

Development of a Characterization Methodology for Composite Plates in UAV Wing Applications

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ABSTRACT

Prior to taking flight, unmanned aerial vehicles (UAVs) must be designed, tested, and built under careful consideration of the loading from flying and the design's sequential response. Composite materials have emerged as an effective method for achieving the most beneficial material characteristics in the least amount of square footage. This has led to their increased use in the field of aerospace, including UAVs, which is an area subjected to rigorous testing to meet high-quality standards as is. Due to the customization of such composites and the importance of their resulting material properties to safely achieve flight, emphasized testing must be done to ensure they reach that goal. The objective is to create a test protocol to both statically and dynamically evaluate custom fiberglass-epoxy (GFRP) composites for future use in UAV wing applications. The use of composites can make UAV designs more efficient, and more efficient UAVs are important because they excel in remote areas and traditionally inconvenient field tasks across private and public sectors. Currently, carbon fiber-epoxy (CFRP) composites have taken the field by storm, but GFRPs share similar qualities to CFRP composites, such as higher strength-to-weight ratios, but are cheaper and require less effort to cure, thus making them more accessible to smaller manufacturers and hobbyists. The project's current GFRP design consists of hand-laid 12 inches $\times$ 6 inches glass-fiber/PVC-foam sandwich panels that are then pulled and cured through a vacuum. The testing protocol involves a custom test bed that nondestructively clamps to a test specimen plate in a cantilever beam orientation. Preliminary tests have been conducted statically and dynamically on a plexiglass mock specimen to build the test protocol's credibility in property assessment. Static testing is necessary to find the initial property maximums of the specimens, such as stiffness and loads; verified weights were suspended from the free end of the cantilevered plates in small increments to achieve this. The dynamic methodology presently includes a small-scale shake table with manual sinusoidal inputs operated between a range of 1 to 20 Hz. These composite testing results will provide a database for UAV design, specifically aimed at fixed-wing UAVs. Our preliminary results accurately assessed our mock specimen and will provide a foundation for future work in composite characterization testing techniques, further working toward investigations into cell-level structural battery composite wings.

INTRODUCTION

Unmanned aerial vehicles have become increasingly popular in both public and private sectors, and even among hobbyists. They excel in remote areas and tasks that would have been otherwise inconvenient for a person to do alone, especially fixed-wing UAVs (Adawy et al., 2023). Fixed-wings mimic commercial planes in both their design and function; this means that they retain all the good features, such as flight quality and payload capabilities, but it also means that they suffer from inefficient designs and less-than-ideal weight-to-function ratios. To combat these flaws, composite materials have taken over the aircraft design scene. Popular choices such as carbon fiber and fiberglass have higher strength-to-weight ratios, making the UAVs lighter and, in turn, making them more fuel efficient and providing more payload flexibility (Ashrith et al., 2023). Moreover, structural batteries are another aircraft optimization method. While batteries themselves possess little loading capabilities, adding them to composites eliminates the need to house a separate power source, further improving strength-to-weight ratios and efficacy (Jin et al., 2023). However, before these composites can be approved for flight, they must be rigorously tested for material and loading properties to ensure they can withstand airtime. This is less of a problem for bigger companies with large-scale facilities and resources, but many smaller companies and hobbyists do not have the means to do themselves.

In commercial and private aircraft creation, there is a long design and testing process performed before planes are cleared to take flight. These tests evaluate the material and loading properties of the build components, which can accurately predict their in-flight capabilities. There are two broad testing categories: static and dynamic. Static testing is among the simpler tests and assesses the specimens' material properties by applying a concentrated load and recording how the specimen holds up against it; this is considered static because the load is only applied once without repetition (Sullivan et al., 2006). Dynamic testing similarly applies a concentrated load, but it is applied repeatedly at a set rate. Lastly, under the umbrella of dynamic testing lies modal testing, which assesses a specimen's vibrational response by applying a frequency.

The latter two test types are more complex, but the aerospace industry has standardized methods for conducting them. For dynamic testing, iron-birds (i.e., large aircraft frameworks with only essential parts) are assembled and attached to cables that pull across the length of the frame (Blasi et al., 2021). This accurately emulates the force distribution of flight.

For modal testing, ground vibration tests (GVTs) are commonplace. Originally, modal testing had to be done manually in what is known as impact hammer tests (Saheb & Deepak, 2023). Accelerometers were attached to respective portions of the wing, and a person would walk around and hit the designated area with a hammer. Years later, it was realized that digital inputs were more convenient and consistent. That's where GVT comes from. In more recent years, accelerometers and shakers are applied to their respective positions, and software is used to apply the frequencies. The turn to digital inputs is also what allows testers to employ digital twins and hybrid simulation models, which help verify the real-life results as well as provide a quicker simulated playground for further curiosities.

Where do the composites come in? Simply, they take the place of regular materials in these tests, whether that be in the spars, the ribs, or the panels extending from the wing root. The beauty of composites is that they combine the preferred qualities of multiple materials into one piece. However, property testing gains heightened importance due to the custom and, in our case, handmade nature of these composite panels. To prove that the composites are of a more beneficial design, they must undergo the same test methods related to flight, with additional tests to evaluate how the mixed media holds up together.

