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# Manufacturing and Scale-Up of Natural Fiber Composite eVTOL Propeller Skin and C-Channel

*Allison Christy, Meelad Ranaiefar, and Sandi Miller*
*Glenn Research Center, Cleveland, Ohio*

*Paula Heimann*
*Universities Space Research Association, Cleveland, Ohio*

*Andrew P. Santos, Alex Mazhari, and Jon Sasaki*
*Ames Research Center, Moffett Field, California*

*Sang-Hyon Chu*
*Langley Research Center, Hampton, Virginia*

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National Aeronautics and
Space Administration

Glenn Research Center
Cleveland, Ohio 44135

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This report is a formal draft or working paper, intended to solicit comments and ideas from a technical peer group.

This report contains preliminary findings, subject to revision as analysis proceeds.

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NASA STI Program/Mail Stop 050
NASA Langley Research Center
Hampton, VA 23681-2199

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National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

Sang-Hyon Chu
National Aeronautics and Space Administration
Langley Research Center
Hampton, Virginia 23666

## Summary

This report presents the manufacturing and scale-up of natural fiber composites for aerospace applications, conducted within NASA's Convergent Aeronautics Solutions portfolio to advance aircraft capabilities and efficiency. The effort focused on the development and demonstration of two proof-of-concept articles, an electric vertical takeoff and landing (eVTOL) propeller skin and a C-channel subcomponent, produced through an iterative design and process optimization approach. Best practices and guidance on addressing key challenges with bio-based composite materials and manufacturing are provided. Ideally suited for non-load-bearing structural components, these emerging materials offer potential for weight reduction, vibration damping, noise mitigation, interference-free communication, and cost savings, without compromising the performance of safety-critical primary structures.

## Nomenclature

### Acronyms

| | |
|---|---|
| AAM | advanced air mobility |
| AHRCM | Ames High-Rate Composite Manufacturing Facility |
| CAS | Convergent Aeronautics Solutions |
| eVTOL | electric vertical takeoff and landing |
| FRP | fiber-reinforced polymer |
| NFC | natural fiber composite |
| PA-11 | polyamide-11 |
| PHB | poly-3-hydroxybutyrate |

| | |
|---|---|
| PLA | polylactic acid |
| PTFE | polytetrafluoroethylene |
| RF | radio-frequency |

### Variables

| | |
|---|---|
| $A$ | area, $m^2$ |
| $F$ | force, n |
| $P$ | pressure, psi |
| $wA$ | areal weight, $g/m^2$ |
| $t$ | time, s |

## Introduction

Fiber-reinforced polymer (FRP) composites are widely used in aerospace structures due to their high specific strength and stiffness, low density, and tunable anisotropic properties that enable application-specific performance optimization (Refs. 1 and 2). While carbon and glass fibers dominate FRP usage for primary structures in current aircraft, there is increasing interest in natural fiber composites (NFCs) for selected noncritical applications (Refs. 3 and 4). Derived from plant-based reinforcements such as flax and hemp, NFCs are cost effective and can provide competitive specific stiffness relative to E-glass fiber at certain fiber volume fractions (Refs. 5 and 6) while also offering intrinsic multifunctional benefits such as improved vibration damping, acoustic attenuation, and reduced radio-frequency (RF) interference (Refs. 7 to 9). These characteristics are particularly aligned with emerging requirements for next-generation electric vertical takeoff and landing (eVTOL) rotorcraft, which must withstand persistent vibratory loads, operate in urban noise-sensitive environments, and increasingly incorporate embedded antennas and sensors that benefit from materials with favorable RF transparency.

Flax fiber is one of the most extensively studied and industrially adopted natural reinforcements, with significant use in automotive, marine, and sporting goods sectors owing to its favorable mechanical properties and processability (Refs. 10 to 13). With an average density near 1.5 $g/cm^3$, flax fibers are lighter than carbon fiber (1.8 $g/cm^3$) and substantially lighter than glass fiber (2.5 $g/cm^3$), which enables weight reductions at equivalent reinforcement levels (Ref. 14). Additionally, the hollow, microfibrillar morphology of flax fibers, as seen in Figure 1, imparts natural damping capacity and enhanced acoustic absorption. Their electrically insulating nature also eliminates the risk of electromagnetic shielding, which is a challenge in carbon fiber composites, thereby enabling reliable communication, navigation, and sensing in aerospace systems (Refs. 15 and 16). These combined advantages make flax fibers especially attractive for secondary aircraft components where multifunctionality can be leveraged without imposing safety-critical requirements.

