Shear Modulus Testing in Composite Sandwich Panels

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Composite sandwich panels are commonly used in aerospace applications due to their lightweight yet strong structure, enhancing overall performance. Characterizing their strengths is essential to meet safety standards and provide a thorough understanding of their mechanical properties under various operating conditions. This paper presents a method to experimentally determine the shear modulus of composite sandwich panels as well as a comparison of the experimental results to Finite Element Analysis (FEA) simulations. An experiment was developed to characterize the shear modulus and torsional stiffness of sandwich panel fins on vehicles built by Georgia Tech Experimental Rocketry (GTXR), a project team of the Ramblin' Rocket Club (RRC) at Georgia Tech. The tested articles were 5" x 5" panels of Rohacell foam core with carbon fiber facesheets. These articles were deformed in torsion on an Instron load frame using a four-point loading setup. This test verified the club's composite sandwich panel modeling and proved the viability of this test procedure for GTXR. Moreover, this test will elevate the accessibility of similar testing in the composites research space with a simple geometric approach and provide insights on improving the accuracy of composite finite element models.

I. Nomenclature

G = Shear Modulus
J = Polar Moment of Inertia
L = Length
T = Torque
a = One Half Article Rectangular Cross Section Width
b = One Half Article Rectangular Cross Section Thickness
γ = Shear Strain
τ = Shear Stress
ϕ = Angular Displacement

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II. Introduction

WITHIN the aerospace industry, carbon fiber is frequently utilized in the construction of many components that must function in high stress environments. It is used in wings [1], fins [2], structures [3], and more, due to its high strength-to-weight ratio. The process of laminating aerospace vehicles with carbon fiber can bring significant weight savings while ensuring that the part can survive the expected loads. In the scope of this research, sounding rocket fins were the primary consideration. The material properties of composites are dependent upon several parameters such as core material, number of carbon fiber plies, and fiber orientation of the plies [4]. Furthermore, the properties of composite materials are process dependent because steps taken during the manufacturing process, including surface preparation, can impact critical properties such as the shear modulus[4, 5]. Knowledge of the in-plane shear modulus of a given composite is critical for designing aerospace structures, ranging from fins to ailerons and more [6]. Specifically, the effective shear modulus of composite fins is necessary when calculating fin failure modes such as aeroelastic fin flutter [7]. The process dependence, true bond quality, and other manufacturing defects lead to a lack of confidence when relying solely on simulated models in the design stage [8]. To validate a simulated analysis of composite structures, experimental testing of the structure was necessary.

This paper provides a summary of the experiment undertaken by students at Georgia Tech Experimental Rocketry, a project team of the Ramblin' Rocket Club at the Georgia Institute of Technology. It details a comparison between experimental and computational results, modeled with a Finite Element Model (FEM) in ANSYS. Specifically, it determined the shear modulus of composite sandwich panels made of Rohacell foam with quasi-isotropic carbon fiber. In verifying this computational model, design time of future composite articles can be greatly reduced by determining the shear response of various similarly constructed sandwich panels through simulation.

The plate twist test was an ideal candidate for verifying the computational model. The test provides data of force and displacement of the composite material through the application of torque which creates a shear stress field. The experimental values allowed for the calculation of the in-plane shear modulus of any given composite [5, 6]. The combination of data and the given geometry of the test article can be used to derive the in-plane shear modulus of the specific sandwich panel tested [5].

Once an experimental value for the shear modulus of a specific composite sandwich had been obtained from the plate twist test, the value was then compared against the Finite Element Analysis (FEA) simulations. If the experimental and computational results were found to be within 5 percent of one another, the computational model would be deemed verified and used in future design processes where an effective shear modulus is required. This enables the team to make predictions on the fin flutter velocities of given rocket fins [7].

III. Experimental Setup

The plate twist test is a torsional loading test of a square of material in order to determine the in-plane shear modulus of said material, regardless of composition [6]. For the plate twist test, a rig was manufactured with two identical attachments consisting of 1 inch thick plates of aluminum with inset steel ball bearings at 2 opposite corners. The bottom fixture is oriented 90 degrees off the upper fixture to create a couple in each in-plane axis. The opposing ball bearings cause a flexural motion of the sample plate [5]. The compressive force of the two plates is achieved by mounting the plate twist attachments to an Instron load frame. This machine records the applied force and displacement data.

