

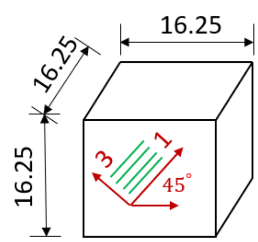

Figure 51.—Specimen geometry and layout.

TABLE 27.—ONE-THREE PLANE 45° OFF-AXIS COMPRESSION TEST SPECIMEN DIMENSIONS

Replicate	Width, in.	Thickness, in.	Cross sectional area, in^2
IM7O13-2	0.583	0.583	0.336
IM7O13-4	0.578	0.577	0.333
IM7O13-5	0.578	0.578	0.334

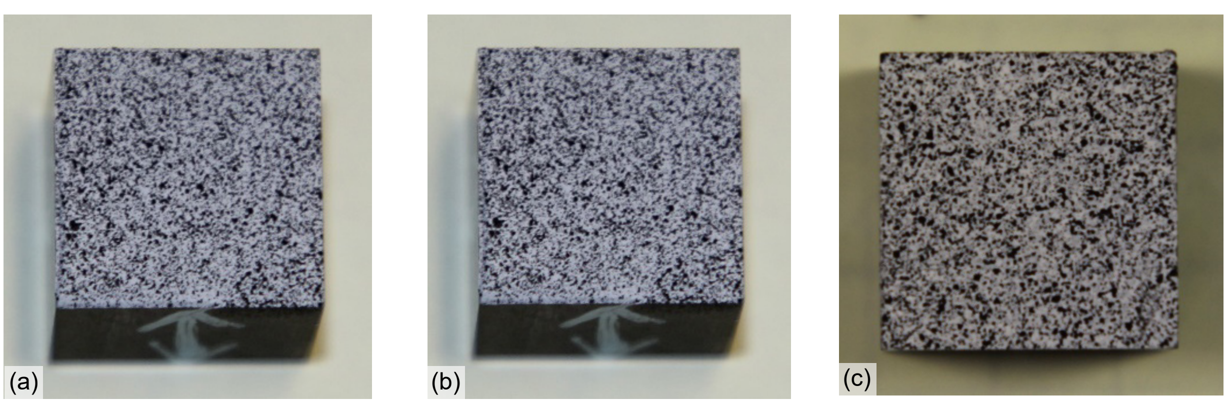

Figure 52.—One-three plane 45° off-axis compression test specimens prior to testing (a) IM7O13-2, (b) IM7O13-4, and (c) IM7O13-5.

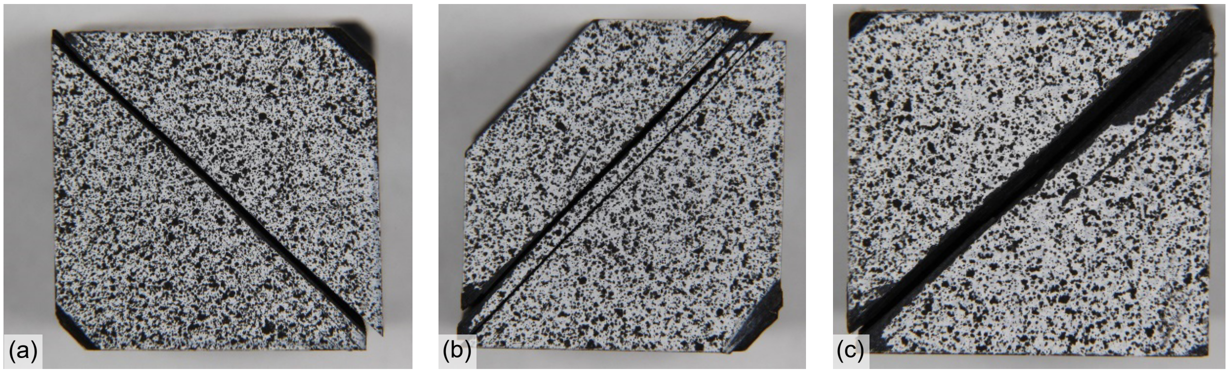

Figure 53.—One-three plane 45° off-axis compression test specimens after testing IM7O13-2, (b) IM7O13-4, and (c) IM7O13-5.

