Data Article

Experimental dataset on the in-plane tensile, shear, and compressive properties of a carbon-epoxy twill woven composite

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A R T I C L E   I N F O

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A B S T R A C T

This data article presents experimental data on the in-plane mechanical behavior of a carbon-epoxy twill woven composite. Properties under tension, shear, and compression are measured and reported, which include force vs. stroke curves, stress vs. strain curves, in-plane on-axis and off-axis moduli, in-plane shear modulus, tensile and compressive strengths, post-peak residual stress under compression, and on-axis and off-axis Poisson ratios. Laminate plates of the composite were ordered from a commercial vendor and specimens of desired dimensions were cut using a waterjet cutter. Tests were conducted in accordance with ASTM standards D3039 and D6641, under on-axis and off-axis tension, and under on-axis compression. The data represents a complete set of in-plane mechanical properties for the composite and can be used directly as lamina level input to numerical FEA models and design analyses with woven composite laminates. It can also serve as benchmark for the calibration and validation of these models. It can be used to calculate properties for other off-axis configurations using transformation equations. Since the data is intended to be a lamina level input, it can be used to determine and model the in-plane behavior of any laminate layup with this composite. The data also serves to demonstrate the marked anisotropy and tension compression asymmetry exhibited by woven composites.
Specifications Table

| Subject          | Ceramics and Composites |
|------------------|-------------------------|
| Specific subject area | Mechanical properties for carbon-epoxy twill woven composites |
| Type of data     | Tables, graphs, figures, and images |
| How the data were acquired | - Shimadzu Universal Testing Machine with 300kN Load Cell and Trapezium X Data Acquisition software  
- Mechanical Tensile grips from Shimadzu  
- Combined Loading Compression Fixture of ASTM D6641-ADJ manufactured by MTS  
- Omega pre-wired strain gauges (X-Y Planar Tee Rosette, 0°/45°/90°) for in-situ strain measurement during the tests used in conjunction with Micro-measurements strain gauge indicator and recorder (of Vishay Precision Group) along with Model P3 software  
- Keyence VHX-500 optical microscope at x100 magnification for optical micrographs  
- Photographs taken with Pixel 3a XL cellphone with 12.2 MP camera |

Data format: Analyzed
Description of data collection: Filtered

Data source location:
- Stony Brook University
- Stony Brook, NY, USA

Data accessibility:
- Repository name: Mendeley
- Data identification number: DOI:10.17632/w32mrdmw7h.2 (Ref. [8])
- URL: https://data.mendeley.com/datasets/w32mrdmw7h/2
- Rest of the processed data is included with this article

Value of the Data

- Data presents a complete set of in-plane mechanical properties for a carbon-epoxy twill woven composite under tension, shear, and compression.
- Data can be used to calculate mechanical properties for other off-axis angles using transformation equations.
- Data can be used as lamina level input of mechanical properties for analytical or finite element models, thus being applicable to all possible laminate configurations.
- Data can be used as reference for further mechanical tests of the same material as a form of validation.
- Data can be compared with other datasets on carbon-epoxy composites fabricated by various techniques to benchmark commercially purchased woven composite laminates against those fabricated in the lab.
- Data can be used as calibration and validation of numerical models intended to predict failure and damage under tension, shear, and compression.
1. Data Description

The data presented here shows the characterization of the mechanical behavior of a carbon-epoxy twill woven composite. This includes the measured raw load vs. displacement plots, the stress vs. strain plots, and the elastic moduli, strengths, and Poisson ratios. In addition, images and optical micrographs of failed specimens are also presented. Both on-axis and off axis properties at 45 degrees are reported. Following is a list of experiments conducted:

- In-plane, on-axis tension (0 degrees) (in accordance with ASTM D3039 [1]).
- In-plane, off-axis tension (45 degrees) (in accordance with ASTM D3039 [1]).
- In-plane, on-axis compression (0 degrees) (in accordance with ASTM D6641 [2]).