Natural fibers can be processed with a range of resin systems, including traditional thermosets and bio-derived thermoplastics such as polylactic acid (PLA), poly-3-hydroxybutyrate (PHB), and polyamide-11 (PA-11), which are produced from renewable feedstocks. Thermoplastics in particular offer recyclability, repairability, and weldability, which reduces reliance on mechanical fasteners, simplifies assembly, and improves end-of-life recovery. When combined with natural fibers, these resins enable the production of NFCs that are fully bio-derived, lightweight, and can be tailored for multifunctional behavior such as vibration damping and RF transparency. Furthermore, thermoplastic NFCs may be processed using advanced manufacturing techniques such as automated tape laying, thermoforming, and welding, which are scalable to the high production rates envisioned for advanced air mobility (AAM) platforms.

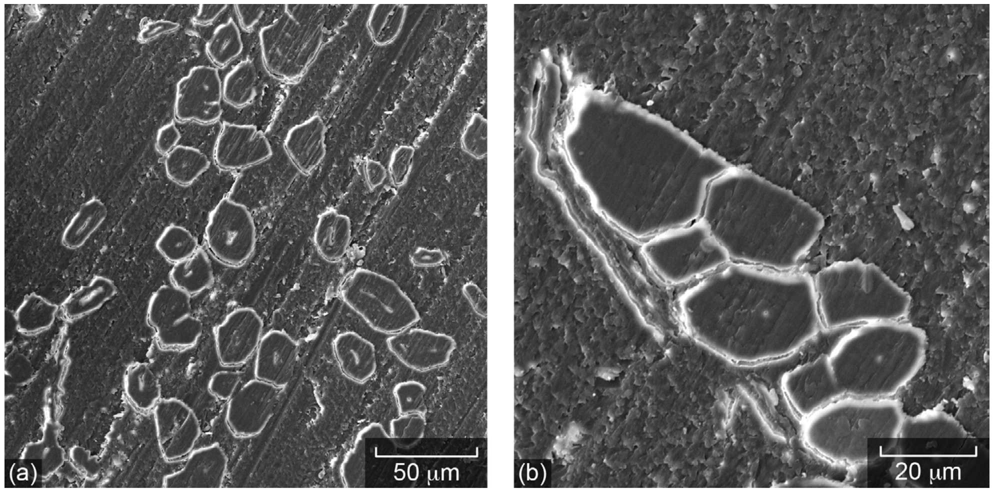

Figure 1.—Scanning electron microscope images of hollow flax fiber cross sections.

The work described in this report was conducted within NASA's Convergent Aeronautics Solutions (CAS) portfolio and represents a focused effort to evaluate, mature, and demonstrate NFC manufacturing in aerospace-relevant geometries. This effort forms part of a larger NASA initiative investigating natural fibers, resins, material life cycle considerations, computational modeling, integrated sensing, manufacturing, and mechanical testing, with results detailed in a separate comprehensive report (Ref. 17). The current report details a culminating effort focused on the manufacturing and scale-up of NFCs for two demonstration articles: a propeller skin for an eVTOL propulsion system and a C-channel structural element intended for integration into a seat assembly. In this report, emphasis is placed on refining layup sequences and optimizing material processing conditions to demonstrate NFC scalability and achieve consolidated parts with consistent quality. The resulting fabrication approaches and lessons learned are intended to inform future applications of NFCs in AAM platforms.

## Materials

The selection of materials for this study was guided by the dual objectives of demonstrating manufacturability and enabling scalability for aerospace-relevant NFC components. Key considerations included fiber architecture, resin compatibility, and processability, ensuring that the materials could accommodate both curved and complex component designs while achieving consistent consolidation and laminate quality. In particular, the commingled flax braid/PA-11 system was chosen to provide a representative pathway for producing components that meet practical manufacturing constraints of AAM structures. Detailed information on the fiber, matrix, and preform configuration and a description of how these materials were prepared for the fabrication of demonstration articles is provided here.