TABLE 28.—SUMMARY OF 1-3 PLANE 45° OFF-AXIS COMPRESSION TEST RESULTS

Replicate	Loading rate, in./min	Strain rate, 1/s	Modulus, psi	Ultimate strain	Peak stress, psi
IM7O13-2	0.005	9.256×10^{-5}	1,995,239	0.070082	37,066
IM7O13-4	0.005	9.256×10^{-5}	2,249,129	0.065622	37,561
IM7O13-5	0.005	9.256×10^{-5}	2,003,492	0.069653	35,716
Average	------	-------------	2,082,620	0.0685	36,781
Standard deviation	------	-------------	117,788	0.0020	780
Coefficient of variation	------	-------------	5.7%	2.9%	2.1%

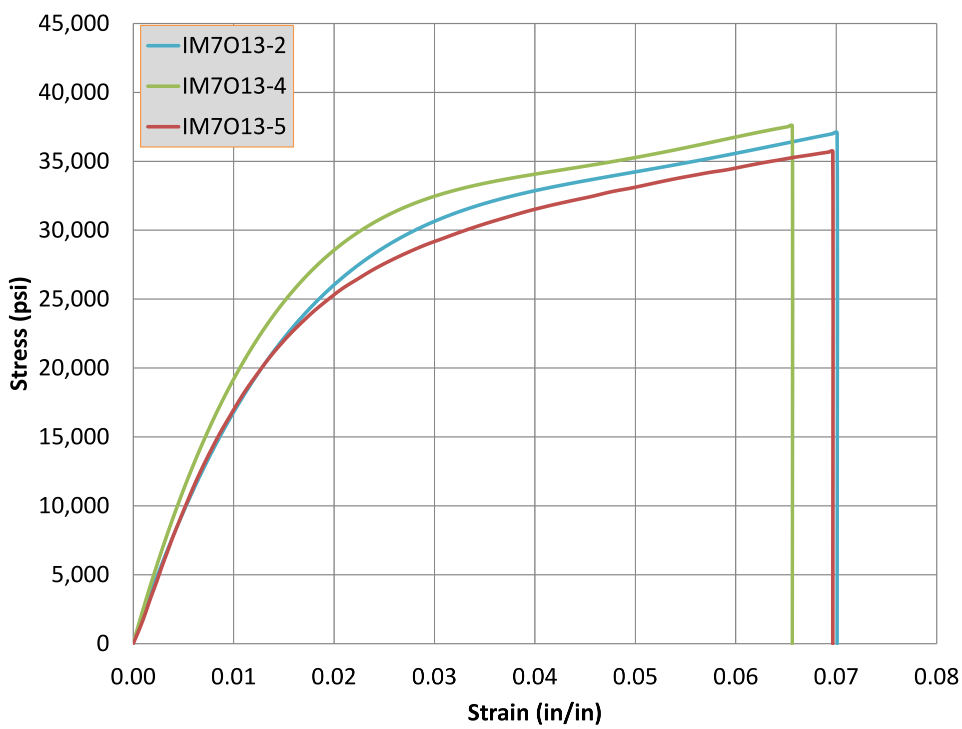

Figure 54.—One-three plane 45° off-axis compression stress-strain curves.

3.13 Test T13: DCB Test

Specimen Geometry: ASTM D5528 standard is applicable for this test. The specimen geometry and layout are shown in Figure 55. The experimental procedure was performed using an MTS Exceed test frame (Figure 2(j)) with spring loaded grips (Figure 2(k)).

The ASTM procedure 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 complete separation of the top and bottom halves of the specimen.

The average specimen dimensions of the test replicates are shown in Table 29.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 56. After testing images are shown in Figure 57.

Test Results: The experimental results for the measured load and displacement that occurred at the load point are shown in Figure 58.