A. Manufacturing and Development

There were three main elements to the plate twist testing rig: the plate base, points of contact, and Instron attachment. Furthermore, there were several constraints that needed to be accounted for during the design and manufacturing process.

Constraint number 1 demanded equal dimensions for both the testing rig and the testing article. The test article was decided to be a 5 inch by 5 inch square, therefore the plate base was created to mimic the dimensions of the test article.

Constraint number 2 called for the plate base to remain intact and stiff throughout the experiment. This ensured the displacement measured was purely of the test article, not the plates. Aluminum plates 1 inch thick were chosen as they satisfied the stiffness requirement.

Constraint number 3 demanded equivalent loading of the testing article to occur at equidistant points from the center. To meet this requirement, plate flatness was paramount. Flatness ensured equal loading at each contact point on the specimen. Low tolerance manufacturing ensured equidistant force application points from the center. Hence, bias was avoided in the data collection

Constraint number 4 required no local puncturing of the test article throughout the experiment. Historically, the points of contact have been conical in shape [5]. Cones, however, have a high probability of puncturing the panel. Thus the design of the contact point was updated to use ball bearings, which due to their spherical shape maintain a point contact force and are less likely to puncture a given material.

Rohacell foam core with quasi-isotropic carbon fiber facesheets were used because they had the lowest chance of delamination between the facesheets and the material itself. Aluminum cores were considered as candidates, but material delamination was prevalent and they were ruled unusable. Alternative wooden sandwiches were made from plywood of uncertain composition, so they were unable to be properly modeled.