The co-ordinate system 1-2-3 represents principal lamina directions, with 1 and 2 indices referring to the fill and warp yarn directions, and 3 index referring to the out of plane direction. The co-ordinate system x-y-z represents the in-plane off-axis configurations. Data from each is described as follows:

1.1. In-Plane, On-Axis Tension

These tests are denoted as 0T1 to 0T4. The measured load vs displacement (stroke) for each test is shown in Fig. 1. The nominal stress vs. nominal strain plot (the latter calculated as the ratio of the stroke and initial length) is shown in Fig. 2. All specimens exhibit a nearly linear initial region followed by a well-defined peak followed by a sudden or nearly sudden drop corresponding to failure.

The initial elastic response for each test, with linear regression is shown below in Fig. 3:

The failure occurred by fiber breaking localized into a band, as shown in Fig. 4. This behavior was observed in all on-axis specimens. The image and micrograph with an additional x100 magnification of one of the failed specimens is shown. The magnification depicts the broken woven fibers as a result of failure.

The on-axis modulus was available from the supplier [3], equal to $E_1=E_2 = 34.45$ GPa. Using this value, the machine stiffness was calculated (as described later in the next section) and is listed in Table 1 along with the specimen dimensions used.

![Force vs Displacement](image)

**Fig. 1.** Force vs. displacement plots from the in-plane, on-axis [0 deg] tension tests on the epoxy/carbon twill woven composite.
**Fig. 2.** Nominal stress vs. nominal strain plots from the in-plane, on-axis [0 deg] tension tests on the epoxy/carbon twill woven composite.

**Fig. 3.** The linear elastic region of the force vs. displacement curves from the in-plane on-axis [0 deg] tension tests for each sample.
**Table 1**
Calculated machine stiffness from in-plane on-axis tension tests.

| Test ID | Total stiffness $K_{\text{total}}$ (N/mm) | Specimen thickness $t$ (mm) | Specimen width $b$ (mm) | Specimen gauge length $L$ (mm) | Calculated material stiffness $K_{\text{material}} = E_1 \cdot b \cdot t / L$ (N/mm) | Machine stiffness $K_{\text{machine}} = 1 / ((1 / K_{\text{total}} - 1 / K_{\text{material}}))$ (N/mm) |
|---------|----------------------------------------|-----------------------------|-------------------------|-------------------------------|-------------------------------------------------|-------------------------------------------------|
| 0T1     | 4.62e3                                  | 2.1                         | 25.39                   | 126.19                        | 14.56e3                                          | 6.77e3                                           |
| 0T2     | 4.54e3                                  | 2.07                        | 25.4                    | 127.41                        | 14.24e3                                          | 6.67e3                                           |
| 0T3     | 4.55e3                                  | 2.01                        | 25.43                   | 125.67                        | 14.01e3                                          | 6.74e3                                           |
| 0T4     | 5.76e3                                  | 2.02                        | 25.5                    | 124.51                        | 14.03e3                                          | 9.67e3                                           |
| **Average** | **7.46e3**                          |                             |                         |                               |                                                  |                                                  |

**Table 2**
On-axis [0 deg] tensile strength and in-plane Poisson's ratio of the carbon/epoxy twill woven composite.

| Test ID | On-axis tensile strength $F_{\text{R}}$ (Max stress) MPa | In-plane Poisson's ratio $\nu_{12}$ |
|---------|----------------------------------------------------------|-------------------------------------|
| 0T1     | 711.13                                                   | NA                                  |
| 0T2     | 865.35                                                   | 0.145                               |
| 0T3     | 716.04                                                   | 0.174                               |
| 0T4     | 915.75                                                   | 0.081                               |
| **Average** | **802.07**                                                | **0.133**                           |

The on axis tensile tests also provided the peak stresses each specimen reaches before failure as well as the Poisson’s ratio shown in Table 2. The Poisson’s ratio was obtained using longitudinal and transverse strain data obtained from the strain gauge in the linear region of the stress vs strain plot. For specimen 0T1, the strain gauges had issues with proper attachment and yielded inaccurate readings, these are marked as N/A on Table 2.
1.2. Off Axis Tension Tests (45 Degrees)

These tension tests are denoted as 45T1 to 45T6 and are convenient pseudo-tests for obtaining the shear response. The measured load vs. displacement (stroke) response of these tests is shown in Fig. 5. In addition, the nominal stress vs nominal strain plot, the latter derived from the stroke of the machine, is shown in Fig. 6. In contrast to the on-axis tests, these exhibited a markedly nonlinear response. An initial linear elastic response was followed by nonlinearity, followed by another linear region of a reduced slope, followed by a peak load and then a softening response terminating with a sudden vertical drop. The overall pre-peak plot resembles a plot exhibiting elastic-hardening plasticity and is consistent with that obtained in shear tests in literature [4].
The off-axis stiffness was obtained as the slope of the initial linear region, which for each individual test is shown in Fig. 7.