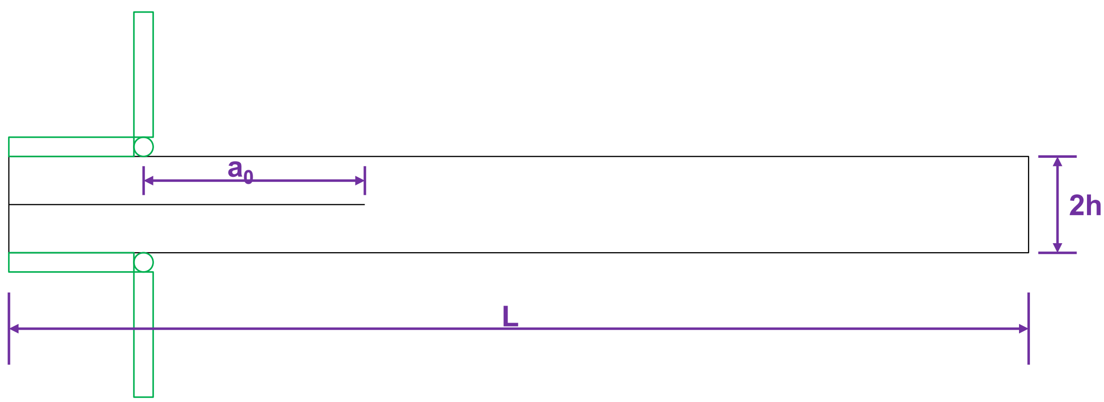

Figure 55.—Typical specimen geometry and layout.

TABLE 29.—DCB TEST SPECIMEN DIMENSIONS

Replicate ID	a_0, in. NPC	a_0, in. PC	h, in.	b, in.	L, in.
IM7DCB-2	2.261	2.250	0.188	1.003	5.005
IM7DCB-3	2.291	2.250	0.188	1.007	4.999
IM7DCB-5	2.311	2.250	0.186	1.004	5.002

