

Missing the Warning Signs: Strain-Gauge Detection of Fatigue Damage in Carbon-Fiber Laminates

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Abstract—Carbon fiber composites fail by cascading internal damage that does not produce many visible warnings, seen in the 2023 loss of the *Titan* submersible. The carbon fiber composite cylinder was the point of failure in the catastrophe, and this experiment examined whether surface strain measurements can resolve that damage as it accumulates. Six carbon fiber laminate strips, three of 0.838 mm thickness and three of 3.354 mm thickness, were tested in four-point flexure on a displacement controlled Instron 5967 universal testing machine (UTM) using custom machined clamps fixed at both ends of the laminate. Each specimen carried three $120\ \Omega$ quarter bridge strain gauges, one centered and two 63.5 mm to either side, read by an Arduino based data acquisition (DAQ) system at 5 Hz. One specimen of each thickness was loaded until failure, and the other four specimens were cycled roughly 30 to 60 times at 600 N or 3400 N, respectively, before a final loading to fracture. The thin specimen reached a peak of $(2891 \pm 28)\ \mu\epsilon$ and the thick specimen reached $(3659 \pm 34)\ \mu\epsilon$, corresponding to a flexural stress of $(97.0 \pm 9.7)\ \text{MPa}$. All six specimens fractured at a clamped end rather than at the center because of the custom-machined jig edges inducing a stress concentration, so the gauges failed to capture the critical section with no precursor to failure determined.

Index Terms—carbon fiber laminate, cyclic loading, data acquisition, four-point flexure, strain gauge, stress concentration, universal testing machine

I. INTRODUCTION

The objective of this lab was to simulate OceanGate's *Titan* disaster to analyze whether failure surfaces can be detected before permanent failure occurs. The experiment will use two types of carbon fiber laminates (thick and thin), strain gauges, DAQ's and Arduino, and will be tested on a Universal Testing Machine (UTM). The carbon fiber laminate will be exposed to a four-point force test using the UTM, shown in Fig. 1. Subsequently, the strain gauges attached to the laminate will generate resistance. A Wheatstone bridge configuration is used to convert the small change in resistance of the strain gauge into a measurable voltage, which is then amplified and acquired by a data acquisition (DAQ) system and analyzed by Arduino code.

On June 18, 2023, the OceanGate *Titan* submersible experienced an implosion while descending to the wreck of the RMS *Titanic*, resulting in the loss of all five persons aboard the vessel. The submersible had a carbon fiber composite pressure hull designed to withstand the extreme hydrostatic pressures at depths approaching 3800 m. Unlike conventional metallic pressure vessels, the carbon fiber composite hull was selected because of its high specific strength and stiffness, allowing the submersible to achieve a lightweight design while maintaining the structural capacity required for deep-sea

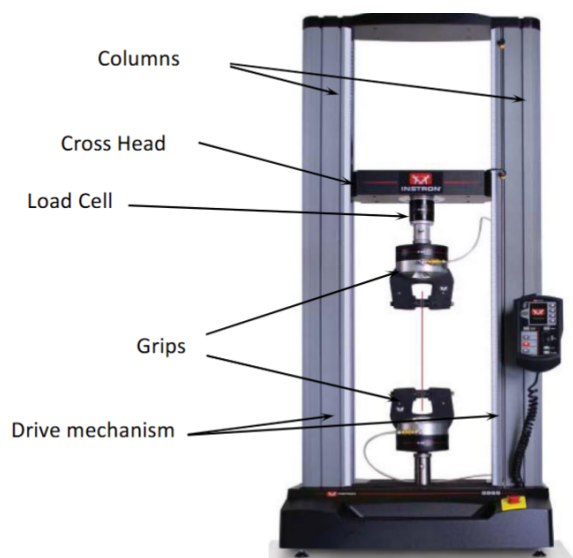


Fig. 1. Instron 5967 Universal Testing Machine showing the load cell, crosshead, and drive mechanism.

exploration. However, composite materials exhibit complex failure mechanisms that differ significantly from those of traditional engineering metals, making their long-term structural integrity more difficult to evaluate [1].

Following the accident, the National Transportation Safety Board (NTSB) concluded that the pressure hull, shown in Fig. 2, likely experienced progressive internal damage after repeated dive cycles, including delamination and other defects that weakened the cylinder before its final descent. Although the *Titan* was equipped with a real-time structural health monitoring system consisting of strain gauges and sensors, the collected data was incorrectly interpreted, allowing the damaged pressure vessel to run until failure occurred. The investigation emphasized that damage within composite materials can accumulate gradually beneath the surface while producing few visible indications of structural degradation. As a result, reliable methods of monitoring composite structures and identifying early warning signs of failure have become an increasingly important area of research [1].

This investigation examines whether strain measurements collected during controlled laboratory testing can be used to identify changes in the mechanical response of carbon fiber specimens prior to catastrophic failure. Rather than reproducing the conditions experienced by the *Titan*, the experiment applies cyclic four-point bending loads to carbon fiber laminates while

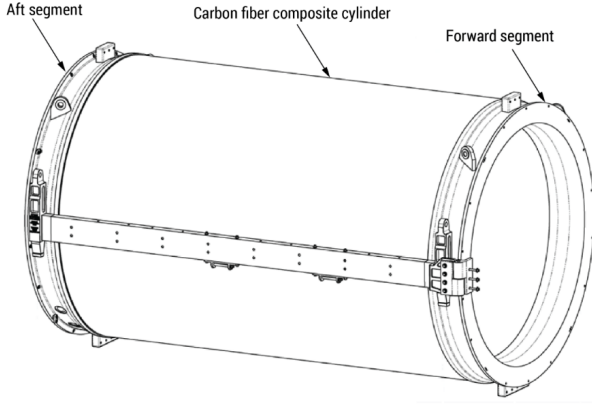


Fig. 2. Pressure vessel composite cylinder and titanium end segments. Titanium spherical domes were bolted to the segments at either end. [1]

continuously monitoring strain using bonded strain gauges and a custom data acquisition system. By comparing the strain response of specimens tested directly to failure with specimens subjected to cyclic loading before failure, the experiment investigates whether measurable changes in structural behavior occur as damage accumulates. Understanding these changes not only provides insight into the failure behavior of carbon fiber composites but also demonstrates the potential role of structural health monitoring systems in improving the safety and reliability of composite engineering structures.

Carbon fiber composites have become common in engineering applications because of their high specific strength, specific stiffness, corrosion resistance, and low density. Unlike materials such as steel or aluminum, carbon fiber composites are anisotropic, meaning their mechanical properties depend on the orientation of the reinforcing fibers. This allows engineers to adjust the laminate to maximize strength and stiffness in the primary loading directions while minimizing overall structural weight. As a result, carbon fiber composites are widely used in aircraft structures, spacecraft, racing vehicles, wind turbine blades, and pressure vessels where reducing weight while maintaining structural performance is critical [2].

Composite materials exhibit more complex failure mechanisms than traditional engineering metals. Under mechanical loading, damage may begin as microscopic cracks that are not visible on the surface of the material. As loading continues, these cracks can propagate between adjacent laminate layers, producing delamination that reduces the ability of the fibers to transfer load effectively. Additional damage may include fiber breakage, matrix crushing, and interfacial debonding between the fibers and polymer matrix. Because many of these failure mechanisms develop internally before any visible signs of damage appear, composite structures can experience significant reductions in strength and stiffness while appearing externally undamaged. Repeated cyclic loading accelerates this damage, making fatigue one of the concerns when designing composite structures for long-term use. By comparing the measured strain response before and after repeated loading cycles, engineers can evaluate whether measurable changes occur prior to catastrophic failure. This concept forms the basis of the lab, where strain

gauges were used to monitor carbon fiber specimens throughout flexural testing to determine whether strain measurements could provide an early indication of structural degradation [2].

Data Acquisition (DAQ) involves a sensor, DAQ hardware, and computer software such as LabView used to interpret incoming signals [3]. The sensor in this lab will be a strain gauge connected to a feeler gauge which will run through a Wheatstone Bridge to calculate the voltage in analog. The DAQ will be used to measure voltage using an Analog to Digital Converter (ADC). An ADC takes an analog signal and approximates it with a limited number of possible values; this returns a discrete representation in time and magnitude.

The number of possible values an A-D converter has is represented in base 2, whose range can be modified with the application of gains. The DAQ being used has various sample windows that can measure voltages with varying resolution [3], with larger sample windows having a lower resolution and vice versa. Resolution can be described as the minimum change in voltages that can be resolved by considering the voltage range of the ADC and the number of discrete values the ADC can return. The resolution can be described by the following equation:

$$\text{Resolution} = \frac{V_{\max} - V_{\min}}{2^n - 1} \quad (1)$$

Where $V_{\max}$ and $V_{\min}$ are the voltage range and $2^n - 1$ is the number of discrete values the converter can return. The DAQ being used in lab is the Arduino UNO's onboard 10-bit converter, so the number of discrete values will be 1024 when calculating the resolution [3].