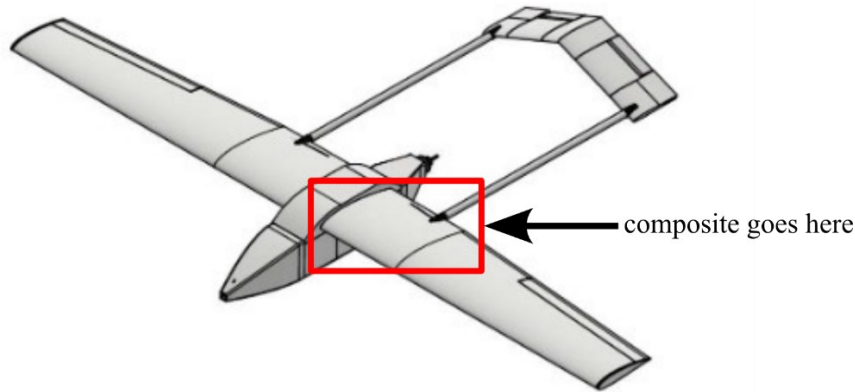


Fig. 1. Exemplary fixed-wing UAV model (ARTS-Lab, 2025).

The purpose of this work is to establish a static and dynamic test methodology that can be used to evaluate the material properties of prospective plate specimens and predict their efficacy in UAV wing applications. This is done by creating a custom testbed that can nondestructively conduct static, dynamic, and modal testing. Preliminary results on mock specimens produced highly accurate results with an error of 0.4%, validating the methodologies. However, with the addition of custom GFRPs and structural batteries, the specimens become more complex, and the error margin increases. Future work will further investigate improving the methodologies' accuracy and eventually contribute to improving our composite and structural battery designs, creating a database of recorded material properties, and optimizing fixed-wing UAVs.

MATERIALS/INSTRUMENTATION

Mock Test Specimen

The custom composite plates are being created alongside the characterization methodology development. To verify that the test setups will be effective in testing the awaited composite plates, they are first tested on mock specimen plates. The mock specimen is made of plexiglass as it has a similar size and material property profile to the composites, which accurately estimates the setup's needed range.

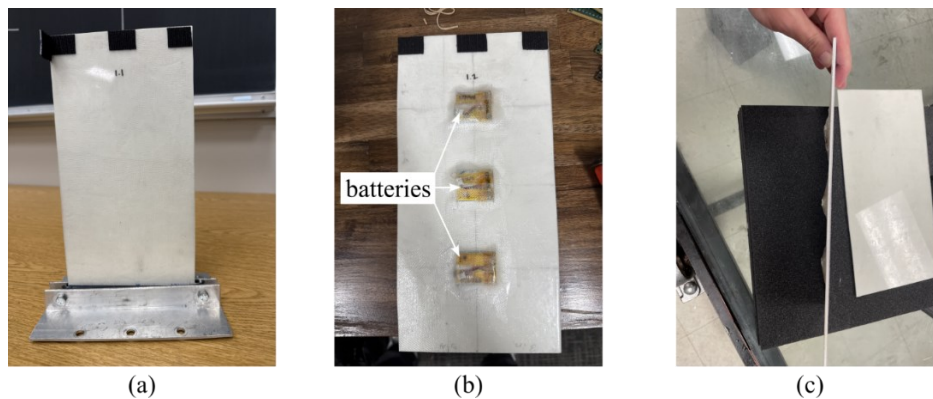


Fig. 2. Showing (a) the control (non-battery) composite, (b) the structural battery composite, and (c) the cross-section of the structural battery composite.

GFRP Composite Test Specimen

Each structural battery (**Fig. 2a**) has a non-battery composite counterpart (**Fig. 2b**) to act as a control to compare how the batteries are affecting the composite. The base composite consists of a PVC-foam core sandwiched between 3 layers of fiberglass at the top and at the bottom. The fiberglass is overlapped over the edge of the foam to better seal the edges during processing. The sandwich preform is set in an epoxy resin matrix. To incorporate the batteries, prior to applying the matrix, evenly spaced gaps are cut into the foam to fit the three discharged LiPo batteries inside. Additionally, the batteries have a resistor to keep the circuit closed as a secondary safety precaution. All composites were hand-laid by soaking in epoxy and then compressed together; afterward, they were pulled under a vacuum to eliminate additional air bubbles and provide a tighter layup.

Test Setup: Static

The static testing was conducted via hanging weights. The specimen is c-clamped on the edge of a foundational beam in a cantilever orientation with a second plate lying on top of the first. The top plate is used as a reference point, and the bottom plate is the test subject. The free end of the bottom plate was fitted with a wire that held a hanging foundation plate. A scale was used to verify the weights' values. A measuring tape was used to record the deflections.

