Three-Point Bending of Honeycomb-Core Sandwich Beams with Composite Oriented Strand Board Face Sheets

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ABSTRACT

Sandwich structures for lightweight construction applications, particularly in the aerospace industry, require high specific strength and stiffness. This study investigates the mechanical behavior of a sandwich structure employing Composite Oriented Strand Board (COSB) face sheets under three-point bending. Given that COSB is an innovative aerospace-grade material derived from reused carbon fiber-epoxy prepreg strands, it is a tunable material with controllable thickness, microstructure, and mechanical performance. The sandwich structure gains its advantage by judicious selection of strand aspect ratio. This study only focuses on one aspect ratio, which is 1:5 prepreg strands. By analyzing two different manufacturing methods, which are mechanical-agitation and mat-stacking, the study aims to identify optimal configurations for enhanced mechanical performance.

Additionally, using COSB promotes material efficiency and offers environmental benefits by repurposing the expired aerospace prepreg strands. This sustainable approach contributes to developing eco-friendly manufacturing processes and reducing waste in the aerospace industry. Findings from this investigation have the potential to significantly impact the development of novel sandwich structures that are efficient, sustainable, and versatile. These advancements in lightweight materials and their structural applications stand to revolutionize the aerospace, automotive, and civil industries, paving the way for more sustainable, high-performance constructions that meet the increasing demands of modern engineering challenges.

1. INTRODUCTION

The automobile industry is actively moving towards a sustainable future. The unsustainability of fossil fuel-driven vehicles has incited a quick shift towards hybrid and electric power systems. Given the current restrictions of battery technology for long-haul electric vehicles, weight reduction is a significant research area. In particular, the design and manufacturing of lightweight sandwich composites from environmentally friendly alternatives is a promising route. In recent times, the utilization of renewable or recycled materials such as balsa wood, bamboo, waste tire rubber, and various foams and honeycombs to create sandwich composites has attracted considerable attention. However, for high-performance applications, the role of Carbon Fiber Reinforced Polymers (CFRP) in creating high-performance, lightweight face sheets with excellent mechanical properties is critical, even after the termination of their usage in aerospace and automotive structures. Due to the high energy and cost associated with carbon fibers, recycling and reusing carbon fiber for high-performance structures is economically beneficial and has become an important area of research.

This feasibility is amplified by the large amount of carbon fiber waste generated annually by the aerospace industry. The commercial aircraft industry is leaning heavily on composite materials to create lighter, more resilient aircraft. For instance, a Boeing 787 airplane comprises 50% composites by weight, equating to about 32,000 kg of Carbon Fiber Reinforced Polymer (CFRP). In 2015, Boeing predicted a demand for 38,050 new airplanes worth $5.6 trillion over the following 20 years, a rise of 3.5 percent from the previous year's forecast. Currently, Boeing and Airbus each produce ~450,000 kg (~1 million lb) of prepreg waste annually from airplane production. If the entire supply chain for these planes is taken into account, the total prepreg waste increases to 1,814,369 kg (4 million lb)/year. With the aerospace industry set to use more carbon fiber (and generate additional production scrap), recycling and reusing composite production waste will soon become imperative.

Jin [1] suggested a recycling carbon fiber method using expired prepreg strand layup to improve the microstructure and mechanical properties of Composite Oriented Strand Boards (COSB) made with reused prepreg scraps. Eight COSB panels were manufactured using two layup methods and four prepreg strand aspect ratios. All the panels were compression molded with the same carbon/epoxy system and process parameters. COSB void content, morphology, and distribution were examined using microscopy and X-ray computed tomography. The findings indicated that COSB panels with reduced variability and useful mechanical properties could be created using the proposed layup method and careful selection of strand aspect ratio.

Building upon Jin's work [1], sandwich composites from recycled carbon fiber prepreg skin and fresh Kevlar honeycomb core were developed in this study. The COSB face sheets were designed to offer excellent mechanical properties, economic feasibility, lightweight structure, reduced environmental footprint, and recyclability. These recyclable sandwich components may find application in automotive truck panels and potentially in the mass transport industry.

This study delves deeper into the "mat-stacking" layup method, which has been proven to exhibit higher tensile modulus, strength, and strain-to-failure, along with a lower coefficient of variation (CoV). The present study harnesses this method to fabricate laminates from prepreg strands, which has shown encouraging results compared to the previous "mechanical-agitation" method employed in the production of Composite Oriented Strand Boards (COSB). This research further extends the exploration by scrutinizing the implications of using these two distinct layup methods when they serve as face sheets for a sandwich beam comprising a Kevlar honeycomb core. The findings could lead to advancements in recycling strategies for high-performance structures, particularly in sandwich beam structure production.

2. EXPERIMENTATION

2.1 Manufacturing of COSB

COSB panels were produced from unidirectional (UD) thermoset prepreg strands distributed in random orientations. These rectangular strands were cut from expired OoA (Out of Autoclave) carbon fiber-epoxy prepreg. The COSBs were formed using compression molding with heated platens. This study focuses on one of the COSB variables, which is the different planar distribution of strands within the board resulting from layup methods. We will show how different layup methods strongly affect the mechanical performance of COSBs when serving as the face sheets of sandwich beam structures.