Currently, strain gauges and Wheatstone bridges are the most common methods for measuring strain. A strain gauge works by converting physical tension and compression into a change in electrical resistance. When the feeler gauge deforms under physical stress, the strain gauge also deforms with it, this deforms the strain gauge's internal wiring which modifies the resistance. A strain gauge consists of a thin metal wire that runs in a zig-zag pattern. When the gauge goes through tension, the electrical resistance increases, and when the gauge compresses, the electrical resistance decreases. Resistance can be calculated using the strain gauge theory.

$$R = \rho \frac{L}{A} \quad (2)$$

Where R is the resistance, L is the length, A is the cross-sectional area, and ρ is the specific resistance. Strain gauges can also contain sensitivities to lateral and shear strains [4], which is why a gauge factor, G_f , is used to account for these strains.

$$R_U = R + \epsilon G_f R \quad (3)$$

Where R is the initial resistance, R_U is the new resistance under the applied strain, ϵ .

The Wheatstone bridge (WSB), as shown in Fig. 3, splits electrical power into two parallel paths. It is utilized to estimate resistance changes by making "small" differential voltage measurements [4]. A Wheatstone Bridge commonly consists of

four resistors, three of which are known to have a resistance of 120 ohms each for this lab. The last resistance is the resistance found from the strain gauge R_U . The output voltage (V_G) is the difference in voltage between the middle points of these two paths. Changing resistance alters the voltage at one node, creating V_G . V_G is calculated as the difference from V_U to V_1 , as shown in Fig. 3.

$$V_G = V_S \left(\frac{R_1}{R_1 + R_U} - \frac{R_3}{R_3 + R_4} \right) \quad (4)$$

With V_G being the bridge voltage, V_S being the supplied voltage, R_U being the resistance found from the strain gauge, and R_1 , R_3 , and R_4 being the three known resistances from the Wheatstone Bridge.

After the voltage change is found, strain is calculated as follows:

$$\varepsilon = \frac{4\Delta V}{V_S G_f} \quad (5)$$

With ε being strain, ΔV being the change in true bridge voltage, V_S being supplied voltage, and G_f being the gauge factor.

An amplifier is a component that takes a weak electrical signal and multiplies its voltage to make it larger for computers to read. Amplifying the signal improves the measurement resolution and increases the signal-to-noise ratio while preserving the relationship between strain and voltage. After amplification, the measured voltage, V_{amp} , is divided by an amplifier gain of 900 ± 4.5 in software to obtain the true bridge voltage for strain and load calculations, which improves its resolution. ΔV for V_{amp} is then:

$$\Delta V = \frac{V_{amp} - \text{tare}V_{amp}}{\text{Gain}} \quad (6)$$

Where Gain is a constant for amplification. Strain can then be calculated for V_{amp} using (5).

The lab utilizes a four-point bending configuration, shown in Fig. 4, to evaluate the flexural behavior of carbon fiber composite specimens. Four-point bending is commonly used for composite materials because it produces a region of constant bending moment between the two loading points, allowing a larger portion of the specimen to experience nearly uniform bending stresses. This loading configuration reduces the influence of localized stress concentrations directly beneath the loading noses and provides a more representative evaluation of the material's flexural properties. Furthermore, because failure typically initiates within the constant moment region, four-point bending provides a suitable method for monitoring the development of structural damage using surface-mounted strain gauges.

For a simply supported beam subjected to four-point bending, the maximum bending stress occurs at the surface of the specimen where the distance from the neutral axis is greatest. The normal bending stress is given by

$$\sigma = \frac{My}{I} \quad (7)$$

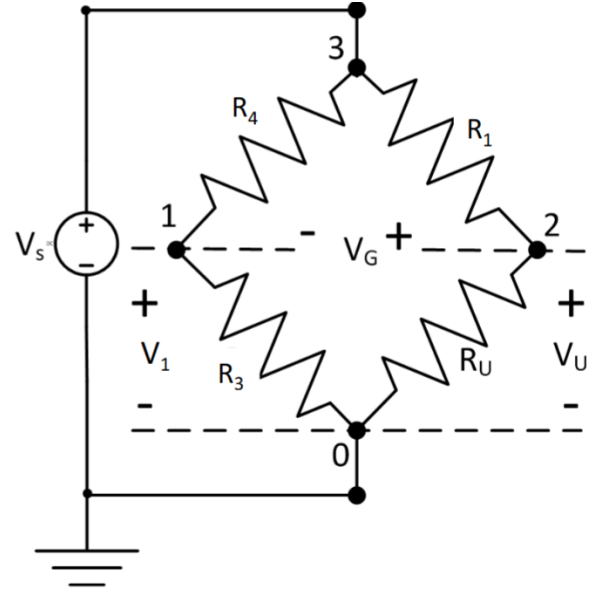


Fig. 3. Wheatstone Bridge. Notation as follows: V_S is the supplied voltage; V_G is the voltage across nodes 1 and 2. [4]

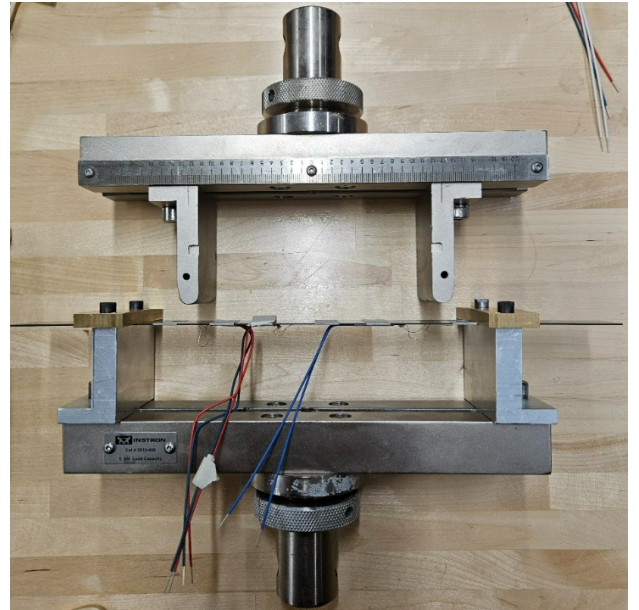


Fig. 4. Four-point bending fixture showing the support span, loading span, and constant moment region with a carbon fiber sample attached.

Where M is the bending moment, y is the distance between the neutral axis to the surface of the beam, and I is the second moment of inertia. For a rectangular cross-section

$$I = \frac{bd^3}{12} \quad (8)$$

Where b is the width and d is the thickness.

Substituting (8) into (7), and using the maximum bending moment for the four-point bending configuration, results in the flexural stress equation used throughout the lab.

$$\sigma_f = \frac{3PL}{4bd^2} \quad (9)$$

Where P is the applied load and L is the support span. This simply-supported form establishes the baseline flexural relation; section III in the Results section describes how the fixed-end (clamped-clamped) boundary condition actually realized by the test fixture modifies the moment expression used for the quantitative results reported later.

The flexural strain at the outer surface of the specimen is related to the midspan deflection and specimen geometry.

$$\varepsilon_f = \frac{6Dd}{L^2} \quad (10)$$

Where D is the measured midspan deflection. Using the calculated flexural stress and flexural strain, stress-strain curves were generated for the initial failure tests of both laminate thicknesses. The slope of the initial linear portion of each curve was then used to determine the flexural modulus.

$$E_f = \frac{\Delta\sigma_f}{\Delta\varepsilon_f} \quad (11)$$

The flexural modulus represents the material's resistance to elastic deformation under bending loads. These flexural properties established the baseline mechanical behavior of each laminate and were later compared with specimens subjected to cyclic loading to evaluate how repeated loading influenced structural response and failure.

While the initial loading tests established the flexural properties of the thin and thick carbon fiber laminates, the primary objective of this lab was to evaluate how repeated loading influences structural degradation and failure. Engineering components are rarely subjected to a single static load during service. They often experience repeated loading and unloading cycles that accumulate damage within the material, known as fatigue. In composite materials, fatigue damage typically develops through the initiation of microscopic cracks, followed by fiber-matrix debonding, delamination between laminate layers, and eventually fiber fracture. As these damage mechanisms accumulate, the stiffness of the laminate gradually decreases, resulting in larger strains under the same applied load. Unlike many metallic materials, where fatigue cracks often propagate from a single location, damage in composite laminates can develop simultaneously through multiple interacting failure mechanisms, making the onset of failure more difficult to identify.

After the flexural properties were established, the remaining specimens were then subjected to cyclic loading before being loaded to failure. Two different cyclic loading conditions were selected to investigate whether increasing the number of loading cycles produced measurable changes in the strain response, flexural stiffness, or ultimate failure point of the carbon fiber specimens. Rather than predicting the complete fatigue life of the material, the experiment focused on determining whether strain measurements collected throughout cyclic loading could identify changes in structural behavior before failure.

Fatigue is commonly classified as either low-cycle or high-cycle fatigue, depending on the number of loading cycles experienced before failure. Low-cycle fatigue typically occurs over approximately 5 to 1,000 loading cycles and is associated



Fig. 5. Original setup for a four-point test on the carbon-fiber laminate sample. The sample is positioned across two lower support anvils and loaded by two upper loading anvils, utilizing an Instron universal testing machine [5].

with relatively large stresses and strains, while high-cycle fatigue generally involves millions of cycles at lower stress levels [2]. The cyclic loading performed in this investigation falls within the low-cycle fatigue regime. Rather than attempting to determine the complete fatigue life of the carbon fiber laminates, specimens were subjected to approximately 30 and 60 loading cycles before being loaded to failure.