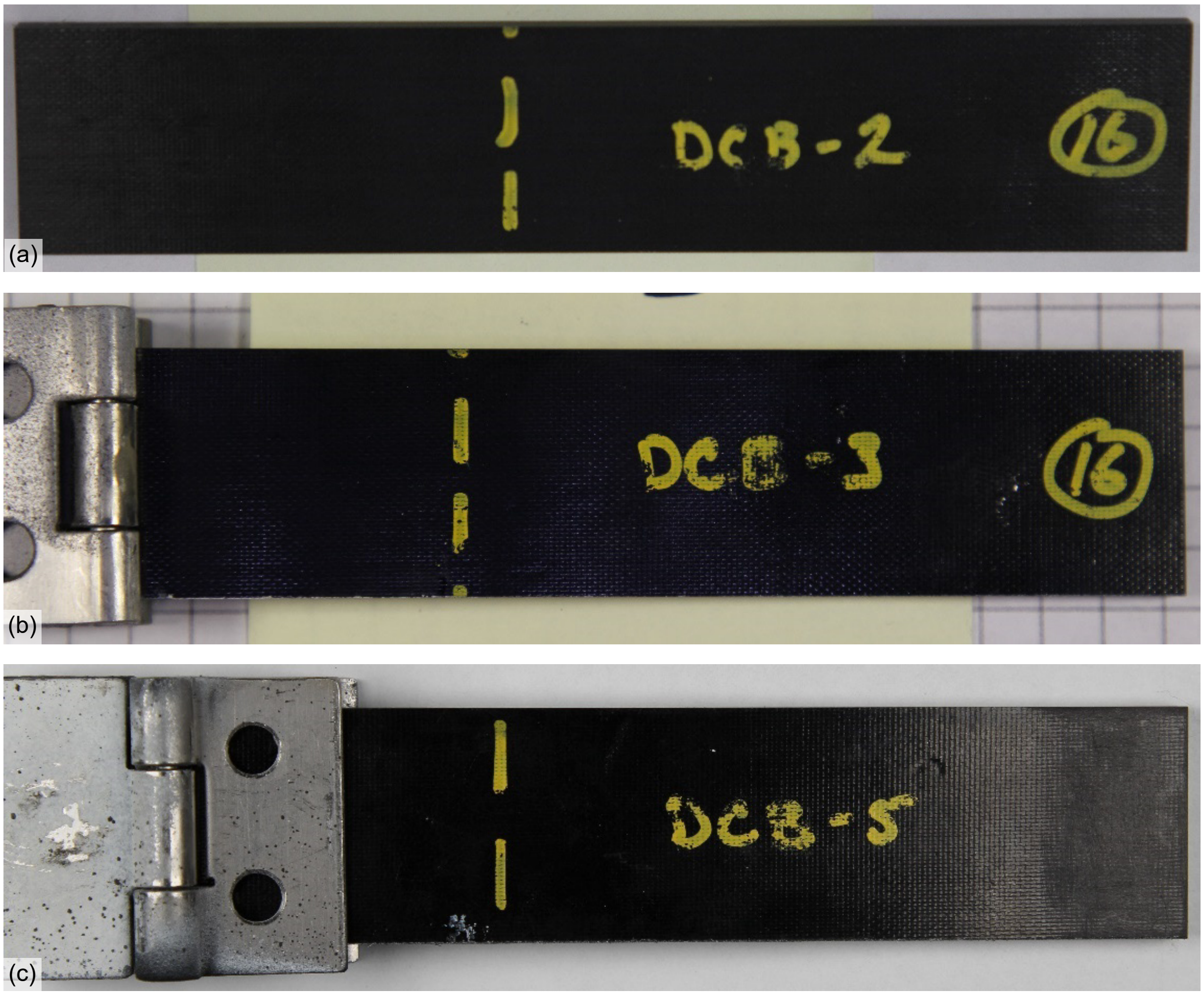

Figure 56.—Image of DCB specimen prior to testing (top surface showing specimen width and side of specimen showing thickness) (a) IM7DCB-2, (b) IM7DCB-3, and (c) IM7DCB-5.