2.1.1 Material

The prepreg strands selected for producing the COSBs were cut from unidirectional carbon/epoxy prepreg (CYCOM T40-800B/5320-1, Cytec Co., Ltd.) designed for OoA manufacture of aerospace structures. The prepreg consisted of a toughened epoxy resin reinforced with carbon fibers (cure temperature of 121ºC) with an elastic modulus of 57.6 GPa and strength of 931 MPa (quasi-isotropic layup), elastic modulus of 156 GPa and strength of 2703 MPa (0º fiber direction), 0.137 mm cured ply thickness, 1.31 g/cm^3 cured resin density, 220 g/m^2 and 145 g/m^2 of areal density for prepreg and dry fibers, respectively, and 67% nominal fiber volume fraction. All prepregs used in this work were seven years beyond the specified shelf life, and thus the mechanical properties were compromised compared to a fresh prepreg system.

2.1.2 Manufacturing techniques

The fabrication procedure involved strand cutting, lay-up, and heated plate compression molding. Care was taken in the process to ensure (a) that the cuts on strand ends did not damage adjacent fibers, (b) a controllable orientation and distribution of strands during the layup procedure and an acceptable thickness variation of the final part, and (c) the surface and bulk void contents were eliminated/minimized. Mechanical properties were benchmarked to those of quasi-isotropic laminates.

2.1.3 Strand cutting and geometry

Prepreg sheets were cut into strands using a razor blade, taking care to avoid shearing of fiber ends in cuts parallel to the fiber direction. However, cuts across fibers and cuts through resin-rich areas presented challenges with regard to avoiding shearing of fiber ends. Cutting tools such as fabric shear scissors and shear cutters were suitable for clean cuts (Figure.1 (D)). Paper shear cutter boards also provided clean cuts for strands with rectangular shapes (Figure.1 (C)). Fully automated cutting systems will be required for large-scale production of COSB products.

The aspect ratio (AR) of each rectangular composite strand is defined as the strand length-to-width ratio. Strands with AR = 5 were prepared, and all had a width of 10 mm and length of 50 mm (Figure 1 (A)). While COSB panels with lower AR strands are expected to yield inferior tensile strength due to limited fiber continuity, such panels may have manufacturing advantages. The effects of utilizing different AR strands are beyond the scope of this study. In the future, An optimal strand geometry that considers processing challenges can be obtained from experimental and numerical simulations.

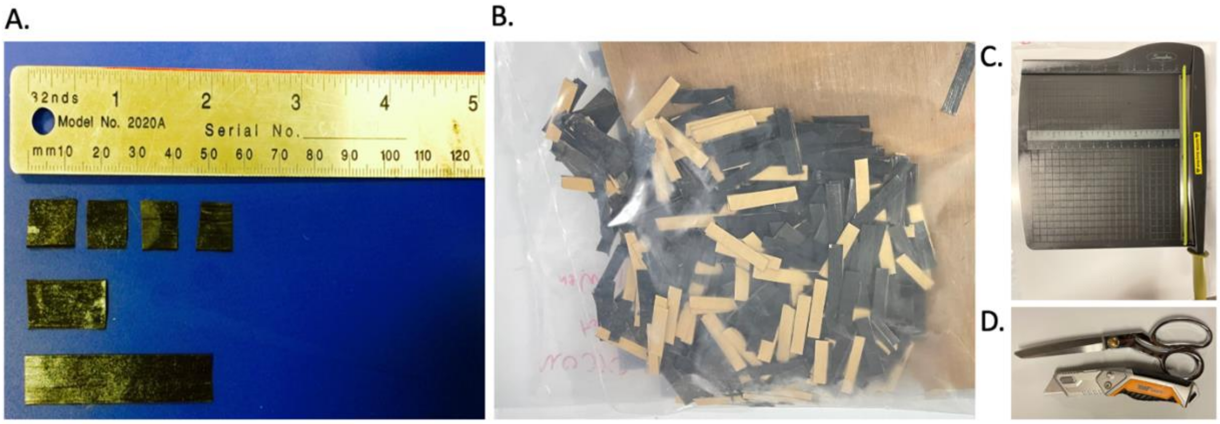


Figure 1. (A) Prepreg strands cutting for aspect ratio 1:1, 2:1, and 5:1. (B)storage of prepreg strands. (C) shear Cutting Boards. (D) scissors and cutters used in strand cutting

2.1.4 Layup and distribution methods

Three layup methods are respectively used in this study. We first study [0/90] cross-ply laminates made by continuous, aged prepreg sheets. We cut all prepreg sheets into 3 inches x 24 inches, then stack them together following the layup sequence of $[0/90]_{2s}$.

Two alternative lay-up methods were used to produce COSB panels in comparison to the aged, continuous fiber group. In the first method, a “randomly distributed” layout was created by a “mechanical-agitation” method (Figure 2). In this method, UD strands of 80 g were placed in an open box (3 inches x 24 inches x 4 inches) and manually shaken. Strands were then pressed using a heated press to achieve a near-uniform layup. Fresher strands tended to adhere mutually on initial contact, restricting redistribution and sliding during shaking. Strands with more than 1-2 weeks out-time showed increased sliding mobility because of reduced tack and were hence used with the mechanical-agitation method.