Experimental uncertainty was considered throughout the testing and data analysis process. Sources of uncertainty included the dimensions of the carbon fiber specimens, strain gauge measurements, crosshead displacement, and the resolution of the Arduino data acquisition system. These uncertainties influence the flexural stress, flexural strain, and flexural modulus, as well as the measured strain response during cyclic loading. Uncertainty propagation was performed using the root-sum-square (RSS) method for the calculated flexural properties.

II. PROCEDURE

Four-Point Bend Fixture Construction

All sample tests were performed using an Instron 5967 Universal Testing Machine (UTM), equipped with a 30 kN load cell. The UTM was used to apply a four-point flexural load on carbon-fiber laminates to analyze the flexural modulus of each sample during direct failure and cyclic loading tests. The original idea was to have the carbon-fiber laminates resting on two lower anvils, as shown in Fig. 5, with the two upper anvils equidistant from the center of the laminate. However, this was an issue, as the beam would slip or experience end rotation under applied loading.

To resolve this issue, the lower anvils were replaced with two manufactured clamps, changing the beam fixture from a simply supported to a fixed-end beam. The modified clamps used for the four-point tests are shown in Fig. 6.

The modified clamping mechanism consists of fixtures to establish fixed ends for the carbon-fiber beam during flexural testing. The fixtures are made up of an aluminum base block and a brass clamping plate. The brass plate was securely fastened to the top edge of the aluminum base via two black hex socket-head cap screws. This creates a rigid clamping mechanism to firmly anchor the carbon-fiber sample during testing. Additionally, the brass plate can be raised after

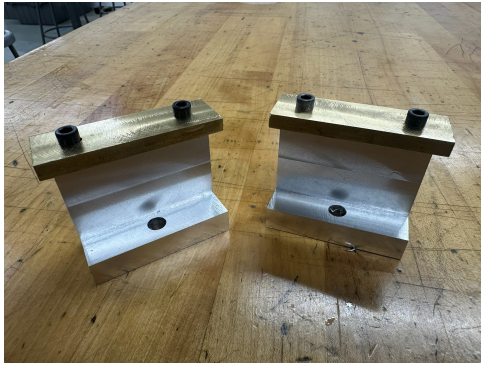


Fig. 6. Custom-machined lower support fixtures designed for the four-point flexural bend test. Each fixture features a multi-material assembly consisting of a lightweight aluminum base block and an upper brass clamping plate.

unfastening the screws, which is where the carbon-fiber rests to fixate the beam as the brass plate is fastened.

Carbon Fiber Specimen Preparation

Six rectangular carbon fiber laminate samples were tested during this investigation. Three specimens were classified as thin, with a thickness of 0.838 ± 0.001 mm, and thick, with a thickness of 3.354 ± 0.001 mm. The thickness of the carbon fibers was measured using a digital micrometer with an accuracy of ± 0.001 mm [6]. The width of the carbon fibers was measured using a digital caliper with an accuracy of ± 0.02 mm [7]. These measurements would later be used to calculate bending stress and flexural properties for each sample.

Strain Gauge Installation

Before applying the strain gauges, each sample was cleaned with denatured alcohol wipes to remove contaminants that could interfere with adhesive bonding. The laminates were then marked with masking tape to denote the positioning of each strain gauge. Using a standard ruler, the center of the laminate was marked with tape. Then, on each side of the center, additional tape was marked 2.5 inches to denote the position of the other two strain gauges. Each strain gauge was transferred using pliers and application tape, aligned with the desired strain direction, and bonded using cyanoacrylate adhesive. Firm pressure was applied while the adhesive was cured. Electrical lead wires were prepared by stripping both ends. Additionally, a strain-relief loop was included near each gauge to prevent loading of the solder joints during flexural testing. The ends of the wires were soldered to the strain gauge ends and secured to the beam using masking tape. After soldering, each installation was inspected and verified using an ohmmeter to confirm proper bridge resistance. The full setup of the instrumented carbon-fiber beam is shown in Fig. 7.

This process was done for six carbon-fiber beams: three thin and three thick. Each carbon-fiber sample was instrumented with three $120\ \Omega$ quarter-bridge strain gauges positioned longitudinally along the beam. One strain gauge was bonded at the center of the beam while the two additional strain gauges were mounted symmetrically on opposite sides of the center gauge. The instrumented beams would be used to measure flexural strain, stress, and load throughout testing.



Fig. 7. Carbon fiber laminate sample prepared for four-point flexural testing. The sample features three surface-mounted strain gauges: one at the center and two equidistant from the center on opposite sides. Embedded electrical lead wires, with relief, extend from both ends to facilitate direct connection with Arduino.

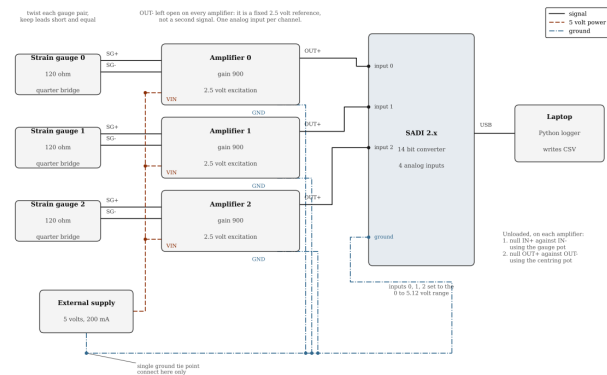


Fig. 8. Schematic wiring diagram of a multi-channel strain gauge data acquisition system. The setup features three $120\ \Omega$ quarter-bridge strain gauges individually connected to amplifier units.

Amplifier and Arduino Wiring

Each strain gauge was connected to an independent quarter-bridge instrumentation amplifier configured with a bridge excitation voltage and an amplifier gain. Along with the amplifiers, additional electrical components used to connect and wire the strain gauges for data collection were an Arduino UNO microcontroller for data acquisition and a circuit board for organization. In Fig. 8, a wiring diagram was created to organize where all the components for this experiment need to be wired.

In this schematic, the ELEGOO Arduino UNO was used as an external power supply and an analog-to-digital (ADC) converter. For each instrumented carbon fiber beam, the ends of each strain gauge were wired into the SG terminals for each amplifier. In this case, three strain gauges correspond to three amplifiers. Through the OUT+ terminal, the amplifiers were connected to the Arduino UNO through the A0, A1, and A2 terminals. Using a USB-C cord, the Arduino Uno

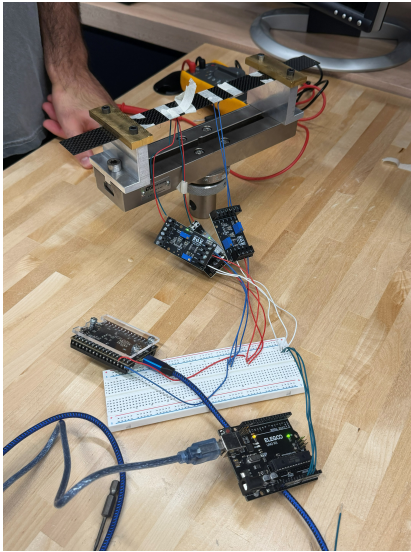


Fig. 9. Hardware implementation of the experimental strain gauge data acquisition setup. An instrumented carbon-fiber sample with lead wires are routed to the adjacent amplifier. The amplifier interfaces with the circuit board to connect to the Arduino UNO board for analog-to-digital conversion.

is connected to a laptop for data collection. To complete the electrical circuit, power and ground must be implemented for the circuit to function effectively. From the Arduino UNO, the 5V power goes into the VIN terminals of the amplifiers. Also, the ground terminals from the amplifiers are connected to the ground terminal in the Arduino UNO. The fully wired circuit with the beam is shown in Fig. 9. To connect the required inputs to their designated outputs, all electrical wiring was done on a circuit board.

Signal amplification and conditioning were powered by a shared 5V external supply from the Arduino with a single-point common ground. The analog voltage outputs would be converted into digital data through the Arduino and streamed via USB to a laptop running a Python logging script for comma-separated values (CSV) data collection. Prior to testing, each amplifier was balanced using the bridge null and output centering adjustments until the unloaded output voltage was centered. Furthermore, twisted-pair wiring was used to minimize electrical noise.