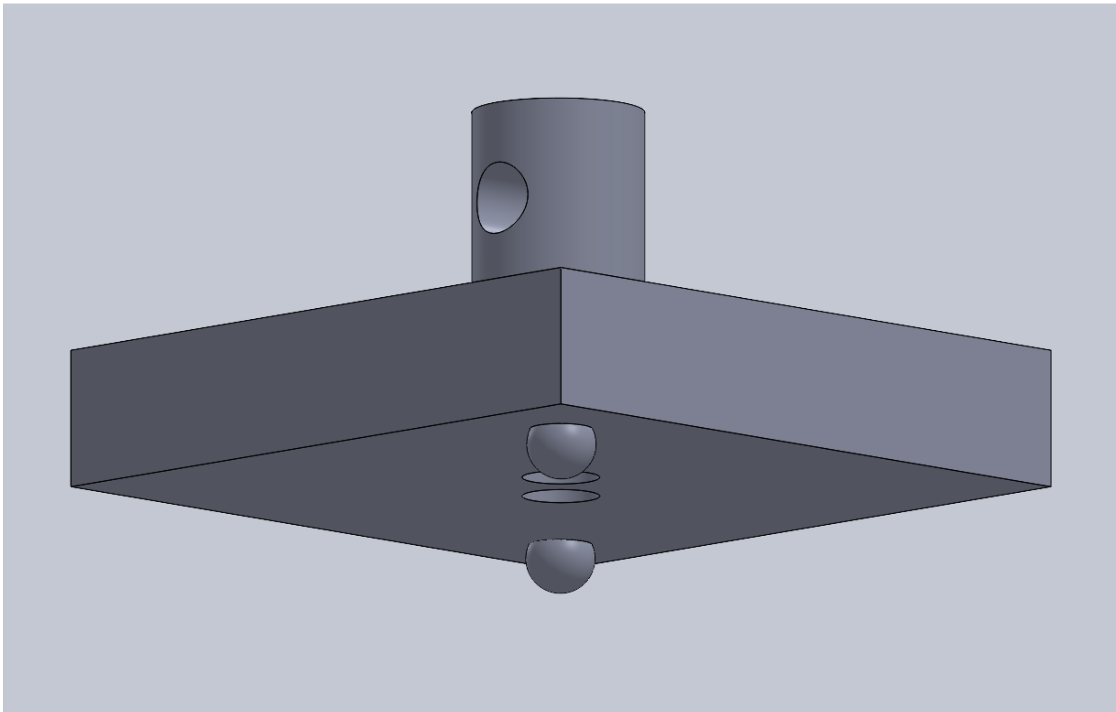

Fig. 1 Computer aided design (CAD) of plate twist test attachment

B. Instron Procedure

To complete this experiment, the Instron 5982 Universal Materials Testing System was utilized as it has an especially rigid frame that is ideal when testing composite materials, specifically applicable to this experiment [9]. Before the Instron was turned on, the testing rig was mounted. The orientation of the ball bearings of the top attachment were required to be 90 degrees offset from those in the bottom attachment. The Instron was then calibrated to acquire accurate data. A lower limit of 9 millimeters between the plate bases was set to ensure the testing article never contacted either plate base. Appropriate Personal Protective Equipment (PPE) was worn by all attending members. The test article was then inserted between the plates and centered. The Instron was lowered to first contact with the test article, ensuring the test article was not able to move across the x-y axes but remained in contact with all four ball bearings. For the experiment, the crosshead speed of the Instron was 1 millimeter per minute until an appropriate angular displacement of the article occurred, as long as the applied force did not exceed 0.75 kN. This limit was chosen based on how far the test article could be displaced before delamination and plastic deformation occurred.

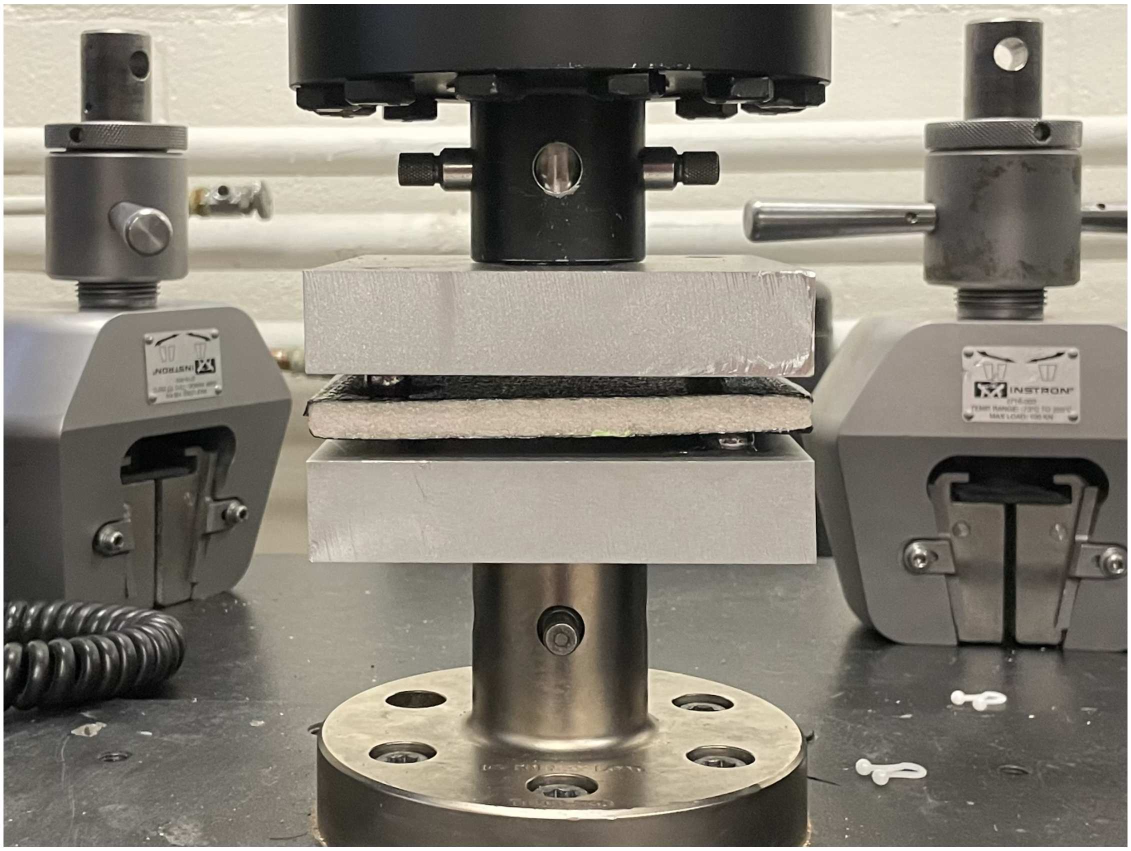

Fig. 2   Foam 1 test article undergoing plate twist testing

IV. Results

A. Calculations

The experimental data was reduced with a MATLAB algorithm which calculated the G (shear modulus) (4) using a manipulation of the shear stress and strain equations due to torsional loading (3)[10].

$$\tau = \frac{TL}{J} \tag{1}$$

$$\gamma = \phi \tag{2}$$

$$\tau = G\gamma \tag{3}$$

$$G = \frac{TL}{J\phi} \tag{4}$$

$$J = ab^3[\frac{16}{3} - 3.36\frac{b}{a}(1 - \frac{b^4}{12a^4})] \text{ for a} \geq \text{b} \tag{5}$$

The relationship between torque and angular displacement was reasoned by multiplying the force data by the moment arm distance and utilizing an inverse tangent function of the vertical displacement over the moment arm distance as shown in Fig. 3.