Though the "mechanical-agitation" method provided a rapid method to produce COSB, the mass distribution was not homogeneous, and strands tended to cluster, creating regions with high and low fiber concentrations. To address this, a uniform layout was created by “mat-stacking” layup (Figure 3), in which multiple thin layers (mats of UD prepreg strands) were formed first as a COSB prepreg sheet, then stacked and finally pressed. Each strand of UD prepreg was attached to a Teflon sheet. During the stacking process, each strand was positioned to fill the largest opening in the array of strands. This “fill-in-the-blanks” process was considered complete when openings in the mat were no longer evident. A mat produced in this manner consisted of a single layer of COSB strand prepreg and constituted the structural unit in this method. Each final mat-stacked COSB consisted of 4 layers of prepreg strand mats (each 3 inches x 24 inches mat weighing 20g) and had a total weight of 80 g per face sheet, equivalent to the total weight of a COSB produced by mechanical-agitation. This method resulted in 430.56 g/m^2 of areal weight per layer as compared with the 145 g/m^2 of the raw UD prepreg and indicates the degree of surface coverage by strand overlapping obtained with the proposed "mat-stacking" method.

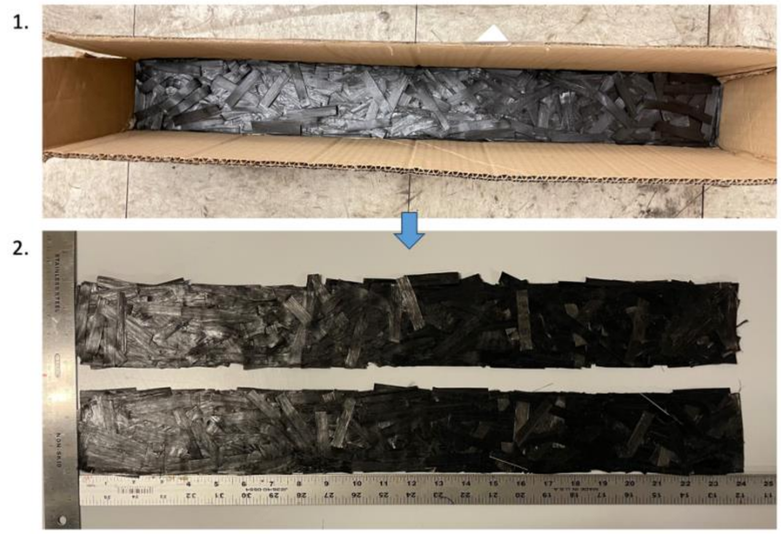


Figure 2. Mechanical-agitation layup method.

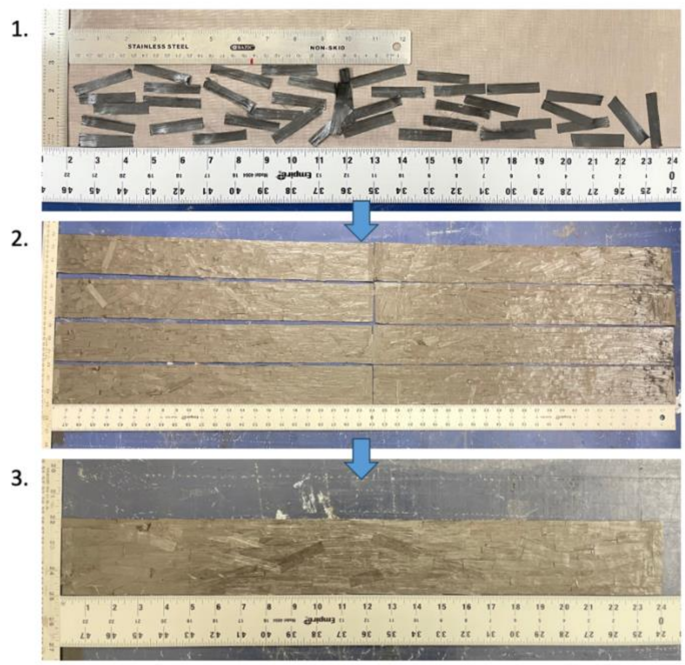


Figure 3. Mat-stacking layup method.

2.1.5 Curing for continuous carbon fiber / COSB face sheets

All COSB face sheets were cured by compression molding in a heated platen press. The assembly process starts with laying down a chipboard, providing a firm and even base. A caul sheet, which helps distribute the pressure uniformly across the entire assembly, is placed onto the chipboard. Two types of release films, XA10 and XA50, are positioned in the assembly sequence. These films prevent the adhesive from undesirable bonding with other parts of the press or assembly setup.