Since these tests used the same machine and grips as the on-axis tests, the previously calculated machine stiffness could be subtracted from this response, to yield the off-axis modulus of the material. In turn, this could be used to calculate the in-plane off-axis modulus $E_{45}$ (or $E_{45}$). The average value of $E_{45}$ is **9.98 MPa**. The calculations are described in the next section, and the results are presented in Table 3.
Table 3
Calculated off-axis modulus $E_x$ (at 45 degrees), i.e., $E_{45}$, for each in-plane off-axis [45 deg] tensile test.

| Test ID | Total stiffness $K_{\text{total}}$ (slope of the force vs. stroke) N/mm | Specimen thickness $t$ (mm) | Specimen width $b$ (mm) | Specimen gauge length $L$ (mm) | Material stiffness $K_{\text{material}} = 1/((1/K_{\text{total}} - 1/K_{\text{machine}}))$ | Off axis modulus $E_x$ ($E_{45}$) MPa $=K_{\text{material}} \times L/bt$ GPa | Calculated in-plane shear modulus $G_{12}$ GPa |
|---------|---------------------------------------------------------------|-----------------|-----------------|-----------------|---------------------------------|---------------------------------|---------------------------------|
| 45T1    | 3.24e3                                                        | 2.11            | 25.54           | 125.65          | 5.73e3                          | 13.4                            | 4.01                            |
| 45T2    | 2.22e3                                                        | 2.09            | 25.49           | 126.3           | 3.16e3                          | 7.49                            | 2.06                            |
| 45T3    | 2.64e3                                                        | 2.13            | 25.53           | 126.38          | 4.09e3                          | 9.5                             | 2.69                            |
| 45T4    | 2.28e3                                                        | 2.09            | 25.46           | 125.66          | 3.28e3                          | 7.75                            | 2.14                            |
| 45T5    | 2.78e3                                                        | 2.1             | 25.5            | 125.65          | 4.43e3                          | 10.4                            | 2.99                            |
| 45T6    | 2.93e3                                                        | 2.1             | 25.46           | 126.09          | 4.82e3                          | 11.4                            | 3.32                            |
| Average |                                                              |                 |                 |                 | 9.98                            | 2.87                            |                                 |

Fig. 8. Image and micrograph of an in-plane off-axis 45 deg tension test specimen.

In these tests, damage occurred in a more distributed manner compared to the on-axis tests, and it involved a region exhibiting necking as shown in Fig. 8. In this region fibers of 45 deg orientation were seen to rotate to become more aligned with the loading direction, with the inter-fiber matrix region likely undergoing extensive shear damage.

Damage continued to grow in this region, where final failure occurred as well. This behavior was observed in all off-axis specimens. The image and micrograph with an additional x100 magnification of one of the failed specimens is shown in Fig. 8. The magnification depicts the fibers being torn apart because of failure.

Similar to the on-axis tensile tests, the off-axis tensile tests also provide the strength, denoted here as $F_{45t}$ and off-axis Poisson’s ratio $\nu_{xy}$ for each specimen as shown in Table 4.
Table 4
Off-axis tensile strength $F_{45t}$ and Poisson’s Ratio $v_{xy}$.

| Test ID | Off-axis tensile strength (max stress) $F_{45t}$ MPa | $v_{xy}$ |
|---------|---------------------------------------------------|---------|
| 45T1    | 60.36                                             | N/A     |
| 45T2    | 67.84                                             | 0.641   |
| 45T3    | 56.36                                             | 0.643   |
| 45T4    | 56.99                                             | N/A     |
| 45T5    | 64.87                                             | 1.157   |
| 45T6    | 61.63                                             | N/A     |
| Avg     | 61.34                                             | 0.814   |

Fig. 9. Measured force vs. displacement plots from the in-plane, on-axis compression tests on the epoxy/carbon twill woven composite.