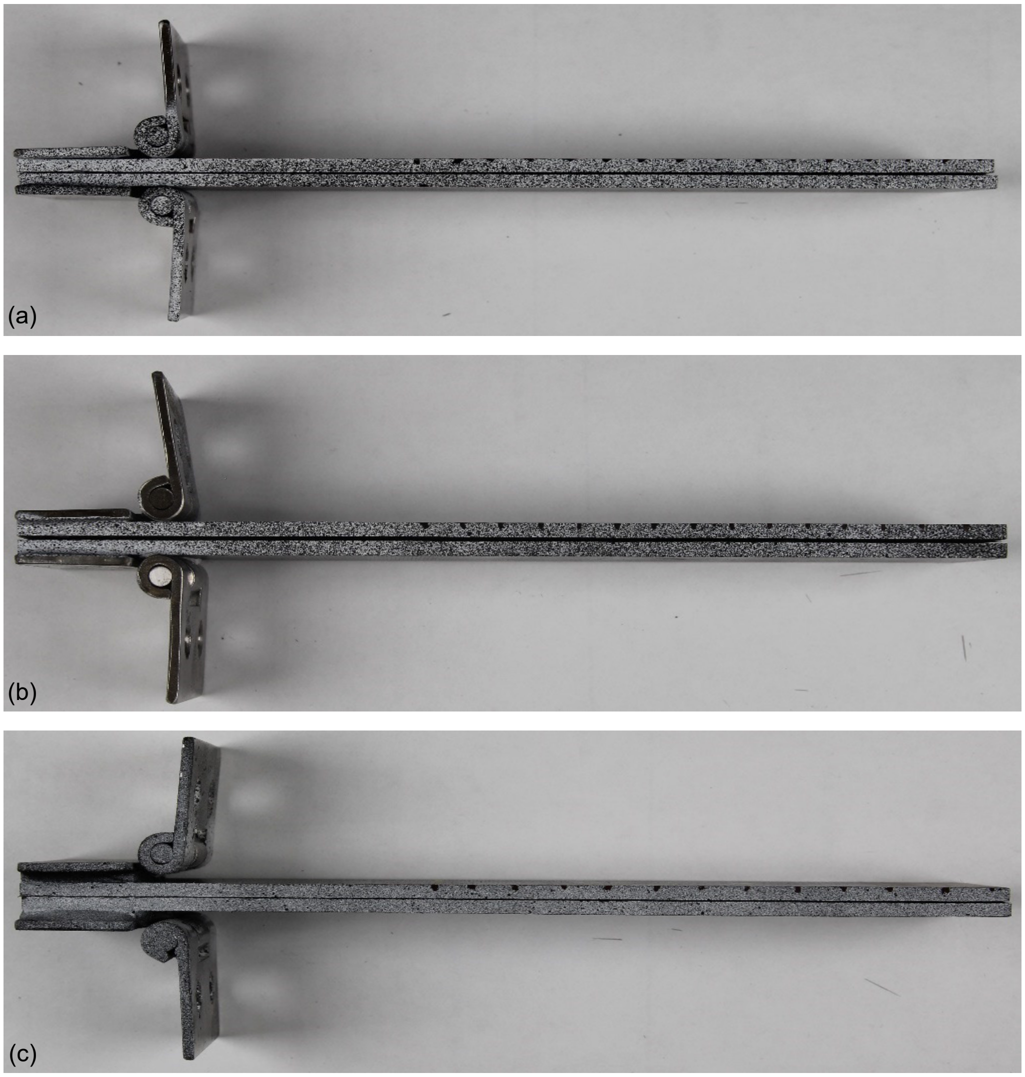

Figure 57.—Image of DCB specimen after testing (a) IM7DCB-2, (b) IM7DCB-3, and (c) IM7DCB-5.

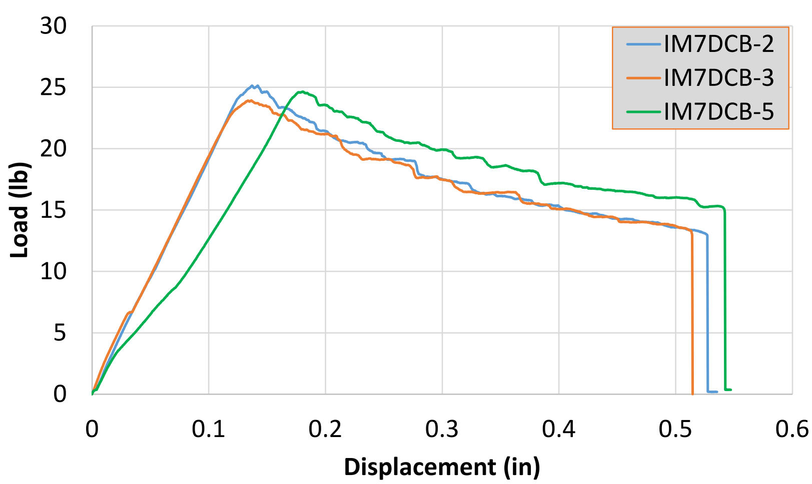

Figure 58.—DCB precrack experimental force versus displacement.

3.14 Test T14: ENF Test

Specimen Geometry: ASTM D7905 standard is applicable for this test. The specimen geometry and layout are shown in Figure 59.

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 cycles. The experimental procedure was performed using an MTS Exceed test frame (Figure 2(j)) with 3-point bend fixture (Figure 2(l)).

The average specimen dimensions of the test replicates are shown in Table 30.

Specimen Photographs: The specimen photographs before the tests are shown in Figure 60. After test images are shown in Figure 61.

Test Results: The experimental results for the measured load and displacement that occurred at the load point are shown in Figure 62.

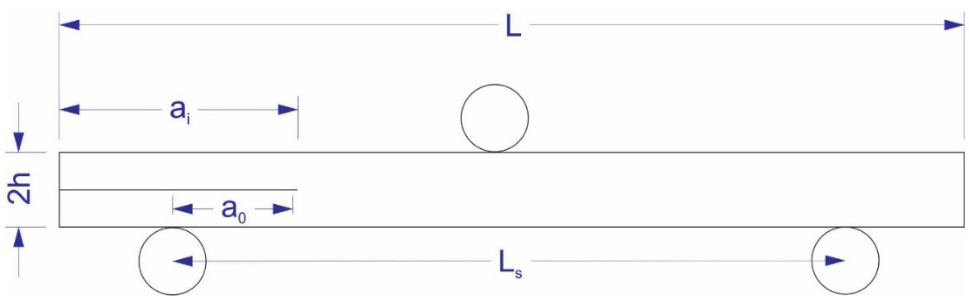

Figure 59.—Typical specimen geometry and layout.