Script Writing and Troubleshooting

An Arduino program was developed to collect data from the strain gauges, and in parallel a Python Serial Logger was developed to listen to the Arduino's serial port and automatically and dynamically save data to CSVs as the test proceeded. Upon startup, the Arduino program delayed three seconds to allow the instrumentation amplifiers to stabilize before automatically recording an unloaded baseline, or tare, for each strain gauge. During testing, the Arduino repeatedly sampled each analog channel and converted the measured amplifier output voltage into strain using the quarter-bridge equations, where amplifier gain ($gain$), excitation voltage (V_s), and gauge factor (G_f) are given values and the change in the amplified bridge voltage (ΔV_{amp}) is the measured value. Only the change in strain relative to the unloaded baseline was

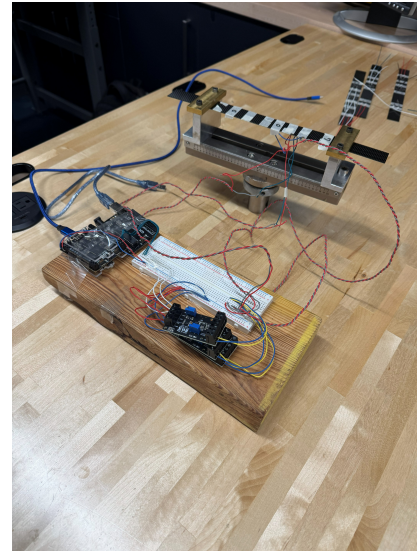


Fig. 10. Overview of the complete mechanical setup of the instrumented carbon-fiber beam used for flexural testing. The carbon-fiber beam is clamped at each end with the modified lower support fixture. The electrical components were attached to a wooden block to keep from being damaged.

reported. The Arduino transmitted the real-time microstrain values for all three gauges over serial at 5 Hz, where the Python Serial Logger's running output allowed strain evolution to be monitored and recorded to CSV continuously throughout each experiment. This process involved troubleshooting by applying small loads to the instrumented beam to ensure the connection between the strain gauges and the lead wires is not compromised. Following every specimen failure, each strain gauge channel was verified to ensure electrical continuity and confirm that any signal loss resulted from specimen damage rather than instrumentation failure.

Flexural Testing

Before conducting the 4-point test, all of the electronic components were organized and arranged on a wooden block as shown in Fig. 10. The wooden block assisted in keeping all electrical components from dangling from the instrumented beam as loads were being applied. Additionally, male-to-female wires were used between the lead wires of the strain gauge and amplifiers to ease the interchangeability between each carbon-fiber beam.

When implemented into the UTM, the loading fixture was lowered until the loading noses lightly contacted the sample. This setup is shown in Fig. 11. At this position, the Arduino strain acquisition system was tared to establish a zero-strain baseline while the sample remained unloaded within the fixture. Taring after the beam was clamped eliminated strain offsets caused by installation and clamping. The 4-point flexural test was applied to all six instrumented carbon-fiber beams. One thin and one thick sample was tested by applying a monotonic load to failure to determine the flexural properties. For the thin laminate, the feed rate was 7 mm/min, while the thick laminate had a feed rate of 14 mm/min. Load, displacement, and strain were continuously recorded until catastrophic failure occurred.

The remaining two specimens for each thickness were



Fig. 11. Configuration of the carbon-fiber beam when implemented into the Instron UTM. The lower clamps keep the ends of the beam fixed, while the upper anvil applies an axial load to produce bending.

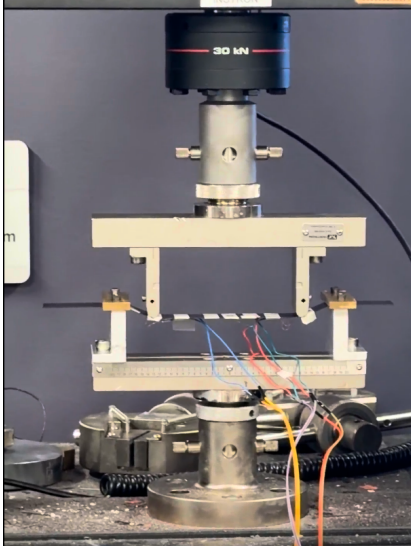


Fig. 12. Instrumented carbon fiber beam experiencing bending through cyclic loading in the four-point flexural test.

subjected to cyclic loading prior to final failure testing. The cyclic tests were designed to investigate whether repeated loading influenced the subsequent flexural failure behavior of the laminate. The effects of cyclic loading were observed in Fig. 12.

The thin samples were cyclically loaded to 600 N, while the thick samples were cyclically loaded to 3400 N. Two different cyclic loading rates were investigated. One sample was cycled 31 times, while the other was cycled 60.5 times before being loaded monotonically to failure at 14 mm/min. Throughout each experiment, synchronized load, crosshead displacement, and three-channel strain measurements were collected. These data were later used to determine flexural properties and comparisons of material response.

Data Analysis

After each specimen fractured, the strain gauge wiring and solder joints were inspected to verify electrical continuity.

Each strain gauge channel was individually tested to confirm that power and instrumentation remained operational after catastrophic failure. The Instron load-displacement data were synchronized with the strain measurements collected from the Arduino. The center strain gauge was used as the primary measurement location for calculating flexural stress-strain behavior, while the two outer gauges were used to evaluate strain symmetry across the sample width. The flexural modulus was determined from the initial linear portion of the stress-strain curve obtained from the direct failure tests. Results from the cyclic samples were compared with the baseline flexural properties to evaluate the influence of low-cycle fatigue on stiffness degradation and failure behavior.

III. RESULTS

Results are presented in five parts: the specimen test matrix, the flexural load-determination method applied to the strain records, the thin-specimen results, the thick-specimen results, and a comparative summary. Because the load back-calculation could not be reconciled with the known applied loads for the thin specimens even after correcting the governing beam theory and a firmware configuration error (detailed in section III), thin-specimen results are reported as strain only; thick-specimen results are reported as strain, flexural stress, and back-calculated load.

Specimen Test Matrix

Six carbon-fiber laminate strips were tested in four-point flexure: three of nominal thickness $t = (0.838 \pm 0.001)$ mm (thin) and three of nominal thickness $t = (3.354 \pm 0.001)$ mm (thick), both with width $w = (25.56 \pm 0.02)$ mm. One specimen of each thickness was loaded monotonically to failure; the remaining two specimens of each thickness were subjected to cyclic loading prior to a final loading ramp. The loading parameters for all six specimens are summarized in Table I.

TABLE I
SPECIMEN TEST MATRIX.

Specimen	Type	Cyclic Load (N)	Cycles	Feed Rate (mm/min)
Thin 1	Monotonic	–	–	7 ± 0.0070
Thin 2	Cyclic	600 ± 3.0	31	25 ± 0.025 (cyc.), 14 ± 0.014 (final)
Thin 3	Cyclic	600 ± 3.0	60.5	50 ± 0.050
Thick 1	Monotonic	–	–	14 ± 0.014
Thick 2	Cyclic	3400 ± 17	30	50 ± 0.050 (cyc.), 14 ± 0.014 (final)
Thick 3	Cyclic	3400 ± 17	60.5	50 ± 0.050 (cyc.), 14 ± 0.014 (final)

Flexural Load Determination

Strain was measured at three longitudinal positions on the tension (bottom) face of each specimen: one gauge at beam

center and two gauges mounted symmetrically $63.5 \text{ mm} \pm 0.79$ on either side of center. Because per-channel gauge identity was not independently logged, the gauge exhibiting the highest strain response in a given trial was taken to occupy the center position, consistent with the center gauge sitting in the region of maximum bending moment under the beam theory developed below.

The support fixture used custom-machined clamps rather than simple pin supports, converting the loading condition from a simply supported to a fixed-end (clamped-clamped) beam. For a fixed-end beam of support span L carrying two symmetric point loads of magnitude $P/2$ each, applied a distance a from each clamped end, the redundant end moment M_f developed at each clamp is

$$M_f = \frac{Pa(L-a)}{2L}. \quad (12)$$

The resulting bending moment at beam center, M_c , follows from superposing the statically determinate (simply supported) moment with the constant correction contributed by (12) at both ends, giving

$$M_c = \frac{Pa^2}{2L}. \quad (13)$$

The second moment of area I and the distance from the neutral axis to the tension surface c follow from the specimen cross-section:

$$I = \frac{wt^3}{12}, \quad c = \frac{t}{2}. \quad (14)$$

Flexural stress σ at the tension surface follows from (13) and (14) as $\sigma = M_c c / I$; assuming linear-elastic behavior with modulus of elasticity E , strain and applied load are related by

$$P = \frac{2LEI\varepsilon}{a^2c}. \quad (15)$$

The tensile modulus of this laminate determined in prior uniaxial testing, $E = 26.5 \text{ GPa} \pm 2.7$, was used in (15) as an approximation for the flexural modulus; true flexural and tensile moduli are not necessarily identical for a laminate loaded in bending rather than pure tension, and this substitution is a stated assumption rather than an independent measurement.

Prior to applying (15), reported strain values required a correction identified during data reduction: the data acquisition firmware's analog-to-digital conversion window was configured to 0.05 V ($\text{WINDOW} = 0.05$) rather than the 2.5 V value appropriate for the amplifier's 0 V – 5 V output centered at 2.5 V , per the firmware's own inline documentation. Because the computed microstrain value scales linearly with this window setting, all reported strain values were corrected by a factor of $2.5 \text{ V} / 0.05 \text{ V} = 50$ prior to any further analysis. All strain values reported below reflect this correction.

Applying (15) to the two thick cyclic specimens' steady-state cyclic strain reproduced the nominal applied load ($3400 \text{ N} \pm 17$) to within a factor of 2–3, which was judged acceptable given the stacked approximations of a borrowed tensile modulus and gauge-to-gauge mounting variability. The same procedure applied to the thin cyclic specimens reproduced the nominal $600 \text{ N} \pm 3.0$ load to only within a factor of 10–18, an error too large to attribute to modulus approximation alone.