1.3. On-Axis Compression Tests

These tests are denoted as OC1 to OC4 and were used to not only characterize the compressive response, but also to verify the on-axis modulus supplied by the material supplier. The measured load vs. displacement (stroke) response of these tests is shown in Fig. 9. In addition, the nominal stress vs nominal strain plot, the latter derived from the stroke of the machine, is shown in Fig. 10.

In addition, the linear portion of the stress vs. the strain measured using strain gauges is also plotted, which was used to obtain the in-plane elastic modulus (since it does not include the effect of machine or grip stiffness). (Note: strain in Fig. 11 is from strain gauges, and strain in Fig. 10 is the nominal strain obtained as stroke divided by length).

Fig. 12 is verification that the tests were valid since the percent bending remained below 10% for the region of interest from 1000 to 3000 micro-strain. The average strain is calculated from the two strain gauges placed on either side of the specimen during testing.

Fig. 13 is an example of the failures that occurred during the tests. For all four tests it occurred in the gauge length section. The fracture plane angle of this specimen is $10^\circ$ with respect to the loading direction, in the out of plane direction as shown in Fig. 13. Table 5 shows the maximum load, specimen dimensions, compressive strength, and compressive modulus that verifies the supplier provided on-axis modulus. The average measured on-axis modulus is 40.8 GPa.
Fig. 10. Measured nominal stress vs. nominal strain plots from the in-plane, on-axis compression tests on the epoxy/carbon twill woven composite.

Table 5
On-axis [0 deg] compressive strength, modulus, and residual stress of the carbon/epoxy twill woven composite.

| Test ID | Maximum load at failure (N) | Specimen thickness t (mm) | Specimen width b (mm) | Specimen gauge length L (mm) | Compressive strength $F_{1c}$ (MPa) | On-axis modulus $E_{1c}$ (MPa) | Average residual stress MPa |
|---------|-----------------------------|---------------------------|-----------------------|-----------------------------|--------------------------------|-------------------------------|---------------------------|
| 0C1     | 3928.12                     | 2                         | 12.07                 | 13.01                       | 162.72                         | 49.73                         | 20.45                     |
| 0C2     | 3815.63                     | 2                         | 12.19                 | 12.99                       | 156.5                          | 37.98                         | 22.19                     |
| 0C3     | 3684.38                     | 1.9                       | 12.09                 | 13.02                       | 160.39                         | 39.65                         | 19.21                     |
| 0C4     | 3918.75                     | 1.8                       | 12.1                  | 13.05                       | 179.9                          | 35.85                         | 32.26                     |
| Average |                             |                           |                       |                             | **164.88**                     | **40.8**                      | **23.5**                  |
with a standard deviation of 6.15 GPa, which agrees well with the suppliers provided value of 34.45 GPa.

Also shown in Table 5 is the non-zero residual stress in the post-peak region – which does not occur under tension. To summarize, the average measured properties of the composite are listed in Table 6 with their respective standard deviations.
Table 6
Summary of the mechanical properties of the epoxy/carbon twill woven composite.

| Composite Property                          | Symbol   | Average value | Standard deviation | Unit |
|--------------------------------------------|----------|---------------|-------------------|------|
| On-axis modulus (tension)                  | $E_1 = E_2$ | 34.45         | NA (obtained from supplier) | GPa  |
| On-axis modulus (compression)              | $E_{1c} = E_{2c}$ | 40.804       | 6.15              | GPa  |
| Off-axis 45° modulus                       | $E_x = E_y = E_{45}$ | 9.98         | 2.23              | GPa  |
| In-plane on-axis shear modulus             | $G_{12}$ | 2.87          | 0.737             | GPa  |
| In-plane on-axis Poisson’s ratio           | $\nu_{12} = \nu_{21}$ | 0.133       | 0.0475             |      |
| In-plane off-axis (45 deg)                 | $\nu_{xy} = \nu_{yx}$ | 0.814       | 0.297             |      |
| Poisson’s ratio                            |          |               |                   |      |
| On-axis tensile strength                   | $F_{1t} = F_{2t}$ | 802.07       | 104.24            | MPa  |
| Off-axis tensile strength                  | $F_{45t}$ | 61.34         | 4.46              | MPa  |
| On-axis compressive strength               | $F_{1c} = F_{2c}$ | 164.886     | 10.35             | MPa  |
| On-axis residual stress after compressive failure | $\sigma_R$ | 23.5         | 5.94              | MPa  |