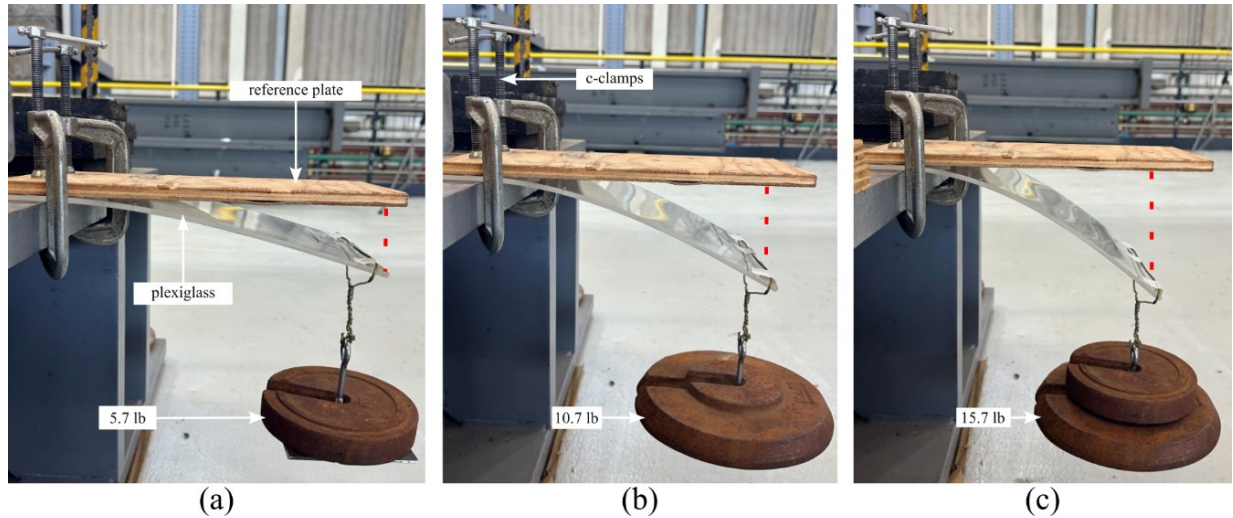


Fig. 3. Preliminary static characterization setup on plexiglass with load progression of (a) 5.7 lb, (b) 10.7 lb, and (c) 15.7 lb.

Test Setup: Dynamic

The modal testing was conducted on a small-scale shake table. The table itself moves unilaterally, but imposing various strength sine waves creates the shaking force. This shake table is connected to a control station consisting of a function generator, power supply, data acquisition (DAQ) system, and a computer. The mock specimen has two L-brackets compressed to one edge of the plate. A piece of rubber is placed between the brackets and the plate that serves two purposes: (1) it dampens the vibrations in the fixed end, and (2) it closes any gaps and ensures that the brackets will not slide off or change direction when a load is applied. This compression clamp is held together by a bolt on both sides of the plate. It is vertically affixed to the shake table by an additional six bolts on the horizontal face. Velcro is glued directly onto the specimen to attach a 2g accelerometer at the middle of the edge of the free end.

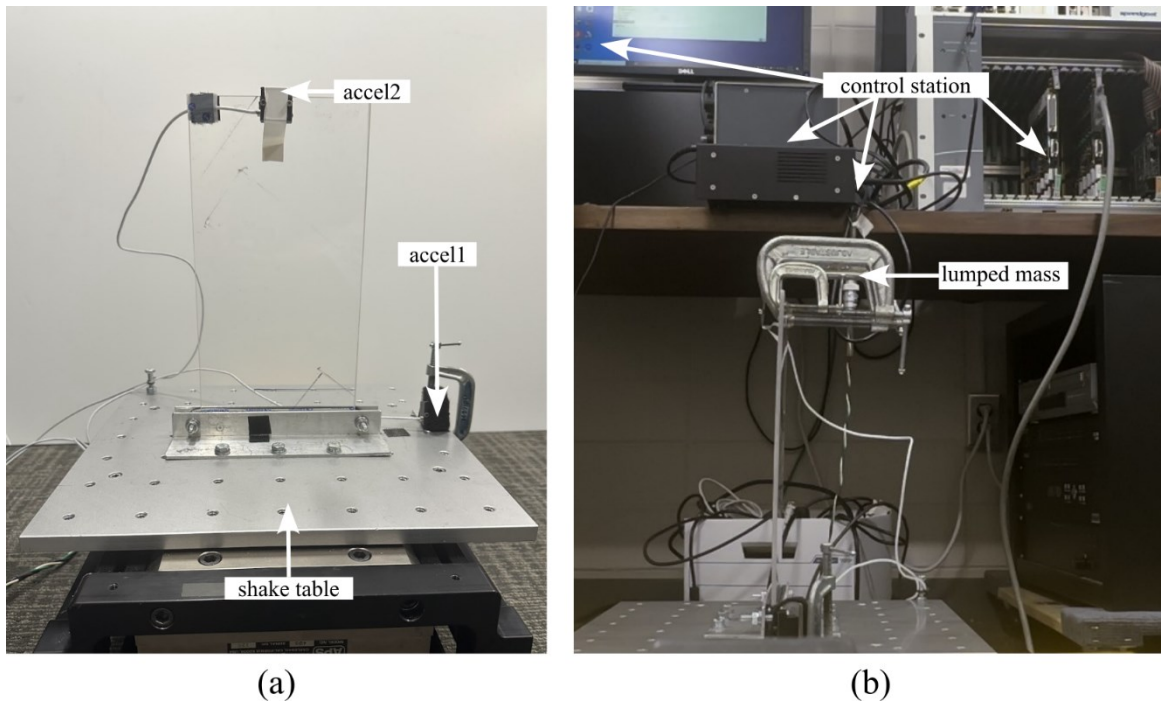


Fig. 4. Preliminary dynamic (modal) characterization setup with (a) a continuous mass system and (b) a hybrid mass system.

Data Analysis

The shake table was connected to software by the brand Pacific Instruments. The software records the raw data and displays it in real time before saving it in the form of a CSV after the test. CSV files are universally used as they can be opened with Microsoft Excel, Google Sheets, or any coding platform.

METHODS

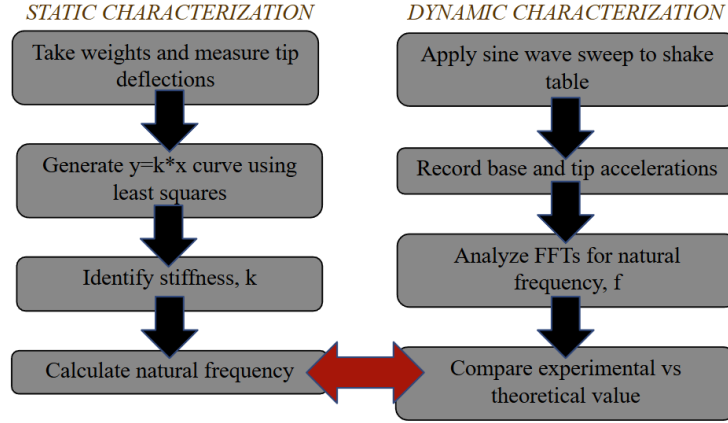


Fig. 6. Flow chart showing overall methodologies for both static and dynamic characterization.