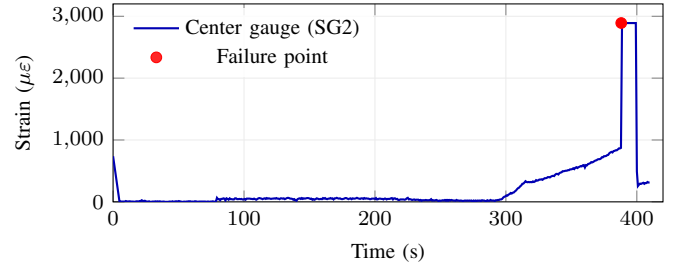


Fig. 13. Strain vs. time, Thin Specimen 1 (monotonic), including a brief post-failure interval showing strain relaxation.

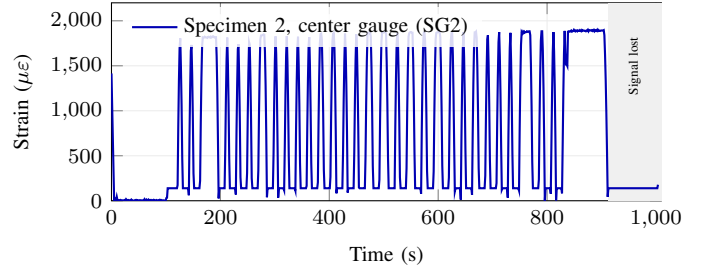


Fig. 14. Strain vs. time, Thin Specimen 2 (cyclic, 31 cycles). The shaded region marks a period of instrumentation signal loss near the expected end of testing; the true failure strain was not captured.

Consequently, (15) was applied only to the thick specimens; thin-specimen results are reported in strain terms only, without a corresponding stress or load value.

Thin Specimen Results

Monotonic Loading

Thin Specimen 1 was loaded to failure at a feed rate of $7 \text{ mm/min} \pm 0.0070$. The center gauge recorded a peak strain of $\varepsilon = 2891 \mu\epsilon \pm 28$ immediately prior to fracture, followed by a sustained drop in strain consistent with load release at failure.

Cyclic Loading

Thin Specimens 2 and 3 were each subjected to cyclic loading at a nominal $600 \text{ N} \pm 3.0$ before a final loading ramp to failure, at 31 and 60.5 cycles respectively. Cyclic-phase strain is summarized in Table II.

For Specimen 2, a sustained loss of signal on two of the three gauge channels was identified beginning near the end of the recorded cyclic phase, consistent with a gauge lead disconnection; no reliable strain value near the point of failure was recovered for this specimen; the last actively-changing reading is reported in Table II in its place, with the understanding that it does not represent the true failure strain.

For Specimen 3, the strain record showed steady cyclic oscillation through 60.5 cycles, ending with an isolated single-sample strain transient of $\varepsilon = 3386 \mu\epsilon \pm 32$. This is more than three times the steady cyclic peak. It was immediately followed by a return to a lower, stable baseline. This transient is consistent with the specimen having fractured during the final (0.5) cycle, at the bottom (fully loaded) position, rather than surviving to a separate post-cyclic breaking ramp.

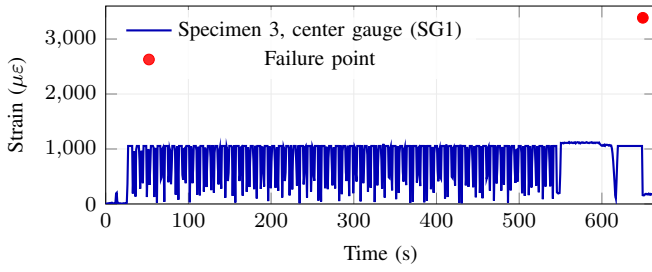


Fig. 15. Strain vs. time, Thin Specimen 3 (cyclic, 60.5 cycles). The marked failure point is an isolated single-sample transient occurring during the final (0.5) cycle.

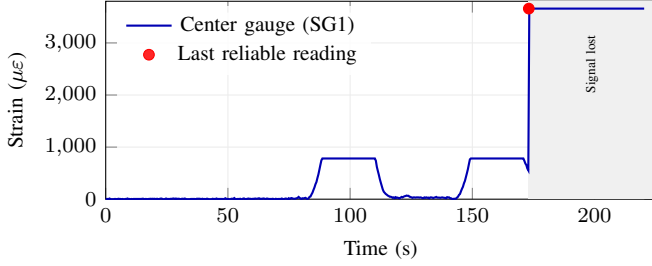


Fig. 16. Strain vs. time, Thick Specimen 1 (monotonic). Signal loss beginning at the marked point means the true peak strain at fracture was likely not fully captured.

TABLE II
THIN SPECIMEN CYCLIC-PHASE STRAIN.[†]

Specimen	Cyclic Median Strain ($\mu\epsilon$)	Final Recorded Strain ($\mu\epsilon$)
Thin 2	1867 ± 21	$226 \pm 13^{\dagger}$
Thin 3	1055 ± 16	3386 ± 32

[†]Not a failure value; last reading before signal loss (see text).

Thick Specimen Results

Monotonic Loading

Thick Specimen 1 was loaded to failure at a feed rate of $14 \text{ mm/min} \pm 0.014$. The center gauge recorded a peak strain of $\epsilon = 3659 \mu\epsilon \pm 34$, corresponding to a flexural stress of $\sigma = 97.0 \text{ MPa} \pm 9.7$ and a back-calculated load of $P = 1859 \text{ N} \pm 218$ via (15). A sustained loss of signal beginning at this same reading suggests the true peak strain, stress, and load at fracture were not fully captured; the values reported here are likely underestimates.

Cyclic Loading

Thick Specimens 2 and 3 were each subjected to cyclic loading at a nominal $3400 \text{ N} \pm 17$ before a final loading ramp to failure, at 30 and 60.5 cycles respectively. Results are summarized in Table III.

For Specimen 2, all three gauge channels lost signal simultaneously for an extended period near the expected end of testing, pegged at values consistent with the steady cyclic amplitude; no distinct failure signature was captured, and the reported final values likely understate the true peak.

For Specimen 3, one gauge channel (positioned at beam center per section III) remained active throughout a period in

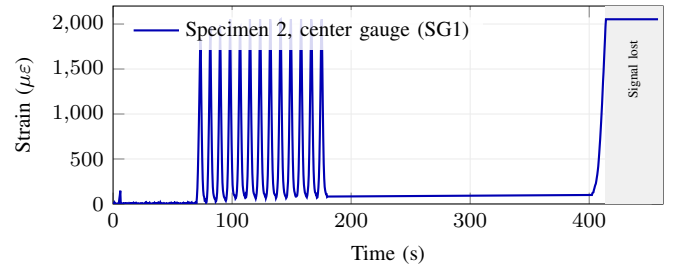


Fig. 17. Strain vs. time, Thick Specimen 2 (cyclic, 30 cycles). All three gauge channels lost signal simultaneously in the shaded region; the true failure strain was not captured.

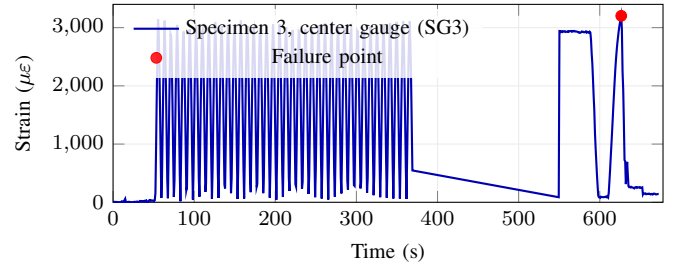


Fig. 18. Strain vs. time, Thick Specimen 3 (cyclic, 60.5 cycles). The center gauge remained active while the two outer channels lost signal; the marked failure point is followed by an irregular, multi-stage strain collapse consistent with fracture.

which the two outer channels lost signal. This center-gauge record shows a sustained cyclic plateau, a complete unload-reload cycle, and a final peak of $\epsilon = 3203 \mu\epsilon \pm 31$ ($\sigma = 84.9 \text{ MPa} \pm 8.5$, $P = 1627 \text{ N} \pm 191$) immediately followed by an irregular, multi-stage strain collapse inconsistent with the smooth unloading seen elsewhere in the same record. This is interpreted as a genuine fracture signature rather than a further instrumentation dropout.

TABLE III
THICK SPECIMEN RESULTS.[†]

Specimen	Strain ($\mu\epsilon$)	Stress (MPa)	Load (N)
Thick 1 (final) [†]	3659 ± 34	97.0 ± 9.7	1859 ± 218
Thick 2, cyclic median	2053 ± 22	54.4 ± 5.4	1043 ± 120
Thick 2, final [†]	2053 ± 22	54.4 ± 5.4	1043 ± 120
Thick 3, cyclic median	3078 ± 30	81.6 ± 8.2	1563 ± 180
Thick 3, final	3203 ± 31	84.9 ± 8.5	1627 ± 191

[†]Signal lost at or before this point; likely underestimates true failure values (see text).

Comparative Summary

Peak recorded strain, and derived stress and load where applicable, are compared across all six specimens in Table IV.

TABLE IV
COMPARATIVE SUMMARY OF PEAK RESULTS.