TABLE 30.—ENF TEST SPECIMEN DIMENSIONS

Replicate ID	a_i, in.	a_0, in.	h, in.	b, in.	L_s, in.	L, in.
ENF-1	2.103	2.25	0.084	1.002	3.941	6.500
ENF-2	2.075	2.25	0.085	1.000	3.941	6.500
ENF-3	2.073	2.25	0.086	1.001	3.941	6.500
Average	2.084	2.25	0.085	1.001	3.941	6.500
Standard deviation	0.014	0	0.001	0.001	0	0
Coefficient of variation	0.007	0%	0.9%	0.1%	0%	0%

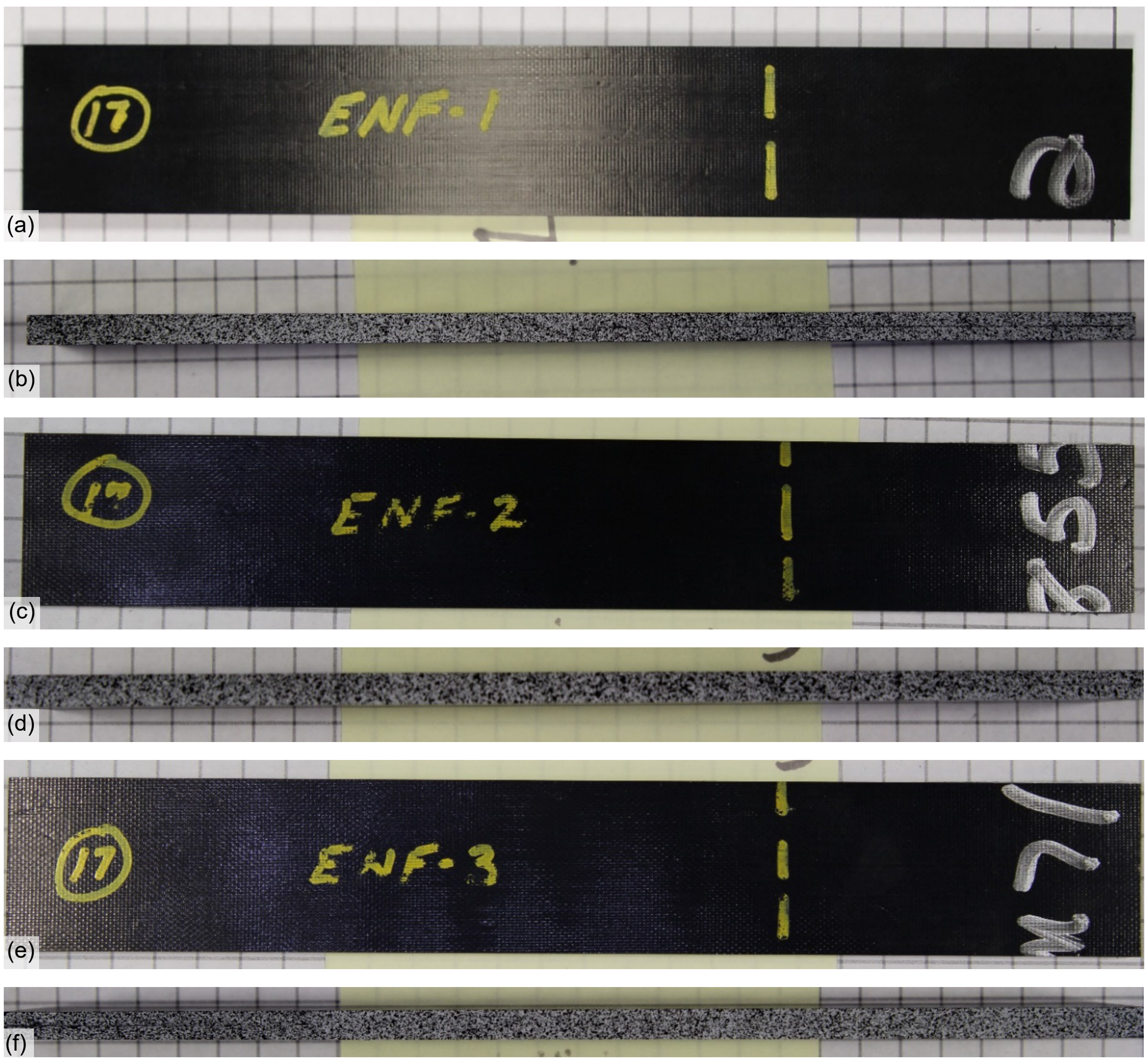