Flax was selected for this study, in part due to its availability in multiple forms, including unidirectional fibers, woven fabrics, and braided preforms. Braided fiber architectures have been successfully implemented in aerospace applications such as wing flaps for Bombardier, jet engine stator vanes, and the fan case of GE Aerospace's GenX engines (Ref. 18). The braiding process allows precise control over fiber angles and orientation and has been shown to improve impact resistance, fatigue performance, and structural robustness relative to unidirectional or woven fibers.

The commingled flax braid/PA-11 material exhibits excellent conformability, which is particularly advantageous for the manufacturing of components with complex or curved geometries. Stiffer or brittle materials may not fully conform to tooling during processing, potentially leading to fracture, inadequate resin infusion, and part defects. The flexibility of the commingled system allows for reliable consolidation and consistent part quality, which is essential for scalable production of aerospace components such as the eVTOL propeller skins and seat assembly subcomponents.

The flax fiber used in this study was sourced from Terre de Lin. Through Concordia Fibers, additional processing enabled the integration of PA-11 filaments (supplied as Rilsan® PA11 from Arkema) via commingling with the flax fiber. This commingling provides enhanced resin dispersion during composite manufacturing and simplifies handling as compared to film infusion methods, as discussed in the C-channel Results and Discussion section. The flax was subsequently braided by A&P Technologies into a quasi-isotropic [0/+60/–60] preform, with an areal weight of 512 g/m$^2$ and 55% fiber volume fraction. This areal weight is slightly higher than that of flax fiber without commingling (405 g/m$^2$), reflecting the added resin filaments. To improve handling and maintain tow integrity during layup, flax tows were lightly bound with cellulose fibers. The commingled preform is shown in Figure 2.

Manufacturing procedures for natural fiber composites depend on multiple factors, including component geometry, material properties, desired throughput, available equipment, final performance requirements, and overall cost. In the current study, the primary focus was on demonstrating the manufacturability and scalability of the commingled flax braid PA-11 system for aerospace-relevant components. The following section outlines the fabrication approaches employed, emphasizing robust processing techniques designed to produce consistent, high-quality NFC components with complex geometries, such as an eVTOL propeller skin and a C-channel seat subcomponent.

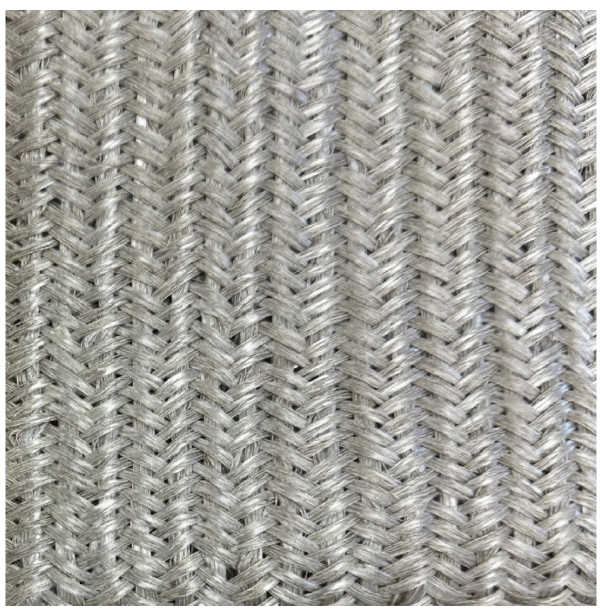

Figure 2.—Braided flax commingled with PA-11 preform.

## Manufacturing Demonstrations

Two complementary fabrication approaches were employed for the manufacture of the propeller skin and the C-channel subcomponent. The Ames High-Rate Composite Manufacturing Facility (AHRCM) at the NASA Ames Research Center was leveraged in combination with a Joby Aviation (Santa Cruz, CA) propeller compression mold to produce the representative eVTOL propeller skin. Separately, an autoclave at the NASA Glenn Research Center was used to fabricate the C-channel subcomponent for a seat assembly. Each component was selected to demonstrate the versatility of the commingled flax braid PA-11 system across different component geometries and manufacturing approaches, with a focus on manufacturability, reproducibility, and scalable fabrication. Details specific to each procedure are provided in the following sections.

### Propeller Skin

This section describes the manufacturing process for the propeller skin and presents results and discussion.

#### Manufacturing Process

A Cannon (Milano, Italy) preformer line at the AHRCM was used to manufacture the propeller skins. Although the line contains automated stack preheating, transferring, draping, and sample removal capabilities, only the heated press component, shown in Figure 3, was utilized. This was intended to replicate the static press manufacturing process developed in the laboratory-scale trials reported in previous work (Ref. 17). The press was fitted with upper and lower propeller molds (Figure 4) provided by Joby Aviation.