Specimen	Loading	Peak Strain ($\mu\epsilon$)	Stress (MPa)
Thin 1	Monotonic	2891 ± 28	–
Thin 2	Cyclic	$1867 \pm 21^\dagger$	–
Thin 3	Cyclic	3386 ± 32	–
Thick 1	Monotonic	$3659 \pm 34^\dagger$	97.0 ± 9.7
Thick 2	Cyclic	$2053 \pm 22^\dagger$	54.4 ± 5.4
Thick 3	Cyclic	3203 ± 31	84.9 ± 8.5

[†]True failure strain not captured (instrumentation signal loss); value shown is the highest reliably recorded reading, not necessarily the peak reached at fracture.

Independent Load and Stiffness Verification

As a cross-check independent of the strain-gauge chain, the Instron UTM's own Load-Extension channel was re-parsed directly for all six specimens. Table V reports the directly measured peak load at failure, with uncertainty from the load cell's 0.5%-of-reading accuracy (Table VII), and the percent change in peak load relative to each thickness group's monotonic (zero-cycle) specimen, propagated via (28).

TABLE V
INSTRON-MEASURED PEAK LOAD, INDEPENDENT OF THE STRAIN GAUGES.

Specimen	Peak Load (N)	Δ vs. Baseline (%)
Thin 1	1394 ± 7.0	– (baseline)
Thin 2	1257 ± 6.3	-9.8 ± 0.6
Thin 3	1633 ± 8.2	$+17.1 \pm 0.8$
Thick 1	3930 ± 20	– (baseline)
Thick 2	3751 ± 19	-4.6 ± 0.7
Thick 3	4086 ± 20	$+4.0 \pm 0.7$

Neither thickness group shows a monotonic strength loss with cycle count: the 30-cycle specimens are weaker than their zero-cycle baseline, but the 60.5-cycle specimens are stronger than baseline, in both thicknesses.

The same Load-Extension channel gives the loading stiffness (slope of Load vs. Extension over the pre-peak loading ramp) at the start and end of the cyclic phase. Table VI reports the percent drift between the last five and first five cycles, with uncertainty propagated the same way from the load cell and crosshead-speed accuracies combined (0.51 % relative); because this omits any additional regression-fit scatter in the stiffness values themselves, it is a lower bound.

TABLE VI
CYCLIC-PHASE LOADING-STIFFNESS DRIFT, LAST 5 VS. FIRST 5 CYCLES.

Specimen	Cycles	Stiffness Drift (%)
Thin 2	31	$+1.7 \pm 0.7$
Thin 3	60.5	$+0.4 \pm 0.7$
Thick 2	30	-3.5 ± 0.7
Thick 3	60.5	-7.0 ± 0.7

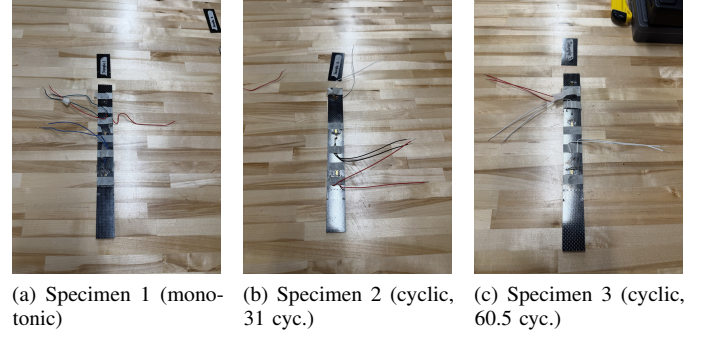


Fig. 19. Fracture region of the three thin specimens. All three fractures are located near a clamped end.

The thick specimens show a real, consistent-in-direction stiffness decrease over the cyclic phase, roughly doubling between 30 and 60.5 cycles; the thin specimens show no comparable trend.

Peak strain per cycle was also assessed for stability, using the same per-cycle statistics already developed in Table VIII: for the two 60.5-cycle specimens, the pooled standard deviation as a fraction of the cyclic mean is 1.83 % for Thin 3 ($19.7/1075.1$) and 1.87 % for Thick 3 ($57.2/3061.2$), so peak strain per cycle was maintained to within 1.9 % of its mean through 60.5 cycles in both cases, comparable to the resolution of the acquisition chain itself.

Failure Observations

Post-failure photographs were reviewed for all six specimens. In every case, fracture occurred near one of the two clamped ends rather than at beam center, where the three strain gauges were located. Figs. 19 and 20 show the fracture region of each specimen.

Among the thin specimens (Fig. 19), Specimen 1 (monotonic) shows a fracture surface combining transverse fiber breakage with localized interlaminar separation along the specimen edges. Specimen 2 (cyclic, 31 cycles) shows more extensive fiber pull-out and a longer region of ply separation than Specimen 1. Specimen 3 (cyclic, 60.5 cycles) shows a more abrupt fracture immediately adjacent to the clamp, without the extended ply separation visible on Specimen 2.

Among the thick specimens (Fig. 20), Specimen 1 (monotonic) shows a stepped, through-thickness fracture pattern rather than a single flat fracture plane. Specimen 2 (cyclic, 30 cycles) shows more extensive interlaminar splitting than Specimen 1, without a single dominant fracture plane. Specimen 3 (cyclic, 60.5 cycles) shows the most extensive fragmentation of the six specimens, with fiber and matrix damage distributed along the specimen length rather than confined to a single break location.

IV. DISCUSSION

The Results section establishes that the strain gauges failed to identify a measurable precursor to failure. Section III could not reconcile the strain-based load back-calculation with the known applied loads for the thin specimens at all. Two independent lines of evidence, one already in Results and one developed here from the Instron machine's own Load-Extension channel, agree on why this happened.

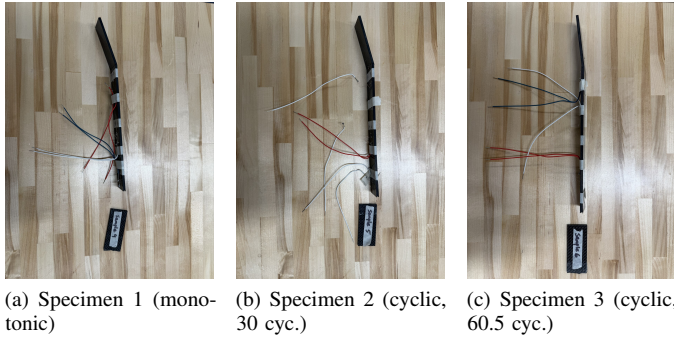


Fig. 20. Fracture region of the three thick specimens. All three fractures are located near a clamped end.

A. Fracture location explains the missing precursor

The failure photographs (Figs. 19 and 20) show every one of the six specimens fracturing near a clamped end rather than at beam center. Equation (13) places the maximum bending moment, and therefore the maximum bending strain, at beam center under the idealized fixed-end model. The center gauge was mounted at that same location. A fixed-end beam also carries a redundant moment at each clamp ((12)). The custom clamp geometry documented in the Procedure section is a plausible local stress concentrator that (12) does not capture, since it assumes an idealized rigid clamp rather than the finite-stiffness brass fixture actually used. The three strain gauges were positioned with one centered and two $63.5 \text{ mm} \pm 0.79$ to either side. If the true peak strain occurred at the clamp rather than at the idealized fixed end, none of them was positioned to record it. The center gauge would then report a stable, sub-critical reading throughout loading even as damage accumulated at the clamp. The strain records show exactly this pattern. A steady cyclic amplitude (Tables II and III) is followed either by signal loss or by a single-sample transient too brief to properly describe (Figs. 15 and 18), rather than by a gradual, trackable rise.

B. Independent verification from the Instron load channel

The Instron UTM records Load and Extension directly, independent of the strain-gauge chain entirely. Re-parsing these raw export files gives a direct measurement of peak load at failure for all six specimens (Table V), including the three thin specimens for which section III could not report a load at all. Comparing the thick-specimen values against the strain-back-calculated loads in Tables III and IV shows the back-calculated values are consistently 50 % to 60 % below the directly measured load, a factor of roughly two. The cyclic-phase reproduction check in section III estimated a factor of 2–3, so the two checks agree on the direction and magnitude of the error. This corroborates, with an independent instrument, the dagger notes in Tables III and IV that flag those values as underestimates. The signal loss identified in the strain records was not a brief artifact as it was already suppressing the reported peak by roughly half before it was lost entirely.