Figure 60.—Image of DCB specimen prior to testing (top surface showing specimen width and side of specimen showing thickness) (a) IM7ENF-1 (plan view), (b) IM7ENF-1 (elevation), (c) IM7ENF-2 (plan view), (d) IM7ENF-2 (elevation), (e) IM7ENF-3 (plan view), and (f) IM7ENF-3 (elevation).

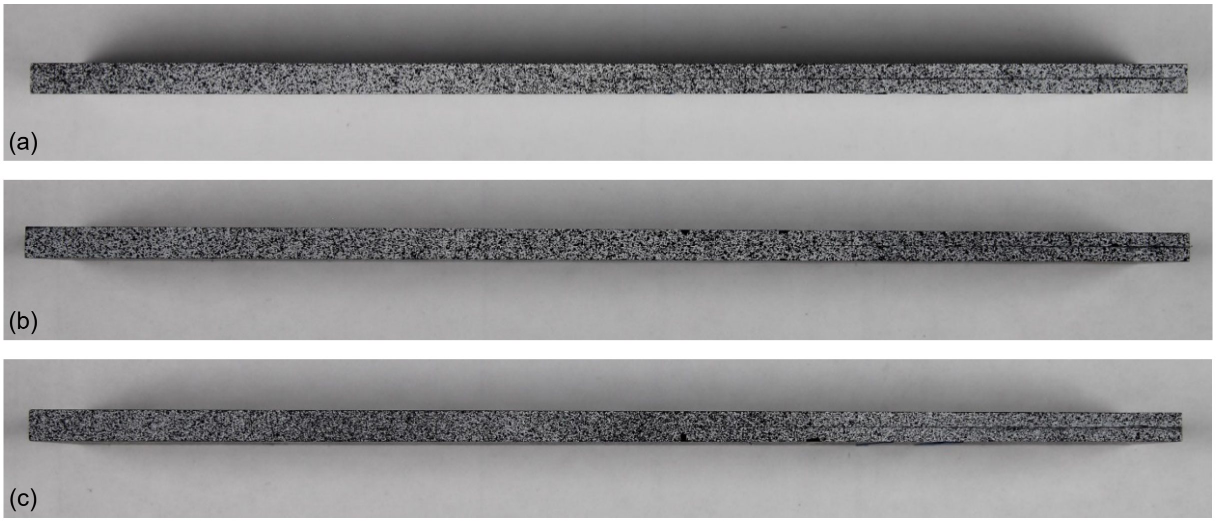

Figure 61.—Image of DCB specimen after testing (a) IM7ENF-1, (b) IM7ENF-2, and (c) IM7ENF-3.