The XA10 film is positioned with the waxy side facing both up and down, while the XA50 is placed with the release side facing down. The continuous carbon fiber face sheets or COSB face sheets are then added into the middle of the sequence. Then, we have another three layers of release films, one layer of caul sheet, and finally, the chipboard on top.
High consolidation pressure was required to achieve low porosity and a suitable resin bleed rate. The compression force was 200 psi, and the curing cycle was 3 hours at 250°F. After hot pressing, we allow it to undergo a freestanding post-cure process. This involves keeping the face sheet at a higher temperature of 350°F for an additional 2 hours. This post-curing process further ensures the material's integrity, enhancing its mechanical properties and dimensional stability.

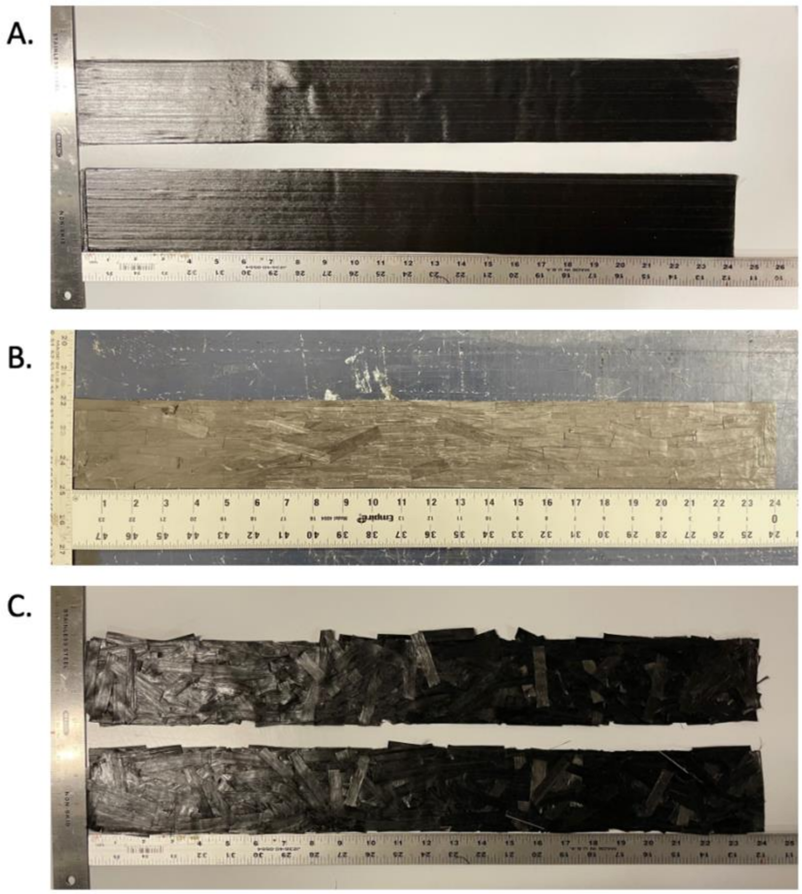


Figure 4. (A) Continuous fiber prepreg face sheets. (B) mat-stacking COSB face sheets. (C) mechanical-agitation COSB face sheets.

2.2 Manufacturing of Sandwich Beam

2.2.1 Honeycomb Core

This study used Gillcore HK 162 honeycomb core, a variant of the para-aramid phenolic-coated core. The HK 162 variant is characterized by a 1/8" cell size and a nominal density of 6.0 pounds per cubic foot (PCF), underscoring its compactness and robustness. Compared to meta-aramid honeycomb cores, Gillcore HK displays superior weight, strength, stiffness, and fatigue properties.

This material is extensively employed in both the interior and exterior of aircraft, including flooring, sidewalls, ceilings, fairings, helicopter blades, access panels, and doors.

2.2.2 Assembly and Curing

Sandwich beam manufacturing involves the assembly of two rigid face sheets and a lower density core. In this case, the face sheets are made of continuous carbon fiber sheets or COSBs, and the core is an HK162 honeycomb core material. The sandwich structure is bonded together using a high-strength epoxy film adhesive, A193, which is a fiber-reinforced high-strength epoxy film adhesive. The assembly sequence utilizes release films (XA10 and XA50), caul sheets, and chipboards to ensure a smooth manufacturing process and a high-quality finished product.

The assembly process starts with laying down a chipboard, providing a firm and even base. A caul sheet, which helps distribute the pressure uniformly across the entire assembly, is placed onto the chipboard. Two types of release films, XA10 and XA50, are positioned in the assembly sequence. These films prevent the adhesive from undesirable bonding with other parts of the press or assembly setup. The XA10 film is positioned with the waxy side facing both up and down, while the XA50 is placed with the release side facing down. The continuous carbon fiber face sheets or COSB face sheets are then added into the sequence. The A193 fiber-reinforced epoxy film adhesive is applied in two layers on either side of the core material. This adhesive ensures a robust bond between the carbon fiber skin and the HK162 core, providing the sandwich beam with its requisite strength and rigidity.

Once the assembly is prepared, it undergoes two pressing stages. The initial pressing, at 250°F and 125 psi of pressure for 10 minutes, enables the onset of curing in the adhesive and allows any trapped volatiles to escape. Following this, the final pressing phase increases the temperature to 325°F and is maintained for 60 minutes while keeping the pressure constant. This stage fully cures the adhesive, creating a solid bond between the carbon fiber skin and the core material. The final steps involve the removal of the sandwich beam from the press, along with the release films, caul sheets, and chipboards.