Preliminary Test: Static on Plexiglass

The static testing on the beam was a manual operation. After assembly, verified free weights were hung from the free end in increments of 5 lb. Between each increment, the deflection was measured by measuring the gap between the control plate and the weighted plate. The empirical results created a dataset in which the slope is the specimen stiffness,

$$k = \frac{F}{\Delta} = \frac{3EI}{l^3} \text{ (Amrita, 2023).}$$

This slope was calculated using the least squares estimation; the least squares method fits the dataset through the origin to minimize the error, which is the vertical distance between the observed and predicted line values (Ramachandran and Tsokos, 2015). In turn, this stiffness value is able to theoretically calculate the first natural frequency of a continuous mass system,

$$f = \frac{3.5156}{2\pi} \sqrt{\frac{k \cdot g}{3 \cdot W}},$$

where g is gravity and W is the weight of the specimen. However, with the addition of the lumped mass to the system in **Fig. 4b**, a hybrid system is formed, and the two equations must be combined to accommodate:

$$f = \frac{1}{2\pi} \sqrt{\frac{k \cdot g}{\frac{33}{140} W_B + W_t}},$$

where W_b is the continuous weight and W_t is the lumped weight (Amritas, 2023). Finally, to accommodate boundary differences in the static and dynamic characterization, a correction factor is applied to the theoretical frequency value,

$$\frac{f_1}{f_2} = \sqrt{\frac{l_2^3}{l_1^3}},$$

where f_1 is the theoretical frequency, f_2 is the corrected theoretical frequency, l_2 is the free length in the dynamic characterization, and l_1 is the free length in the static characterization.

Preliminary Test: Dynamic on Plexiglass

The modal testing on the shake table was also a primarily manual operation. Once everything is assembled, the control station is powered on, the system starts recording, and a small gain is inputted into the table. Over a short span of time, the dials are turned to impose various frequencies between a range of 1 to 20 Hz and amplitudes onto the table. Typically, the amplitude stays low and is in an inverse relationship with the frequency. Subsequently, the plate reacts. This method allows us to find the natural modes and frequencies of the test specimen without heavily altering the plate, as alterations change the mode parameters. All tests were run three times to ensure enough data was repeated to confirm results. The plexiglass was run three times as is and three times with an applied lumped mass of 1.5 pounds on the free end; The additional mass was necessary to decrease the frequency of the first mode to be read within the setup's range.

Static Characterization on GFRP Composites

The above methodology used on the plexiglass was used on the composite plates with a few changes. The incremental weight increase was lowered significantly from 5 lb increments to fractional increments in order to get a more accurate reading with less risk of damaging the specimen. A printed measuring tape was attached to the free end of the reference tape rather than comparing to a free-handed measuring tape; moreover, the deflection was recorded to the center of the test subject instead of to the top of the test plate. This slightly increases the accuracy of the bend because it includes the thickness, which is assumed constant using Euler-Bernoulli beam theory. **Fig. 6** reflects these changes compared to **Fig. 3**, and shows the load progression.

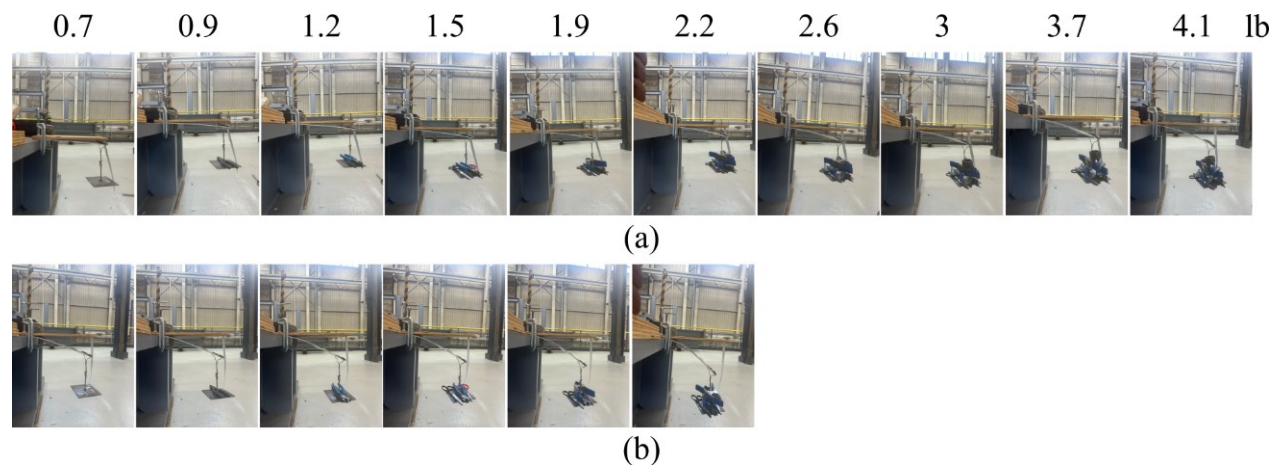


Fig. 6. Updated static characterization on (a) the non-battery control composite and (b) the battery composite.

Dynamic Characterization of GFRP Composites

The aforementioned dynamic methodology was used on the composite plates without any additional changes. **Fig. 7** shows a visual of that. The methodology remained the same, but more spacers in the clamp had to be added to accommodate the composites' thinness, and timed frequency intervals were used to help boost similarity in the tests.