Figure 3.—Preformer line at the AHRCM with heated press used for propeller manufacturing.

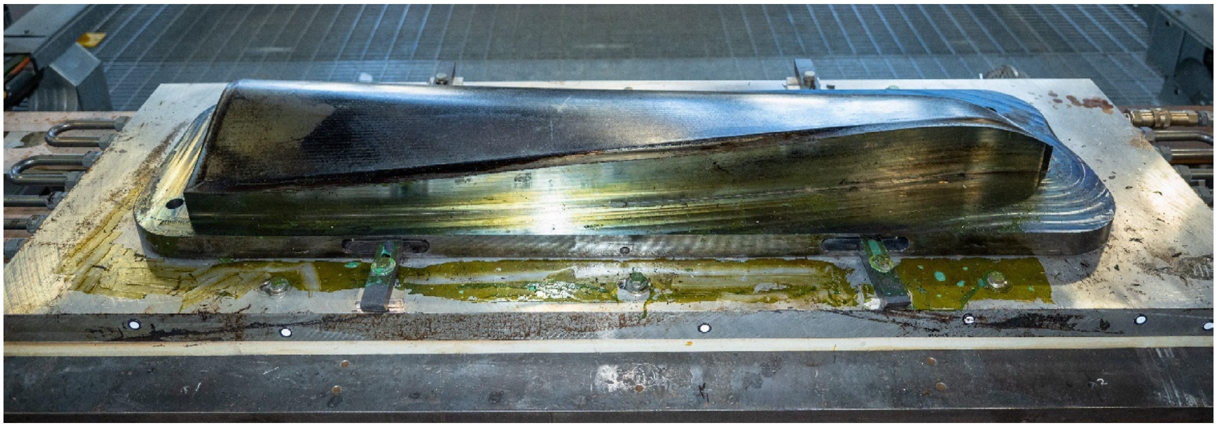

Figure 4.–Bottom propeller skin mold used for compression mold manufacturing.

Figure 5.—Flax plies laid up directly on compression mold.

Before manufacturing, the top and bottom molds were generously coated with a polytetrafluoroethylene- (PTFE-) based mold release agent. In all trials, four plies of braided flax/PA-11 preform were laid up in the same direction with the primary axial tow along the length of the propeller blade. The press was closed, and the molds were preheated to 170 to 200 °C depending on the trial.

In the first trial, the preform sheets were laid up directly onto the propeller molds, as shown in Figure 5, once the temperature of the mold center read 170 °C with a handheld temperature probe. The mold was closed, and the material was allowed to preheat for approximately 40 min until the center of the mold read 190 °C. The pressure was increased to 486 kN (150 psi based on a mold dimension of 52 by 14 in.) and held for 20 min. After pressing, the press automatically opened due to previous settings, which led to delamination of the composite plies. The press was closed again, and a pressure of 700 kN (216 psi) was applied and held as the system gradually cooled to 100 °C while maintaining pressure.

After cooling, the composite material adhered to the tooling, which prevented the press from opening. The press was then reheated to 150 °C to soften the resin, allowing the upper and lower plates to open. Plies of the composite stuck to the top of the mold, resulting in damage to different regions of the propeller (Figure 6(a)). Once removed, the resulting composite, shown in Figure 6(b), was brittle, damaged, and had significant charring, most likely due to the extended amount of time in the press.