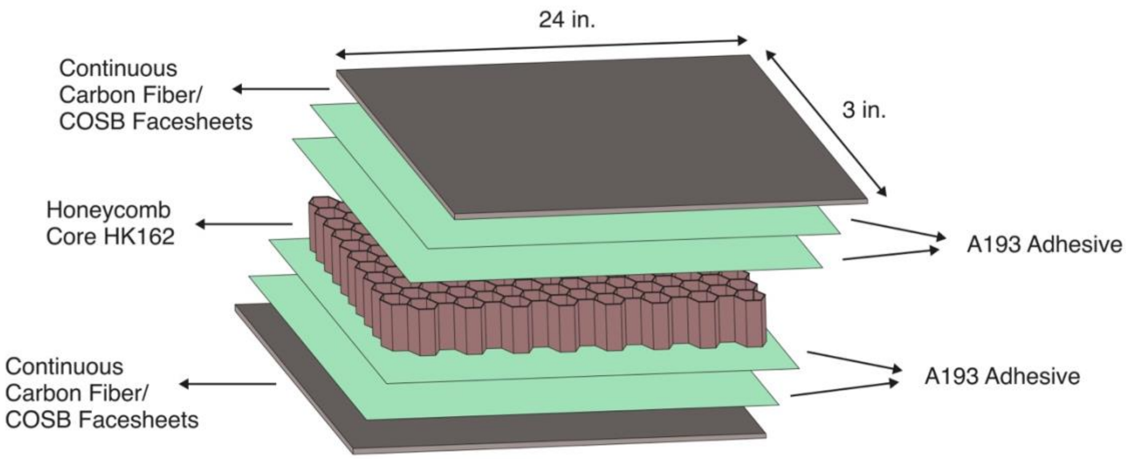
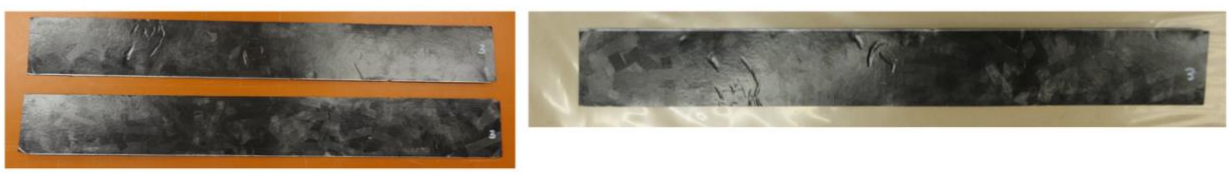


Figure 5. General layup sequence of Sandwich Beams made of honeycomb core and continuous carbon fiber or COSB face sheets.

A. Mat-stacking



B. Mechanical Agitation

Figure 6. (A) The left shows mat-stacking COSB face sheets after pressing, and the right shows after assembling with the honeycomb core. (B) the left shows mechanical-agitation COSB face sheets after pressing, and the right shows after assembling with the honeycomb core.

2.3 Three-Point Bending Test

The Three-Point Bending Test is a commonly used method to evaluate the structural performance of sandwich composites, which consist of thin composite face sheets bonded to a relatively thick, low-density core. These sandwich structures are highly suitable for flexural loading due to the presence of the core that separates the two stiff and strong composite face sheets. During flexural loading, the face sheets of the sandwich composite experience tensile and compressive stresses induced by bending, while the central core primarily undergoes shear stresses. As a result, failures can occur in either the face sheets or the core under such loading conditions. To assess these potential failures, specific test methods have been developed.

We performed a Three-Point Bending Test in this study to determine the maximum load capacity of each sandwich beam. The test setup involves applying a load to the specimen using three points of contact. The distance between the two outer points of contact, known as the span, measures 23 inches. The support diameter, representing the size of the supports at the two outer points of contact, is 1 inch. The dimensions of the loading block are 4 inches in length, 4.1 inches in width, and 1.5 inches in height (L x W x H). The loading block serves as a mechanism to apply the load on the sandwich beam in a controlled manner, allowing for accurate measurements of the maximum load capacity.