The Load-Extension curves also show a structural difference between the two laminate thicknesses that the strain records alone do not show. The thin specimens fail in a single, clean

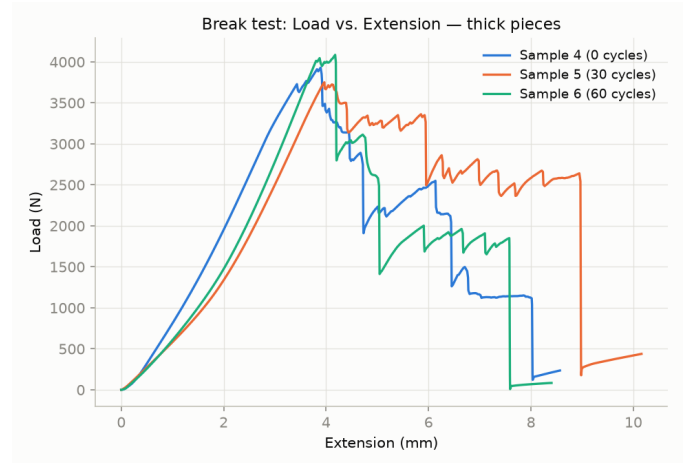


Fig. 21. Directly measured Load vs. Extension at failure, thick specimens, from the Instron raw export files. The repeating partial-drop pattern is the progressive, multi-stage failure referenced in the text.

drop from peak load, consistent with the abrupt single-sample strain transient recorded for Thin Specimen 3 (Fig. 15). The thick specimens instead show a repeating sawtooth of partial load drops and re-rises over several millimeters of additional extension before final collapse (Fig. 21). This is consistent with the “irregular, multi-stage strain collapse” reported for Thick Specimen 3 (section III) and with the more extensive interlaminar splitting and fragmentation reported in the failure photographs for the cyclically loaded thick specimens relative to Thick Specimen 1. Progressive load drops of this kind are the mechanical signature of sequential ply or fiber-bundle failure rather than one brittle fracture. They also explain why Thick Specimen 3’s center gauge remained active long enough to record a transient at all, as unlike other cyclic specimens, the failure process for Thick Specimen 3 was extended over a longer displacement window.

C. A more sensitive, if still inconclusive, damage indicator

Peak cyclic strain was stable to within 1.9 % through 60.5 cycles (section III). This is consistent with the noise floor established in section A-B and is too small to resolve against the strain-measurement uncertainty in Table IX. The Instron Load-Extension record provides a second and independent damage indicator that is not subject to the same signal-loss and gauge-position problems: the loading stiffness (Load-Extension slope) within each cycle, tracked across the full cyclic phase (Table VI). For the thick specimens, this stiffness fell by $3.5 \% \pm 0.7$ over 30 cycles and by $7.0 \% \pm 0.7$ over 60 cycles. This change is small, but it is consistent in direction and roughly proportional to cycle count, unlike the strain amplitude. The thin specimens showed no comparable trend ($1.7 \% \pm 0.7$ and $0.4 \% \pm 0.7$, effectively flat), mirroring their single-event rather than progressive failure mode. This suggests the machine’s own force-displacement measurement, not the bonded strain gauges as instrumented here, was the more sensitive indicator of accumulating damage in this experiment. With one specimen per condition, however, this observation is descriptive rather than statistically established, and it does not extend to predicting

final strength. Comparing each cyclically loaded specimen's failure load against its thickness group's zero-cycle baseline (Table V) gives a $9.8\% \pm 0.6$ strength loss for Thin 2 but a $17.1\% \pm 0.8$ strength *gain* for Thin 3. Thick 2 shows a $4.6\% \pm 0.7$ loss and Thick 3 shows a $4.0\% \pm 0.7$ gain. In both thicknesses, the 60-cycle specimen outperformed the 30-cycle specimen. This is the opposite of what progressive fatigue damage would predict. The most plausible explanation is specimen-to-specimen material variability dominating a real but smaller damage effect, not evidence that more cycling improved strength. This also points to a study limitation: the number of cycles used relative to the strength of the carbon fiber, especially the thick specimens, was not enough to truly accumulate meaningful damage that would have caused premature failure.

D. Improving the measurement

A further limitation concerns how the ADC conversion window (section B-A) was chosen in the first place. The window value was set by manually deflecting an instrumented gauge close to the expected maximum bend radius, and selecting the smallest window (0.05 V) that did not clip the amplifier output under that bench-top loading. This calibration however did not account for the strain the gauges would actually experience once the specimen was seated in the custom clamps. The sharp edges of that fixture likely concentrate strain well beyond what the hand-flex test represented, so the true strain during testing was likely much higher than the window was sized for. A window chosen too narrow for the real loading clips the signal outright, and unlike the uniform scale error corrected in section B-A, clipped readings cannot be recovered after the fact. In future testing, the custom clamps should be machined with curved edges to prevent stress concentrations that can bias the results.

Section A-D attributes 73 % of the load-uncertainty variance to the borrowed tensile modulus alone, and section A-G already identifies the fix. Measuring the flexural modulus from this setup, rather than substituting a prior tensile value, would cut the load uncertainty from 11.7 % to 6.1 % without changing anything else about the instrumentation. That improvement addresses the back-calculation's precision. It does not address its accuracy problem in section III, which is a gauge-placement issue. That problem is better addressed by instrumenting the clamp region directly, as section V recommends, or by redesigning the fixture so that failure is driven back toward beam center where the existing gauges can see it.

V. CONCLUSION

Six carbon fiber laminates of two thicknesses were tested to failure in four-point flexure, four of them after 30 to 60.5 low cycle loading cycles, while three quarter bridge strain gauges per specimen recorded the flexural readings. The objective of determining a measurable precursor to failure was not met. Peak strain per cycle was maintained to within 1.9 % of its mean through 60.5 cycles (section III), comparable to the resolution of the acquisition chain itself, so no gradual stiffness loss could be resolved at this cycle count. More significantly, every specimen fractured next to a clamped end rather than at the center, meaning the fixed end moved the peak bending moment away

from all three gauges. The instrumentation reported a stable signal while the amount of damage increased outside its field of view or window. This is the same failure of interpretation the National Transportation Safety Board identified in the Titan hull monitoring system. Reported flexural stresses and loads carry 10.0 % and 11.7 % uncertainty, of which 73 % of the load variance originates in a tensile modulus. Future experimentation should record the clamped ends where the moment is greatest or redesign the fixture to induce failure at the center of the beam.

APPENDIX A UNCERTAINTY ANALYSIS

Uncertainty is developed in four parts. These are the given uncertainties, the statistical uncertainties, the RSS propagations, and the Monte Carlo development of the load uncertainty. Propagated uncertainty covers strain on all six specimens and flexural stress and load on the thick specimens only, matching the reporting scope of the Results section.

A. Given and Instrument Uncertainties

Strain readings are a chain of three instruments rather than just one. These are the bonded quarter bridge gauge, the inline amplifier, and the 10-bit converter on the Arduino UNO, which spreads 1024 codes across a 5 V reference for a resolution of 4.34 $\mu\epsilon$ per code. The load reading is an Instron 2580-series 30 kN cell accurate to 0.5 % of reading. Support and gauge offset were set with a steel rule graduated in sixteenths of an inch, giving 0.79 mm by rule of thumb. The elastic modulus was carried over from prior uniaxial testing rather than measured here.

$$\varepsilon = \frac{4 \Delta V_{\text{amp}}}{G V_s G_f} \quad (16)$$

$$q = \frac{4 (4.8828 \text{ mV})}{(900)(2.5 \text{ V})(2.00)} = 4.34 \mu\epsilon \text{ per code} \quad (17)$$

TABLE VII
GIVEN AND INSTRUMENT UNCERTAINTIES.

Name	Symbol	Uncertainty	Source
Micrometer accuracy	μ_t	0.001 mm	Manufacturer [6]
Caliper accuracy	μ_w	0.02 mm	Manufacturer [7]
Steel rule	μ_L, μ_a	0.79 mm	Rule of Thumb [7]
Load-cell accuracy	μ_P	0.5 % of reading	Manufacturer [8]
Crosshead speed accuracy	μ_v	0.1 % of set speed	Manufacturer [5]
ADC strain resolution	q	4.34 $\mu\epsilon$ per code	(17)
Gauge factor	G_f	2 ± 0.01	Manufacturer [7]
Amplifier gain	G	900 ± 4.5	Manufacturer [7]
Excitation voltage	V_s	0.5 %	Manufacturer [7]
Carried-over modulus	μ_E/E	10 %	Lab 3 [9]
Sampling interval	Δt	0.201 s (4.98 Hz)	Measured

B. Statistical Uncertainties

Two quantities were developed statistically. The noise floor was found by taking the quietest 150-sample unloaded window from every channel of each record, giving 15 sets, excluding Thin Specimen 3. The pooled standard deviation of 6.30 $\mu\epsilon$ is roughly 1.45 converter codes, so the data precision is already contained in the measured scatter. Each cyclic record was also peak detected, peaks beyond two standard deviations

were removed, and a Student- t interval was formed on what remained.

$$S_\varepsilon = \sqrt{\frac{\sum_{i=1}^k (N-1) S_i^2}{k(N-1)}} = 6.30 \mu\epsilon \quad (18)$$

$$\mu_{\bar{x}} = t \frac{S_x}{\sqrt{N}} \quad (19)$$

TABLE VIII
STATISTICALLY DEVELOPED UNCERTAINTIES.