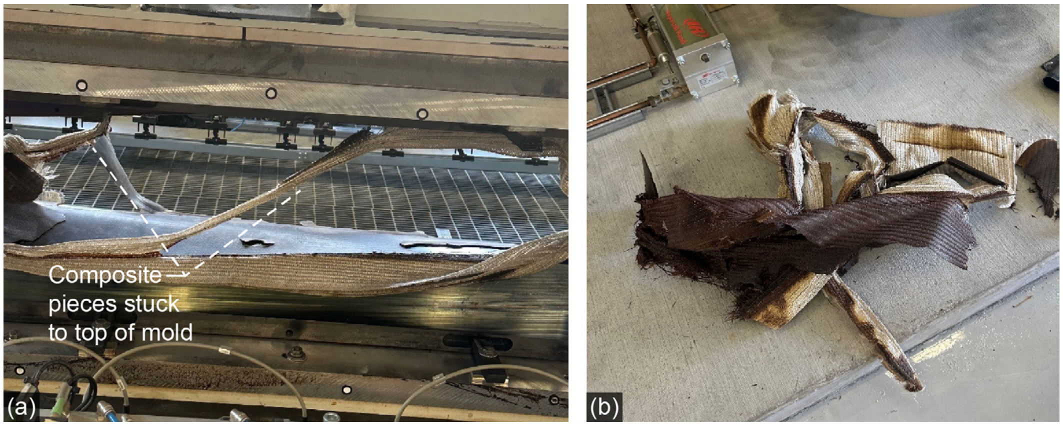


Figure 6.—Results of first manufacturing trial in which plies were laid up directly on compression mold. (a) Material stuck to top of compression mold after processing. (b) Charred composite material after removal from mold.

Figure 7.—Composite layup in between mold-release-coated polyimide release liner.

Based on the results of the first trial, polyimide film coated with a mold release agent was used as a release liner to ensure the composite did not stick to the press. Once the center temperature reached 200 °C, the coated polyimide film and plies were placed in the mold and allowed to preheat for approximately 5 min, as shown in Figure 7. The pressure was then increased to 986 kN (304 psi). After being held at pressure for 20 min, the composite was allowed to cool under pressure, and the press was opened when the temperature probes read 100 °C.

The procedure used in the second trial resulted in a well-consolidated composite propeller, shown in Figure 8. When removed from the mold and the release liner, inconsistencies in the consolidation in the top right corner of the panel were observed. Areas of resin pooling and voids as well as dry fibers are shown in Figure 9. Because of these results, subsequent trials followed a similar approach, with slight modifications to improve the consolidation of the top right corner. Variations included the use of a rubber insert (Figure 10) to apply more pressure in the top corner of the mold, and the addition of PA-11 resin sheets to increase fiber wetting. Details of the various trials are described in Table I. In total, eight manufacturing trials were performed, which resulted in the successful production of six propeller skins.

Figure 8.—Composite propeller in polyimide liner still on bottom plate after opening mold.

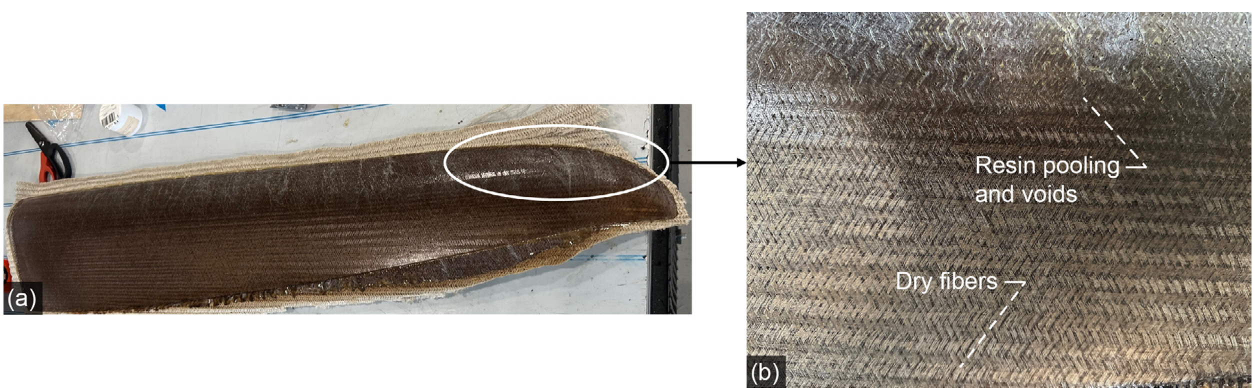


Figure 9.—Second trial propeller skin after removal from mold and polyimide liner. (a) Top view. (b) Closeup of top right corner showing inconsistent resin infiltration and dry fibers.

Figure 10.—Rubber insert gap filler used to evenly distribute pressure of mold.