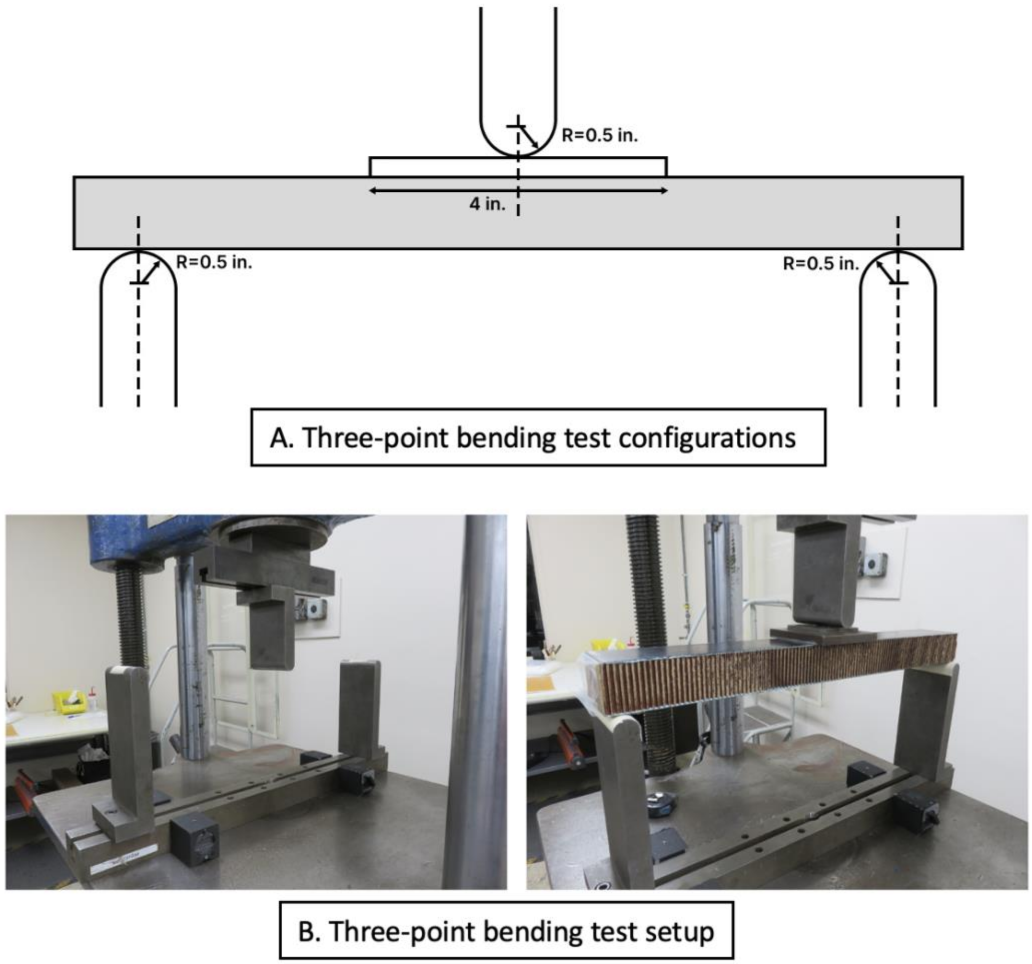


Figure 7. Three-point bending test configurations of sandwich beams.

3. RESULTS AND DISCUSSIONS

3.1 Three-Point Bending Test Results

In the study, we conducted Three-Point Bending Test on the three sandwich panels with different manufacturing methods of face sheets, as shown in Table 1. To ensure a fair comparison, all panels had the same weight for the face sheets and the same sizes of the honeycomb core. Three sandwich panels are only different by the layup/strand distribution of the face sheets, respectively made from [0/90] cross-ply layups of continuous fiber, mat-stacking COSB, and mechanical-agitation COSB.

Table 1. Comparison of Face Sheets, Core, and Overall Sandwich Panel Weights (in grams)

Face Sheet Type	Face sheets Total Weight (top and bottom)	Core Weight	Sandwich Panel Weight
Continuous Fiber	135.88 g	272.98 g	477.7 g
Mat-Stacking COSB	141.70 g	264.01 g	470.5 g
Mechanical-Agitation COSB	147.14 g	245.73 g	457.2 g

Specimens of different thicknesses and layup geometries were subject to three-point bending deformation up to failure. The Mat-stacking COSB sandwich panel shows a reduced thickness of 0.09% compared to the sandwich panel made from continuous, while the Mechanical Agitation COSB panel exhibits an increased thickness of 0.66%. These variations in thickness indicate possible differences in the material consolidation and compaction achieved during the manufacturing processes. According to Jin's paper [1], the mat-stacking layup method yielded greater control of panel thickness and flatness (variation of thickness over the panel surface). The average panel thickness was generally 20-40% less when using the mat-stacking method rather than the mechanical agitation one.

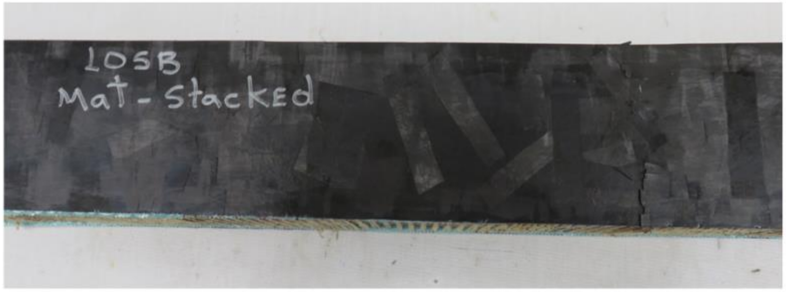
Regarding the maximum load, the mat-stacking COSB panel demonstrates the highest value of 3275 lbf, surpassing the continuous fiber group (3022 lbf) by 8.37% and the mechanical agitation COSB panel (2390 lbf) by 37.02%. This suggests that the mat-stacking COSB technique may have led to improved load-bearing capabilities, potentially due to optimized material orientation or better interfacial bonding between the face sheets and core.