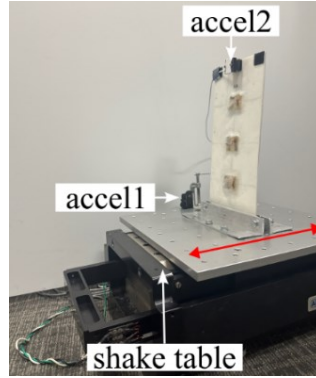


Fig. 7. Dynamic characterization setup with structural battery plate.

RESULTS & DISCUSSION

Preliminary

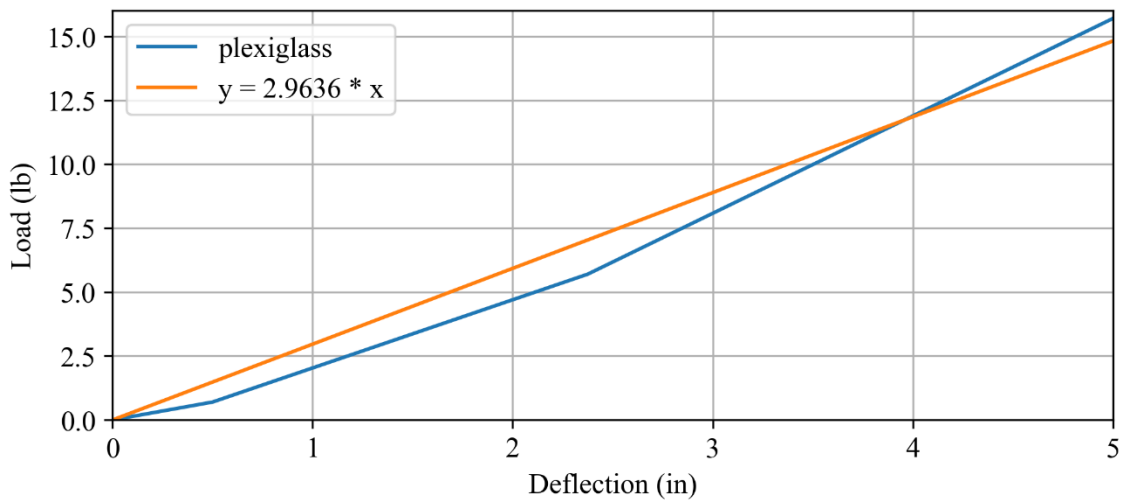
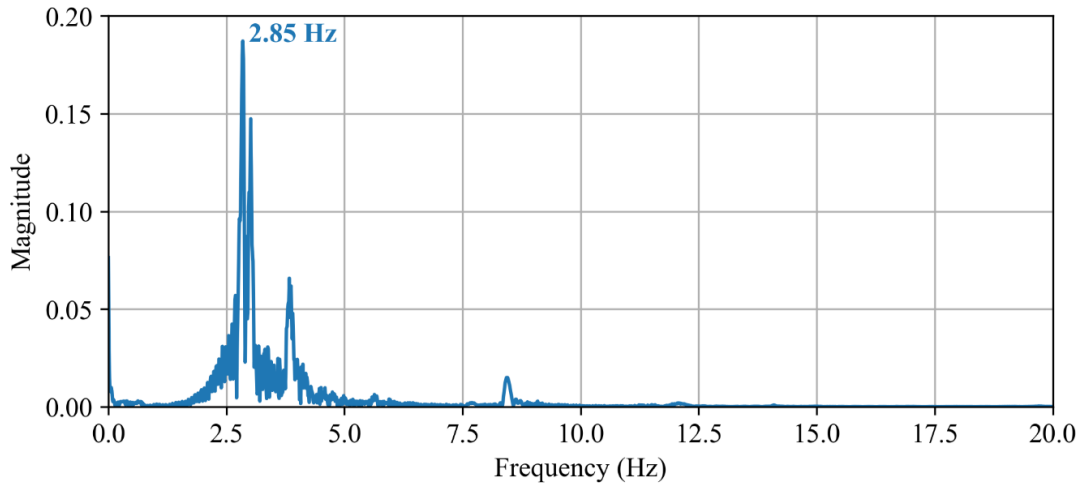
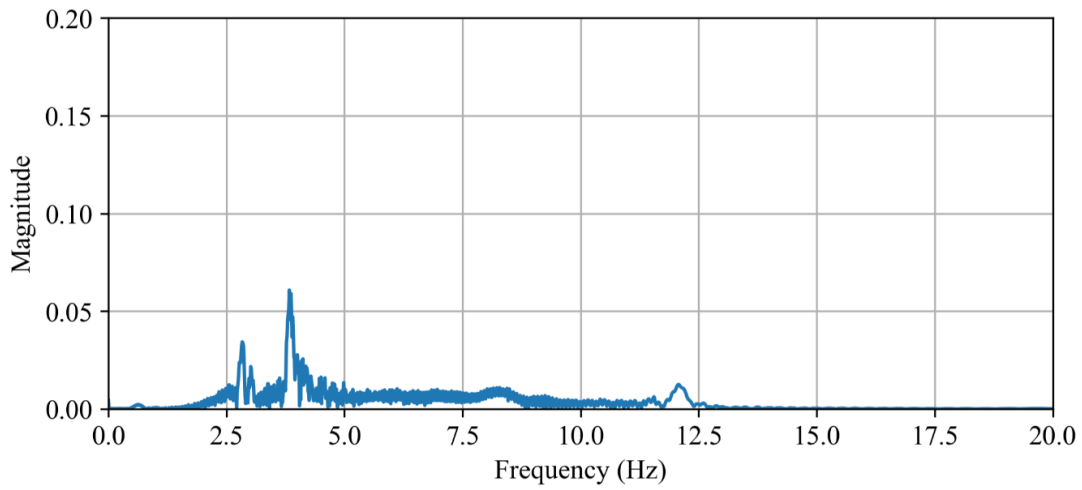


Fig. 8. Graphical representation of plexiglass stiffness.