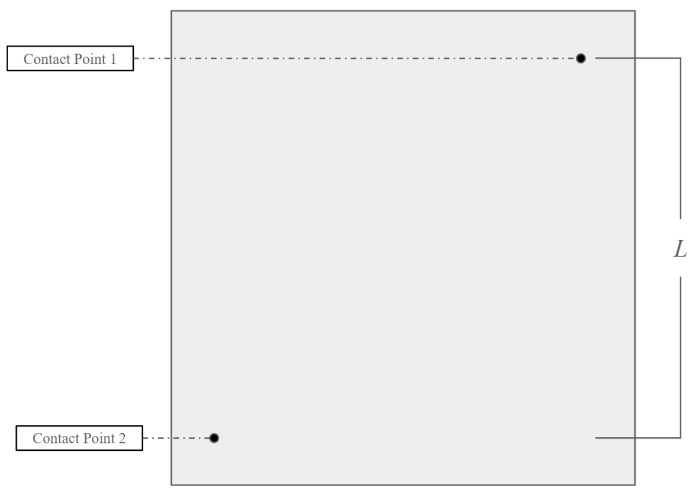

Fig. 3 Relevant dimension shown

The graphical representation show in Fig. 4 displays the values of force and displacement recorded from the experimental data and computational model. In the figure it is clear the observed experimental data curves belong to the same family. In order to compute the experimental shear modulus the data was plotted in terms of torque by length over angular displacement by polar moment of inertia (5), shown in Fig.4. This relationship was then linearized to determine a more precise scalar value. The computational shear modulus was computed directly and averaged for a similar scalar value.

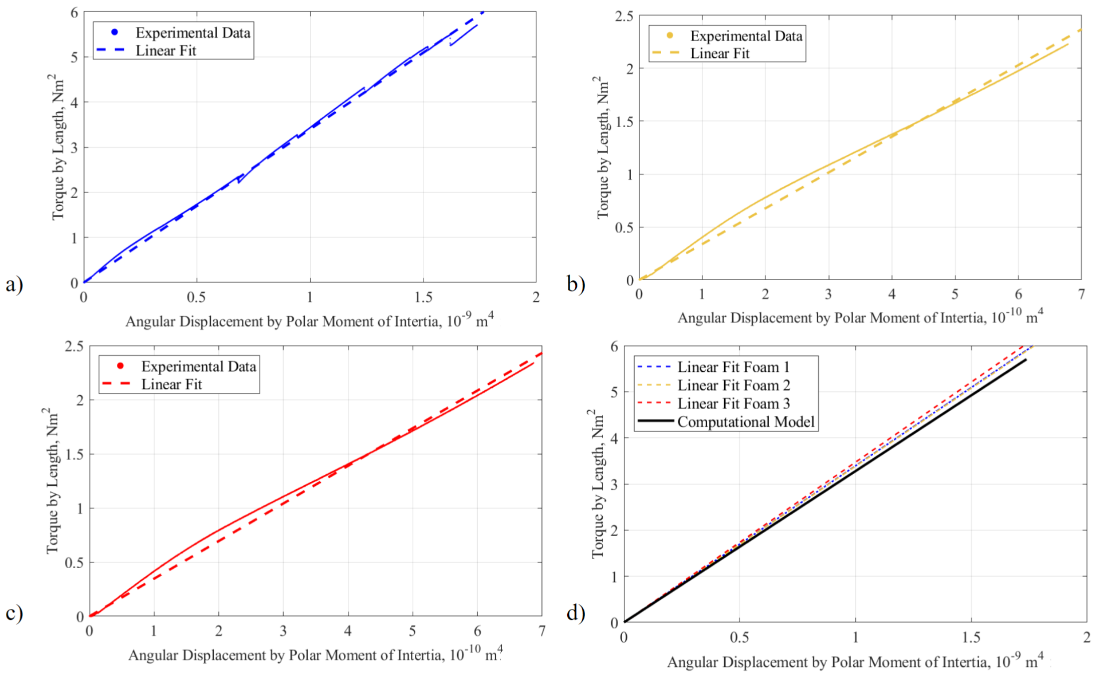

Fig. 4 (a) Experimental data and linear regression of first foam tested, (b) experimental data and linear regression of second foam tested, (c) experimental data and linear regression of third foam tested, and d) linear regression of each foam tested and computational model