Table 2. Comparison of Sandwich Panel Thickness, Width, Length, and Maximum Load (in inches and pounds)

Face Sheet Type	Thickness (in.)	Width (in.)	Length (in.)	Max Load (lbf)
Continuous Fiber	2.111	3	24	3022
Mat-Stacking COSB	2.109	3	24	3275
Mechanical-Agitation COSB	2.125	3	24	2390

Two types of failure modes were observed, and the effects of the material used and layup design were clearly reflected. The failure of both the reference group and the sandwich beam with mat-stacking face sheets features fiber breakage and matrix crack around the midplane of the panel.

The sandwich panel, which features Mechanical-Agitation COSB face sheets, displays distorted shapes after testing.



A. Mat-stacking

B. Mechanical Agitation

Figure 8. Failure modes. Sandwich beam with mat-stacking COSB face sheets (A), sandwich beam with mechanical-agitation COSB face sheets (B).

3.2 Non-Destructive Testing Evaluations

Our results offer insights into the impacts of incorporating COSBs into sandwich panels in terms of properties and performance. Further analysis and comparison, such as microstructural examination, can contribute to a comprehensive understanding of the underlying mechanisms behind these variations. Nondestructive testing methods (NDT), like optical microscopy and X-ray computed tomography (XCT), can provide a valuable characterization of void content, morphology, and distribution.

3.2.1 Micro-XCT of Mechanical-Agitation Panel and Mat-Stacking Panel

Sample preparation procedures included cutting, polishing, and image post-processing. For this study, a Phoenix Nanotom Tomographic machine (General Electric) with a Hamamatsu C-7942 detector and a Mo anode was employed to conduct micro-CT scans on the mat-stacking COSB and mechanical-agitation COSB specimen. Scanning settings were set at 80 kV and 150 uA, with a 500 ms exposure time, achieving a resolution of 13.04 µm/px.

The total void content measured via XCT images was approximately 10% and roughly 2.5% for the panels produced using mechanical-agitation and mat-stacking methods, respectively. From visual observation, the voids' spatial distribution showed substantial differences. Mechanical-agitation panels displayed less amount of small (< 104 µm^3) voids but larger amount of large (>105 µm^3) voids. These larger voids resulted from uneven strand distribution during the stacking process, resulting in bridges and gaps that were only partially filled with resin during consolidation. Comparatively, mat-stacking panels exhibited a finer dispersion of voids. Differences in void shapes were also apparent between the two COSB panel types. The mechanical-agitation panels featured irregular voids, whereas mat-stacking panels mostly had acicular voids. The fibers'

crimping effect in the mechanical-agitation COSB panel was more pronounced than in the mat-stacking panel, impacting mechanical properties.
The mat-stacking method demonstrated an enhanced microstructure with fewer voids. The mat-stacking method utilized the concept of lamination and aimed at an even distribution of strands and internal voids and improved morphology. When properly laminated, structural loads were shared by more prepreg strands, and failure modes advanced from "Wedge-Pullout" to a mixed mode of "Strand-Pullout" and "Strand-Breaking". This process modification led to substantially improved mechanical properties in mat-stacking COSB panels, which explains the sandwich beam with mat-stacking face sheets can withstand 37.02% more of the max load than the mechanical-agitation face sheets.

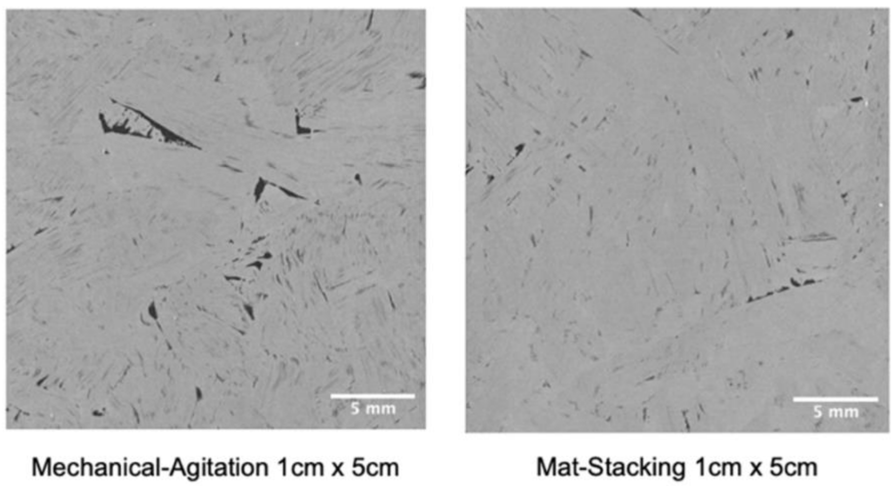


Figure 9. Micro-CT scans of COSBs made of prepreg strands of Aspect Ratio 5:1, with mechanical-agitation and mat-stacking.