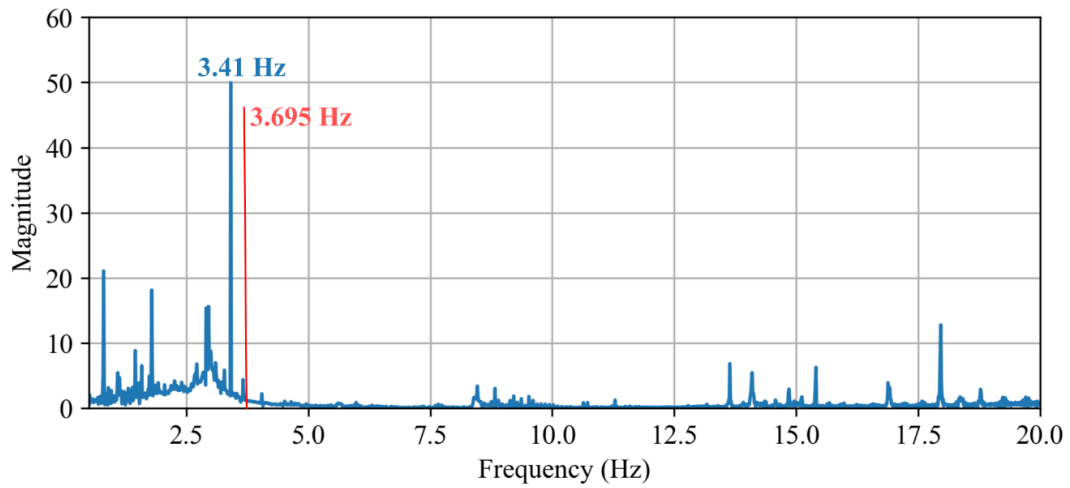
As seen in **Fig. 8**, the graph shows the stiffness found via the least squares estimation method. The slope of that line, denoted by the best-fit line in orange, is used in the theoretical frequency calculation. Using the stiffness value from **Fig. 8**, a theoretical frequency at mode 1 was calculated to be 3.695 Hz; the experimental results show a first mode at 3.41 Hz, giving the methodology an error of 7.71% for this test. Such a low error margin and high accuracy validate the base method for use on desired plates. The dynamic results are shown in **Fig. 9**.



(a)



(b)



(c)

Fig. 9. A trio of FFTs showing (a) plate response, (b) base response, and (c) the ratio of the two for the plexiglass specimen. The red line denotes the theoretical value.

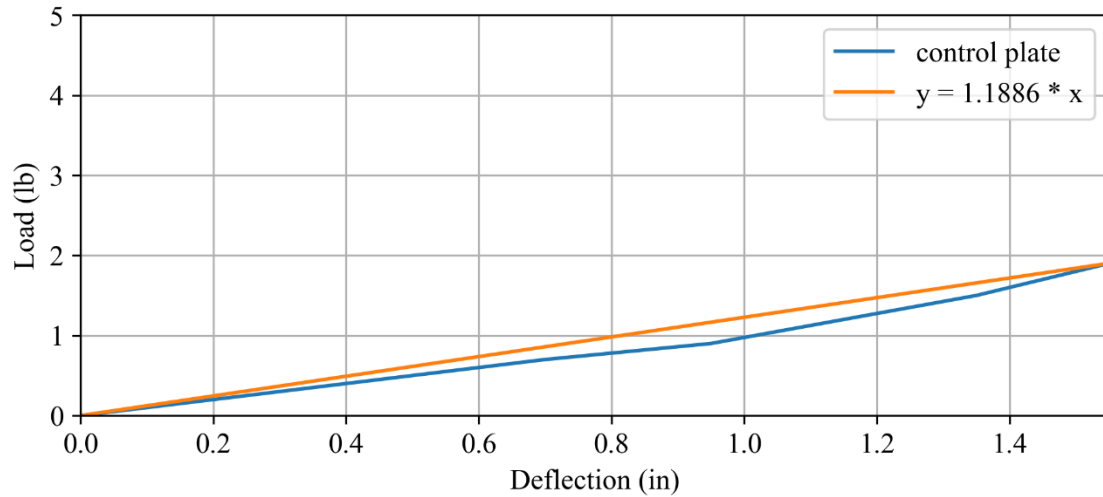


Fig. 10. Graphical representation of control plate stiffness.

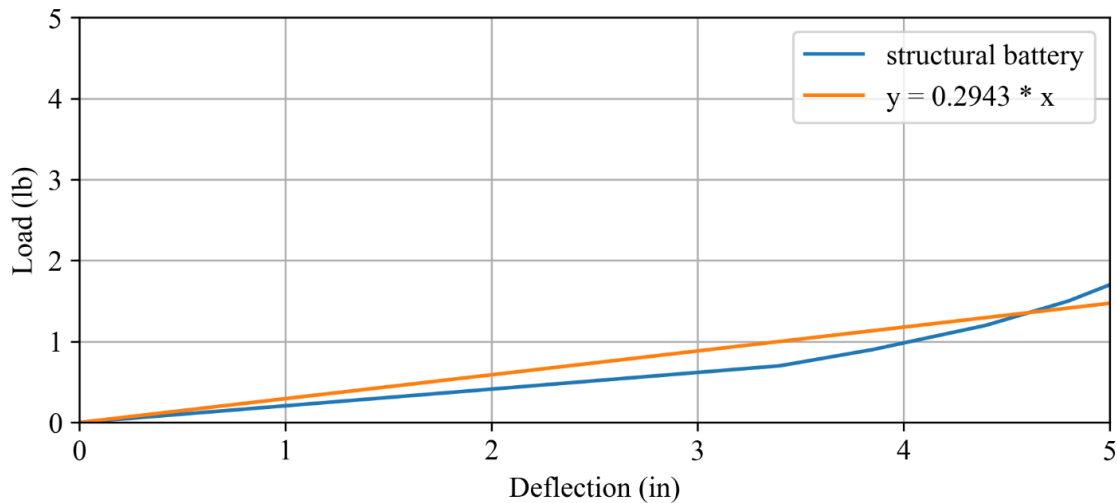


Fig. 11. Graphical representation of structural battery stiffness.