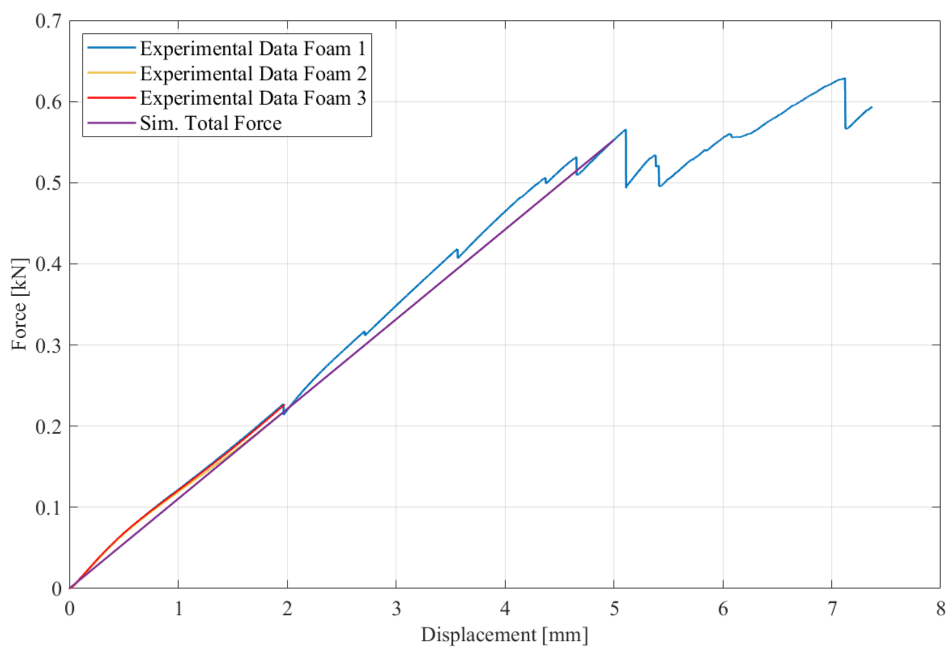

Fig. 5 Measured force with prescribed displacement of each foam tested and computational model

B. Computational Model

In order to create the computational model, ANSYS ACP-Pre and ANSYS Mechanical were used respectively to model the composite-core sandwich and carry out structural analysis. When modeling the layup of the composite sandwich in ACP-Pre, Epoxy Carbon Fiber Woven (230GPa) Pre-preg was utilized as the carbon fiber material. The pre-preg woven carbon fiber was modeled as an orthotropic material with the assumption that inter-laminar stresses due to weave pattern were negligible. Another assumption was perfect bonding between the core and the carbon fiber plies. The core, made out of Rohacell foam, was included as a ply in the ACP stackup and treated as a shell. This approach reduces the complexity of the model and removes the need to have trivial contacts for composite parts. It must be noted that this approach is only suitable for core materials with constant thickness. For aerospace composite structures that do not have uniform thicknesses, such as airfoils, alternative modeling methods must be used. The experiment was simulated in ANSYS Static Structural by prescribing the displacement on the upper load points and fixing the lower load points. This was done to ensure that the model was properly constrained and therefore, the load at each fixed support was expected to be double what was measured during the experiment.