3.2.2 Microscopy Examination of Fresh Continuous Fiber Panel, Aged Continuous Fiber Panel, and Mat-Stacking Panel

The use of optical microscopy offered deeper insights into void morphology, validating the comparative performance of two types of panels: the aged continuous fiber panel and the mat-stacking panel. A fresh continuous fiber panel served as a void-free reference group in this analysis. Figure 10 (a) showcases the fresh continuous fiber panel, void-free and thus representing a reference point for comparison. The aged continuous fiber panels, as presented in the optical micrographs of the XZ cross-section, show a consistent, dot-shaped void distribution (Figure 10 (b)). The laminate structure was clearly visible with an even thickness throughout, and most voids were situated on the boundaries of laminates, representing the significant impacts of aging. In contrast, the XZ cross-section micrographs of the mat-stacking face sheets demonstrated a different void profile (Figure 10 (c)). While these panels exhibited lower overall void content, their distribution was uneven. The voids' shape ranged from cigar-shaped to dot-shaped, indicating a variability not observed in the aged continuous fiber face sheets. Here, the laminate thickness was less discernable, with several areas showing uneven laminate distribution.
Despite their uniform void distribution, the aged continuous fiber panels featured a higher total number of voids and a denser distribution compared to mat-stacking face sheets. This elevated porosity in the aged continuous fiber panels could negatively impact the mechanical properties of

the laminates. Lower strength and potential susceptibility to premature failure under load could be significant consequences of these structural deficiencies.
When compared with [0/90] aged continuous fiber panels, the mat-stacking method shows advantages in terms of lower void content and resulting decreased overall porosity. While the void distribution in the mat-stacking panels was not as uniform, the method's overall benefits, as shown by the reduced void content and variability in void shapes, underscore its potential as a robust strategy for enhancing the mechanical properties and lifespan of composite sandwich panels.

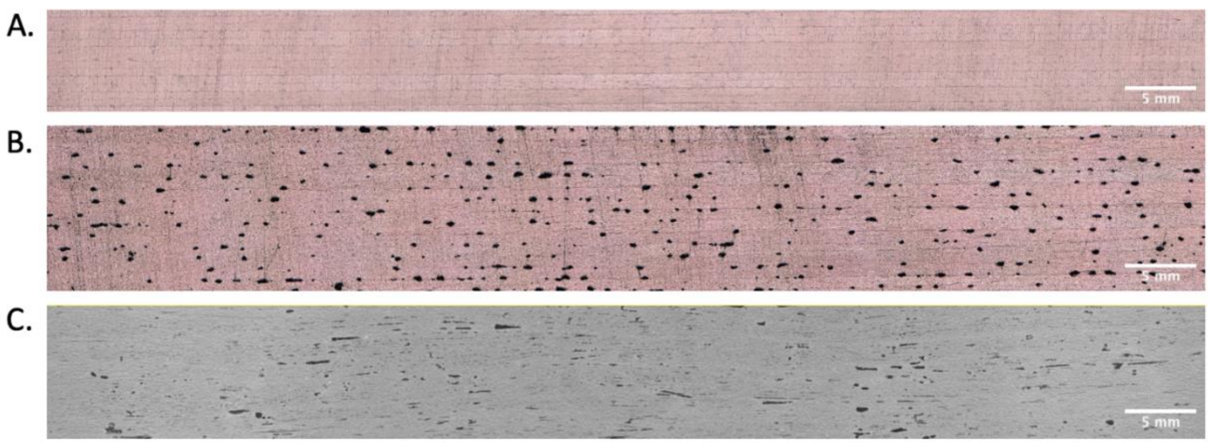


Figure 10. (A) Fresh continuous fiber sample. (B) aged continuous fiber sample. (c) mat-stacking COSB sample with AR = 1:5.

4. CONCLUSIONS

In this study, we have investigated the effects of two layup and strand distribution methods of CFRP prepreg face sheets on the three-point bending performance of sandwich beam structures. Our investigation centered on the comparison between two methods: mat-stacking and mechanical-agitation, as well as a comparison to the traditional [0/90] cross-ply layup of continuous fiber with the same aged material. Our findings suggest that, when serving as face sheets of sandwich beam structures, the mat-stacking method outperforms the mechanical-agitation method with controlled thickness, fewer voids, and a more evenly distributed laminate structure.

Additionally, our results also indicate that mat-stacking COSB panels made from aged materials perform 8.37% better than panels with a [0/90] cross-ply layup of continuous fiber made with the same aged materials. This suggests that using the same aged prepreg, mat-stacking presents an advantageous alternative even when compared to traditional continuous fiber layup methods when serving as face sheets of sandwich beam structures. This underlines the potential of the mat-stacking manufacturing method as an effective strategy for enhancing the performance of aged composites.

In conclusion, the mat-stacking method offers a promising path forward for the production of COSB panels. By improving mechanical properties and producing panels with superior structural characteristics, it has the potential to revolutionize the field of reused and recycled composite material manufacturing, leading to more resilient and durable products. Looking forward, it is important to continue investigating the vast potential of COSB and its practical applications. To this end, our future research will focus on expanding the testing matrix to include an examination of the effects of different Aspect Ratios (AR) of prepreg strands. This will provide a more comprehensive understanding of the relationship between aspect ratio and mechanical behavior, which will help us further enhance the mechanical performances of COSB panels in various production and use.

5. REFERENCES

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