Composite Plates

A similar methodology was used on the composite plates as was used on the plexiglass. However, the complexity of the composites created a change in the results that will need further investigation to correct.

Comparing **Fig. 10** to **Fig. 11**, a stark decrease of approximately 4 times in stiffness occurred when batteries were incorporated into the composite, which was expected due to the battery's aforementioned lack of loading capabilities.

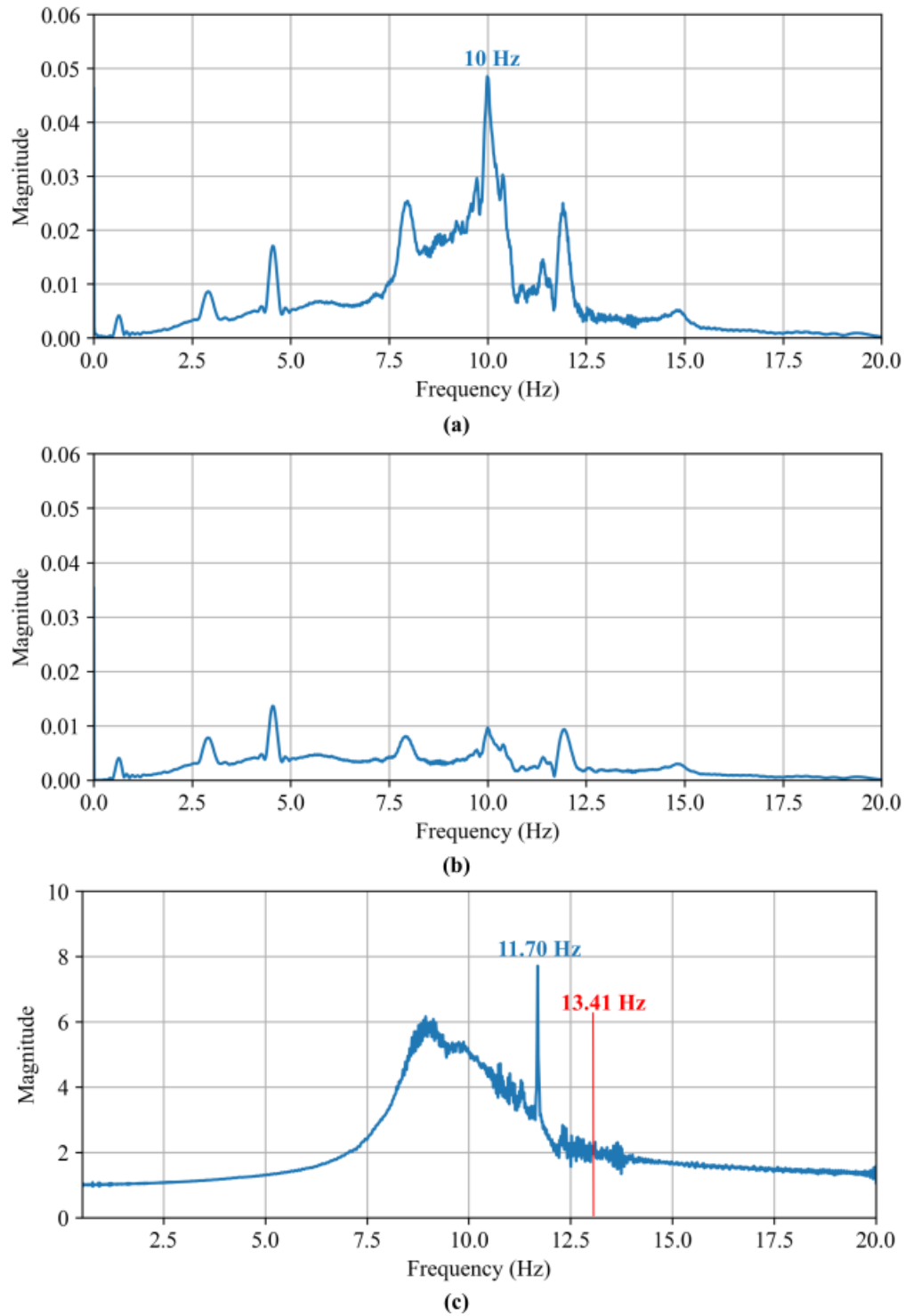


Fig. 12. A trio of FFTs showing (a) plate response, (b) base response, and (c) a ratio of the two for the control composite plate (no batteries). The red line denotes the theoretical value.

The control GFRP FFT ratio in **Fig. 12** has a bigger error margin between theoretical and empirical values than in the plexiglass data shown in **Fig. 9**. This is attributed to the custom nature of the GFRP composite and the subsequent delamination that was occurring prior to testing.