Set	N	Mean	S	Developed μ
Baseline noise ($\mu\epsilon$)	15×150	—	6.30	12.6
Thin 2 peak ($\mu\epsilon$)	33	1863.5	28.7	10.2
Thin 3 peak ($\mu\epsilon$)	69	1075.1	19.7	4.7
Thick 2 peak ($\mu\epsilon$)	12	2044.0	22.1	14.0
Thick 3 peak ($\mu\epsilon$)	47	3061.2	57.2	16.8

C. RSS Propagation, Strain

For a computed quantity $r = f(x_1, x_2, \dots, x_n)$, the general root-sum-square propagation of independent input uncertainties μ_{x_i} is

$$\mu_r = \sqrt{\sum_{i=1}^n \left(\frac{\partial r}{\partial x_i} \mu_{x_i} \right)^2} \quad (20)$$

Applied to the quarter-bridge equation ((16)), the partial derivative with respect to the gauge factor is

$$\frac{\partial \varepsilon}{\partial G_f} = -\frac{4 \Delta V_{\text{amp}}}{G V_s G_f^2} = -\frac{\varepsilon}{G_f} \quad (21)$$

with the excitation voltage and amplifier gain partials taking the same form by symmetry ($\partial \varepsilon / \partial V_s = -\varepsilon / V_s$, $\partial \varepsilon / \partial G = -\varepsilon / G$), since each appears to the first power in the denominator of (16). Substituting these three partials into (20) and dividing through by ε gives the relative form used below. The gauge factor, excitation voltage, and amplifier gain are fixed, so their contributions scale with the reading, while the baseline noise acts as a fixed floor. The two combine in quadrature. The systematic term overtakes the noise floor near 1455 $\mu\epsilon$, so the larger peaks reported in the Results section are systematic limited.

$$\frac{\mu_{\varepsilon, \text{sys}}}{\varepsilon} = \sqrt{\left(\frac{\mu_{G_f}}{G_f} \right)^2 + \left(\frac{\mu_{V_s}}{V_s} \right)^2 + \left(\frac{\mu_G}{G} \right)^2} = 0.866 \% \quad (22)$$

$$\mu_\varepsilon = \sqrt{(2S_\varepsilon)^2 + (0.00866 \varepsilon)^2} \quad (23)$$

TABLE IX
STRAIN UNCERTAINTY EVALUATED AT THE REPORTED READINGS.

ε ($\mu\epsilon$)	μ_ε ($\mu\epsilon$)	Relative (%)
226	13	5.64
1055	16	1.48
1867	21	1.10
2053	22	1.06
2891	28	0.97
3078	30	0.96
3203	31	0.95
3386	32	0.94
3659	34	0.93

D. RSS Propagation, Stress and Load

Flexural stress derives from modulus and strain, and the modulus dominates its uncertainty. This follows directly from substituting a tensile modulus for a flexural one. Substituting the second moment of area and the surface distance reduces the load equation to a product of powers, so every partial derivative collapses to the load divided by its input and scaled by that input's exponent. The result is 11.7% of reading, carried by the modulus and the loading nose offset.

$$\frac{\mu_\sigma}{\sigma} = \sqrt{\left(\frac{\mu_E}{E}\right)^2 + \left(\frac{\mu_\varepsilon}{\varepsilon}\right)^2} = 10.0\% \quad (24)$$

$$P = \frac{L E w t^2 \varepsilon}{3 a^2} \quad (25)$$

Because (25) is a product of powers of its six inputs, each partial derivative reduces to the load itself scaled by the corresponding exponent divided by that input. For the modulus, which carries the largest share of the load uncertainty (Table X),

$$\frac{\partial P}{\partial E} = \frac{L w t^2 \varepsilon}{3 a^2} = \frac{P}{E} \quad (26)$$

and the same pattern holds for every other input: $\partial P / \partial x_i = n_i P / x_i$, where n_i is that input's exponent in (25) ($n_L = n_E = n_w = n_\varepsilon = 1$, $n_t = 2$, $n_a = -2$). Substituting each partial into (20) and dividing through by P turns every term into $n_i \mu_{x_i} / x_i$, which is exactly the relative-error form propagated below.

$$\frac{\mu_P}{P} = \left[\left(\frac{\mu_L}{L}\right)^2 + \left(\frac{\mu_E}{E}\right)^2 + \left(\frac{\mu_w}{w}\right)^2 + \left(2\frac{\mu_t}{t}\right)^2 + \left(\frac{\mu_\varepsilon}{\varepsilon}\right)^2 + \left(2\frac{\mu_a}{a}\right)^2 \right]^{1/2} \quad (27)$$

TABLE X
VARIANCE CONTRIBUTIONS TO (27), EVALUATED AT $\varepsilon = 3659 \mu\epsilon$.

Term	Relative (%)	Variance share (%)
Modulus μ_E/E	10.00	73.0
Nose offset $2\mu_a/a$	5.98	26.1
Strain $\mu_\varepsilon/\varepsilon$	0.93	0.6
Span μ_L/L	0.57	0.2
Width μ_w/w	0.08	< 0.1
Thickness $2\mu_t/t$	0.06	< 0.1
Total	11.70	100.0

E. Percent-Change Propagation

The Discussion section compares a cycled specimen's measured value A against its thickness group's zero-cycle baseline B as a percent change $f = 100(A/B - 1)$. Applying (20) to this f gives

$$\mu_f = 100 \frac{A}{B} \sqrt{\left(\frac{\mu_A}{A}\right)^2 + \left(\frac{\mu_B}{B}\right)^2} \quad (28)$$

since $\partial f / \partial A = 100/B$ and $\partial f / \partial B = -100A/B^2$, each of which reduces to $100(A/B)$ times the corresponding relative uncertainty. When A and B come from the same instrument at the same relative accuracy $r = \mu_A/A = \mu_B/B$, (28) simplifies to $\mu_f = 100(A/B)r\sqrt{2}$. This is used in the Results section to propagate uncertainty onto the Instron peak-load percent changes (load-cell accuracy alone, $r = 0.5\%$) and the cyclic-phase stiffness-drift percentages (load-cell and crosshead-speed accuracies combined in quadrature, $r = 0.51\%$); the latter omits any additional regression-fit scatter in the stiffness slopes themselves, so it is a lower bound on the true uncertainty.

F. Monte Carlo

The RSS propagation linearizes the load equation about its point of interest, which is worth testing because the loading nose offset is squared in the denominator. Each of the six inputs was sampled from a normal distribution whose standard deviation is half its 95% interval, over 100000 trials. The two methods agree to within 0.03%, so the RSS result is verified and applied.

TABLE XI
MONTE CARLO INPUT DISTRIBUTIONS.

Input	Mean	σ	Units
Support span L	139.70	0.395	mm
Nose offset a	26.427	0.395	mm
Width w	25.56	0.010	mm
Thickness t	3.354	0.0005	mm
Modulus E	26.5	1.325	GPa
Strain ε	3659	17.1	$\mu\epsilon$

TABLE XII
MONTE CARLO RESULTS OVER 100000 TRIALS, COMPARED WITH (27).

Quantity	$\varepsilon = 3659$	$\varepsilon = 3203$
Simulated mean P (N)	1860.6	1628.7
Simulated σ_P (N)	108.8	95.5
Monte Carlo $2\sigma_P$ (N)	218	191
Monte Carlo relative (%)	11.69	11.73
RSS relative (%)	11.70	11.70

G. Summary

Every propagated uncertainty is collected in the summary table. Measuring the flexural modulus directly rather than borrowing a tensile value would reduce the load uncertainty from 11.7 % to 6.1 %.

TABLE XIII
SUMMARY OF PROPAGATED UNCERTAINTIES (95 % CI).

Variable	Fixed or $f(\text{value})$	Repr. μ	Units
Thickness t	fixed	0.001	mm
Width w	fixed	0.02	mm
Support span L	fixed	0.79	mm
Gauge offset	fixed	0.79	mm
Feed rate v	$f(\text{value}): 0.1 \%$	0.05 (at 50)	mm/min
Applied load P_{UTM}	$f(\text{value}): 0.5 \%$	17 (at 3400)	N
Strain ε	$f(\text{value}): (23)$	34 (at 3659)	$\mu\epsilon$
Stress σ	$f(\text{value}): 10.0 \%$	9.7 (at 97.0)	MPa
Load P (RSS)	$f(\text{value}): 11.7 \%$	218 (at 1859)	N
Load P (Monte Carlo)	$f(\text{value}): 11.69 \%$	218 (at 1859)	N

APPENDIX B DATA ACQUISITION CORRECTIONS AND ARTIFACTS

A. Conversion Window Correction

The firmware derives its volts per bit from a single constant setting the voltage span the 1024 codes represent. That constant was left at 0.05 V while the amplifier output is a single-ended 0 to 5 V signal centered at 2.5 V, so every logged value is low by a factor of 50. The correction was applied uniformly before analysis and verified against the record. All logged values are exact multiples of $0.0868 \mu\epsilon$, and the corrected step of $4.34 \mu\epsilon$ matches the converter specification.

B. Rectified Output

The firmware prints the absolute value of each computed microstrain. Sign data is discarded, and zero mean noise about the tared baseline is defaulted to positive values, which is why unloaded records read roughly $7 \mu\epsilon$ instead of zero. All three gauges sat on the tension face, so the reported peaks are unaffected, but the baseline is biased upward.

C. Sampling Rate and Timing

The acquisition loop is limited by a fixed 200 ms delay, giving a measured mean interval of 0.201 s. A fracture is

therefore located only to within one sample, and any excursion shorter than 0.2 s can be missed or captured as a single reading. Thin Specimen 3 shows this behavior, its failure appearing as one isolated reading of $3386 \mu\epsilon$.

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