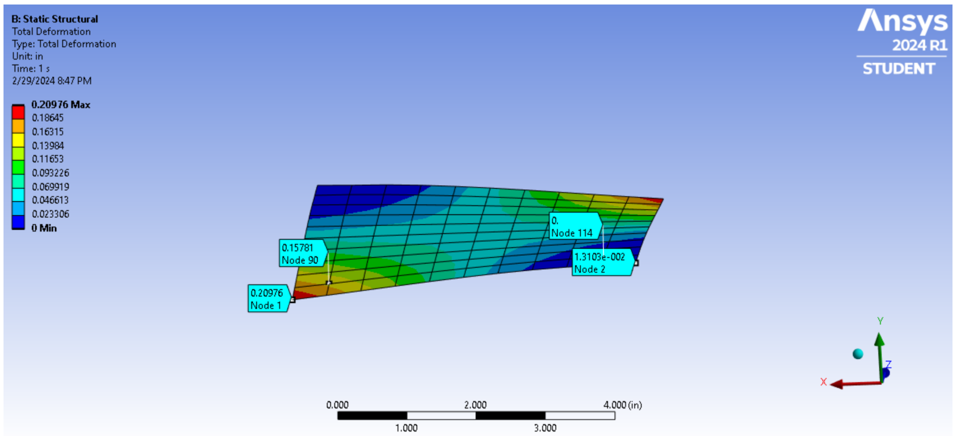

Fig. 6 ANSYS Static Structural demonstrating simulated deformation of test article

Property	Value	Unit
Density	0.0521	g/cm^3
Young's Modulus	0.070	GPa
Poisson's Ratio	0.27	-
Shear Modulus	0.027559	GPa

Table 1 Material properties for Evonik Rohacell® 51 IG-F Foam

Property	Value	Unit
Density	1.42	g/cm^3
In-plane Young's Modulus	61.34	GPa
Out-of-plane Young's Modulus	6.9	GPa
In-plane Poisson's Ratio	0.3	-
Out-of-plane Poisson's Ratio	0.04	-
In-plane Shear Modulus	2.7	GPa
Out-of-plane Shear Modulus	3.3	GPa

Table 2 Material properties for epoxy carbon fiber woven (230GPa) pre-preg

C. Discussion

The experimental value of the in-plane shear modulus was predicted to be close to the computational model value. This proved to be valid, as comparing the results from the ANSYS and experimental approaches in the MATLAB algorithm yielded the combined graphs 4. The correlation factors of linear regression for Torque by Length vs. Angular Displacement, shown in Table3, of the experimental and computational data indicate a high degree of correlation.

Core	Value
Foam 1	0.9975
Foam 2	0.9962
Foam 3	0.9972

Table 3 Values for correlation factor of linear regression (R^2) for experimental data

Figure 5 displays the key takeaway that all foams follow the same trend. More data points for Foam 1 were recorded as it was tested up to its proportional limit. Although these data values were not included in our calculations, they provide valuable insight that could be used in future testing. Further, this accuracy in the Force vs. Displacement transfers directly to the G calculation, as a relationship of torque and angular displacement. Utilizing the G values, shown in Table 4, from the ANSYS and experimental models accounts for the precision of the ANSYS model. These G values also reflect the processed data, focusing on Force and Displacement from initial contact until an appropriate angular displacement of the article occurred. Additionally, the correlation between the data highlights the repeatability of the experiment. This increases the confidence in the testing method in potentially verifying the computational model. The root mean squared error at a 95% confidence level was calculated and is displayed in Table 4. The uncertainty margins and respective percent error are significantly small, providing further evidence towards the reliability and accuracy of the computational model.

Foam	Value	Uncertainty	Percentage Error	Unit
Foam 1	3.3956	±0.0025	0.0736%	GPa
Foam 2	3.3860	±0.0050	0.147%	GPa
Foam 3	3.4743	±0.0044	0.127%	GPa
Ansys	3.2814	-	-	GPa

Table 4 Values for shear modulus (G) of samples with a root mean squared error at a 95% confidence level

V. Conclusion and Future Work

This study produced an experimental and simulated shear modulus value for Rohacell foam composite sandwich panels based on the plate twist test. These values were compared and determined to be within a minimized error margin. The results demonstrated a margin of error within the 5 percent predetermined before the experiment, thus verifying the computational FEA model.

As a verified model, the FEA ANSYS simulation eliminates the testing required to determine the shear modulus of a given composite sandwich. Specifically, future composites would pertain to parameters similar to those of the Rohacell sandwich panel. The simulated shear modulus of such panels will provide essential information regarding aeroelastic flutter of rocket fins constructed of said composite. Future derivations of flutter velocity will be necessary to ensure stable oscillatory response of rocket fins under aerodynamic loads.

Further plate twist testing of composite sandwich panels with varying core materials should be conducted to harbor understanding on the shear modulus of potential fin materials. Additional investigations are necessary to comprehensively assess the shear modulus and structural performance of novel fin geometries which require supplementary specifications.

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