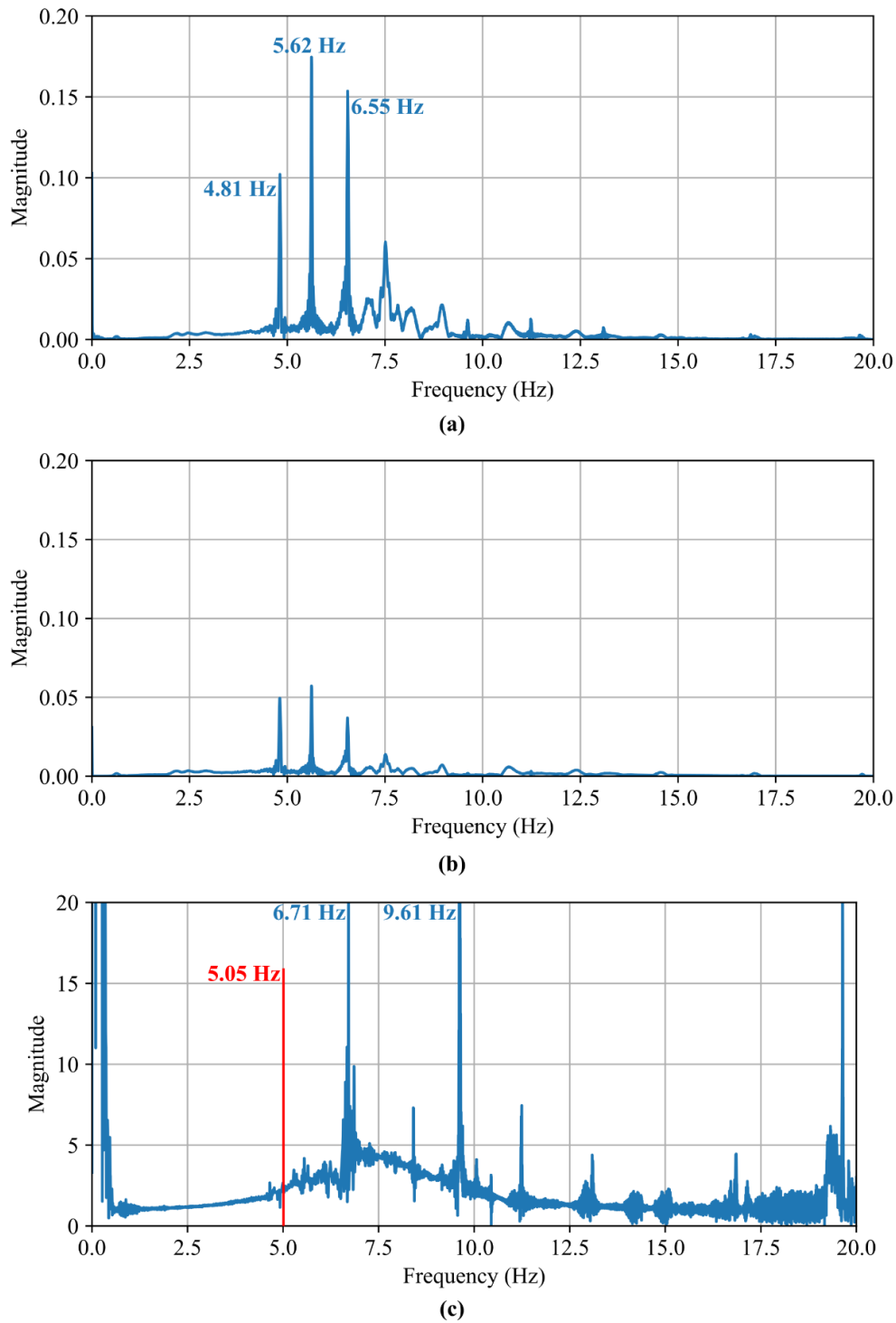


Fig. 13. A trio of FFTs showing (a) plate response, (b) base response, and (c) the ratio of the two for the structural battery specimen. The red line denotes the theoretical value.

The dynamic characterization for the structural battery GFRP, shown in **Fig. 13**, exhibits another larger error gap as well as lots of noisy and false peaks in the ratio. A number of possibilities could be the cause for this: (1) the decreased structural integrity due to the batteries in the core, (2) the delamination of the plate, (3) the mathematical error of dividing by small numbers, and (4) frequency leakage due to rudimentary methodology. Enhanced data processing is being explored to incorporate features such as windows to better understand the peaks. Also, conducting the dynamic testing under a set time period will help complete enough cycles per frequency to process and help avoid leakage.

There should not be peaks where activity is not apparent in individual FFTs, calculations, or by physical observation of the test. Moreover, even more reasonable peaks must be examined closely; when approaching a natural frequency, it is a gradual spike into resonance, not a stark peak.

CONCLUSION

This work was done to begin the development of static characterization and dynamic characterization methodology. This was achieved for static characterization by incrementally hanging weights off a cantilever test specimen to empirically determine stiffness and theoretically determine natural frequency. This was achieved for dynamic (modal) characterization by affixing the test specimen to a shake table and applying a sine sweep to empirically find the natural frequency. We find the base methodologies, static and dynamic, to be highly accurate in characterizing materials as seen in preliminary results, **Figs. 8** and **9**. However, more work must be done to accommodate our custom GFRP structural battery plates, as they are more complex than the mock specimen.

FUTURE RESEARCH

Future work plans to further improve the accuracy of the test methodologies and setups, primarily by replacing the manually intensive aspects with digital counterparts, such as actuators and hybrid simulations. With an improved setup and more accurate testing, plate properties can be better evaluated to create sturdier plates and, eventually, more efficient UAVs. All recorded properties will be recorded in a database and eventually used to predict the flight capabilities of tested composites.

ACKNOWLEDGMENTS

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