2. Experimental Design, Materials and Methods

2.1. Materials

The carbon-epoxy twill woven composites were purchased from DragonPlate Inc, in the form of plates (trade name is Economy Plate [3]). The plates were 2 mm thick and consisted of 6 plies stacked on top of each other. As per the supplier, the fiber volume fraction is 50% and density is 1577.75 kg/m³, and the carbon fiber modulus is 234.4 GPa. Also, the on-axis modulus $E_1$ is 34.45 GPa. As a result of each ply being woven, the on-axis tests have fiber orientations of 0 deg or 90 deg and the off-axis tests have fiber orientations of ±45 deg. For the compressive tests, the same laminates are used with the on-axis configuration.

2.2. Universal Testing Machine

Fig. 14 depicts the setup used for the mechanical tensile tests with each test coupon being dimensioned in accordance with ASTM D3039 [1].

2.3. On and Off Axis Tensile Tests

The on and off axis tensile tests were performed in accordance with ASTM D3039. The tests were conducted in a Shimadzu Universal Testing Machine with a load cell of 300 KN, along with the Trapezium X data acquisition system. A loading rate of 0.5 mm/min was used in all tests. The tests were performed with 0 deg direction representing the on-axis/warp direction while the 90 deg direction represents the fill direction. The specimens were cut from the pre-ordered plates (obtained from the supplier) using a waterjet cutting machine. The dimensions of the specimen are shown in Fig. 16. To facilitate the specimen gripping, square shaped, 1 inch x 1 inch aluminum tabs were attached to the ends of each test coupon. A gripped specimen is shown in Fig. 15. Four on-axis trials and six off-axis trials were conducted, with the results shown previously. For each specimen two strain gauges were attached, one in the longitudinal direction and one in the transverse direction, to facilitate measurement of the Poisson’s ratio.
2.4. Machine Stiffness Calculation

The plots in Figs. 1 and 5 represent the total load vs. displacement (stroke) data, which includes the effect of machine stiffness (as well as that of grips). So, the slopes shown in Figs. 3 and 7 represent the total stiffness of the entire system, $K_{Total}$. The in-plane modulus
$E_1 = E_2$ was available from the supplier, equal to 34.45 GPa. Using this information, the effective machine+grips stiffness, lumped into one quantity $K_{\text{Machine}}$ was determined as follows. As discussed in [5,6], the machine, grips, and the specimen can be assumed to act in series. Then, the stroke, which is the total measured displacement $\delta_{\text{Total}}$, is the sum of the displacement of the coupon $\delta_{\text{Material}}$ and the machine+grips i.e., $\delta_{\text{Machine}}$. So, we have,

$$\delta_{\text{Total}} = \delta_{\text{Material}} + \delta_{\text{Machine}}$$  \hfill (1)

If $P$ is the force and $K_{\text{material}}$ is the stiffness of the material, then we have,

$$\frac{P}{K_{\text{Machine}}} = \frac{P}{K_{\text{Total}}} - \frac{P}{K_{\text{Material}}}$$  \hfill (2)

Since the force is equal in all components due to them being in series, we have,

$$\frac{1}{K_{\text{Machine}}} = \frac{1}{K_{\text{Total}}} - \frac{1}{K_{\text{Material}}}$$  \hfill (3)

The stiffness for each coupon was calculated as

$$K_{\text{Material}} = \frac{E_1 A}{L}$$  \hfill (4)

where $A$ and $L$ are the cross-section area and length of each coupon. Then, using Eq. (3) the machine stiffness was calculated. The results are shown in Table 1 along with the average machine stiffness value.