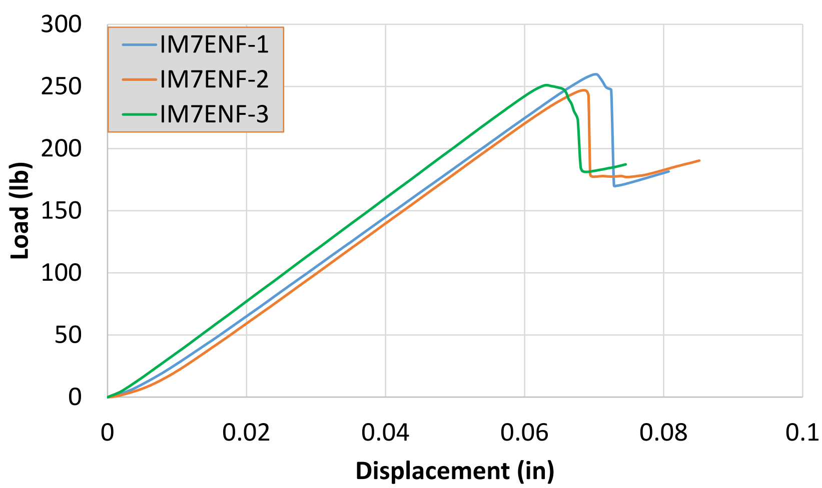

Figure 62.—ENF precrack load versus displacement.

4.0 Test T15: Specific Gravity Test

The mass density of the material is found in accordance with ASTM D792-13. First, the mass of the specimens in air is found using a scale. Second, a beaker is filled with water and the specimens are 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 are recorded. Third, the wire is submerged up to the same point as in the second step and its apparent mass in water is recorded. Using all three measurements, the specific gravity of the material is determined using the equation below. 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 is 2.70, which is within the reported range.

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

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

Mass measurements are made using an AWS AL201S Analytical Balance which has a resolution of 0.1 mg. The stand and beaker shown in Figure 63 are part of a specific gravity kit obtained from Mineralab.[8]

The specific gravity can be multiplied by the mass density of water to determine the mass density of the specimen as shown in Table 31.

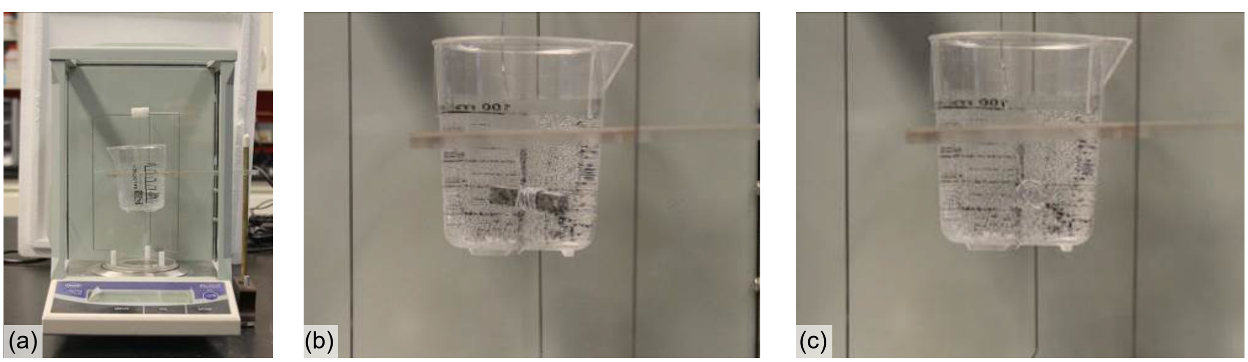

Figure 63.—Specific gravity test showing (a) overall test setup, (b) specimen and wire submerged in water, and (c) wire submerged in water.

[8] http://www.mineralab.com/SGK-B/

TABLE 31.—SPECIFIC GRAVITY

Nominal panel thickness, in. (plies)	Mass: specimen in air, g	Mass: wire + specimen submerged, g	Mass: wire submerged, g	Specific gravity
0.900 (120-ply)	5.16	2.60	0.65	1.61
	5.16	2.61	0.65	
	5.16	2.60	0.65	
Average	5.16	2.60	0.65	
Standard deviation	0	0.0057	0.0057	

5.0 Concluding Remarks

This report presents the details of the laboratory tests conducted at room temperature and at quasi-static loading conditions, and the data obtained from the analysis of the laboratory tests for IM7-8552 unidirectional composite. The stress-strain curves from 12 different tests are obtained and presented. In addition, mass density and volume fraction of the composite are also obtained.

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