2.5. Off-Axis Tension Tests and Shear Modulus Calculation

The off-axis 45° tension tests were conducted in the same manner as the on-axis tests. The off-axis modulus was found using Eqs. (2) and (3) with off-axis parameters. The machine stiffness remains the same as that from the on-axis tests since the test up did not change. As before, the total stiffness $K_{\text{Total}}$ was found as the slope of the linear elastic region of the force vs. stroke plot, shown in Fig. 9. Then, the material stiffness $K_{\text{material45}}$ is obtained using Eq. (3), which then yields the off-axis modulus as,

$$E_{45} = \frac{L}{AK_{\text{Material45}}}$$  \hfill (5)

The calculated values of $E_{45}$ are shown in Table 3 along with the average value. From this value, the in-plane shear modulus $G_{12}$ was calculated using [4]:

$$\frac{1}{E_x} = \frac{m^2}{E_1} (m^2 - n^2 \nu_{12}) + \frac{n^2}{E_2} (n^2 - m^2 \nu_{21}) + \frac{m^2 n^2}{G_{12}}$$  \hfill (6)
Fig. 17. (a) Specimen loaded into the CLC fixture on Shimadzu UTM; (b) Initial loading of the specimen into the CLC fixture.

These calculated $G_{12}$ values are also listed in Table 3. In the above equation $E_x$ represents the off-axis modulus, $(E_{45}$ in this case), and $m = \cos \theta$, and $n = \sin \theta$, where $\theta = 45^\circ$.

2.6. On-Axis Compressive Tests

The on-axis compressive tests were performed in accordance with the ASTM D6641 Standard [2]. The compressive force that is loaded onto the specimen is a combination of both end loading and shear loading. To take advantage of the specimen under compression, they remained untubbed. The specimen dimensions follow the recommendations from the ASTM standard which are: 140 mm in length, 12 mm in width and 2 mm in thickness with a gauge length of 13 mm. A total of 4 on-axis tests were conducted. Each specimen needed to be properly loaded into the CLC fixture (shown in Fig. 17) by applying a torque of 3.0 N-m in an alternating order to prevent end crushing. Strain gauges were placed on both sides of the specimen to determine the percent bending and ensuring that buckling did not occur. The specimen dimensions are shown in Fig. 18.

The strain used for these plots was calculated from the stroke of the machine since the strain gauges broke after the maximum load was reached. To determine the laminate compressive strength of the composite $F_{1c}$, the following equation was used:

$$F_{1c} = \frac{P_f}{bt}$$

Where $P_f$ is the max load to failure, $b$ is the specimen width and $t$ is the specimen thickness. The Compressive Modulus, $E_{1c}$, is calculated between the range of 1000–3000 micro-strain in accordance with the testing standard. The compressive modulus is calculated for each test with the following formula for interpolation between the two points:

$$E_{1c} = \frac{P_2 - P_1}{(\epsilon_{x2} - \epsilon_{x1})bt}$$

Where $\epsilon_{x2}$ equals 3000 microstrain, $\epsilon_{x1}$ equals 1000 microstrain, $P_2$ is the load at strain $\epsilon_{x2}$ and $P_1$ is the load at strain $\epsilon_{x1}$. It is to be noted that these strains represent measurements
from the strain gauge (and not from the total stroke, which includes the effect of machine and fixture stiffness). It should also be noted that the net machine and fixture stiffness is different for compression tests due to the usage of the CLC fixture instead of the mechanical grips shown in Fig. 15. Unlike the tensile response, the compression response also shows a prolonged non-zero load plateau [7] in the post-peak region. This stress is referred to here as the residual stress, and its average value is reported in Table 5.

We note that all the raw data for experiments described here, have been posted on a Mendeley Dataset [8].

**Ethics Statement**

The work presented here did not involve use of human subjects or animal experiments. Also, the data was not collected from social media platforms.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data Availability**

Epoxy/Carbon Twill Woven Composite: Mechanical Properties (Original data) (Mendeley Data).

**CRediT Author Statement**

**Felix Liu**: Software, Validation, Formal analysis, Investigation, Writing – original draft; **Leana Grotz**: Software, Validation, Investigation, Writing – original draft; **Yanyan Cui**: Investigation; **Kedar Kirane**: Conceptualization, Methodology, Resources, Data curation, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.
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