TABLE I.—SUMMARY OF MANUFACTURING PROCEDURES FOR PROPELLER MANUFACTURING TRIALS

| Trial | Experimental approach | Notes |
|---|---|---|
| [a]1 | • Material placed in mold when platens preheated to ~170 °C, held without pressure with goal of reaching 210 °C<br>• Material held for ~40 min with maximum temperature reading ~190 °C<br>• Force increased to 486 kN, held for 20 min<br>• Press automatically opened, which led to deconsolidation of the sample<br>• Same panel pressed at 700 kN and allowed to cool to 100 °C before removing from press | • Material stuck to mold when first attempted to remove<br>• Required additional heating to remove from mold (~150 °C) |
| 2 | • Material placed between two sheets of PTFE-coated polyimide film<br>• Material placed in molds when reading ~200 °C, held under 986 kN (304 psi) pressure for 20 min<br>• Temperature cut to 100 °C and cooled under pressure | • Well-consolidated panel, retained shape of propeller<br>• Visible resin flow outside edges was observed<br>• Uneven pressure appeared to occur, leading to less consolidation at bottom of curved edge of propeller |
| [a]3 | • Material placed between two sheets of mold-release-coated nylon vacuum bag material<br>• Followed same procedure as Trial 2 with addition of 5-min hold time at temperature (25 min total) and use of rubber mold sheet for more uniform pressure<br>• Placed in mold with rubber insert in bottom, temperature reading ~200 °C, top and bottom platen coated in mold release, top covered with coated polyimide release liner<br>• Run started and pressure read 1,274 kN (384 psi), held for 15 min before cooling under pressure | • Vacuum bag material immediately melted upon contact with mold<br>• Switched to using vulcanized rubber insert and coated platens<br>• Resulting part showed obvious charring and was extremely brittle<br>• Temperature set point was ~250 °C, so likely that part experienced significantly higher temperatures than expected |
| 4 | • Material placed between two sheets of coated release liner<br>• Temperature set point lowered to ~180 °C<br>• Used different rubber mold to produce optimum pressure<br>• Held for 15 min at ~180 °C, ~300 psi<br>• Allowed to cool to ~100 °C, press opened and plates read ~150 °C | • Incomplete wetting of fibers observed<br>• A suspected air bubble produced large defect on front of propeller<br>• Uneven rubber insert led to uneven pressure, likely attributed to incomplete fiber wetting<br>• Slightly higher temperatures required<br>• Will allow for longer cooling to occur next run<br>• Next iteration will not use rubber insert |
| 5 | • Plies placed between coated release liner, placed in mold when reading ~190 °C, held at ~300 psi (1,000 kN) for 20 min<br>• Slowly cooled under pressure before removing from mold | • Dry spot still occurred on top right corner of propeller<br>• Will add PA-11 sheet on top and bottom to eliminate dry spots |
| 6 | • Plies with sheet of PA-11 on top and bottom placed between coated release liner<br>• Additional strip of PA-11 added to top right corner<br>• Placed in mold reading ~185 °C (top right corner ~175 °C), held at ~300 psi (1,000 kN) for 25 min<br>• Slowly cooled under pressure before removing from mold | • Top right corner still dry; most likely tooling issue<br>• Overall looked well consolidated |
| 7 | • Plies with sheet of PA-11 on top and bottom placed between coated release liner<br>• Placed in mold reading ~170 °C, held at ~300 psi (1,000 kN) for 30 min<br>• Slowly cooled under pressure before removing from mold | • Top right corner still dry; most likely tooling issue<br>• Overall looked well consolidated<br>• Might reduce time by ~5 min because fiber darkening occurred in some regions |
| 8 | • Plies with sheet of PA-11 on top and bottom placed between coated release liner<br>• Placed in mold reading ~180 °C, held at ~300 psi (1,000 kN) for 25 min<br>• Slowly cooled under pressure before removing from mold | • Overall well consolidated<br>• Top corner still dry<br>• Defect on front most likely due to defects in polyimide film |

[a]Unsuccessful trials resulting in unsalvageable propellers.

## Results and Discussion

Images of the propellers produced in the manufacturing campaign are shown in Figure 11. The propellers from Trials 2, 6, and 7 appeared to be the most uniform based on visual observation, but all the composites were generally well consolidated, though variability in composite quality was seen. The variations observed can be attributed to several different factors. The most notable of these factors was a consequence of the mold design, which produced an uneven distribution of pressure and temperature across the mold. In some instances, the difference in temperature was as much as 20 °C between the center and the edges of the mold. Figure 12 highlights the consequence of nonuniform heating and pressing from the mold. Significant darkening of both the matrix resin and fibers was observed on the bottom edge of the propeller, whereas the resin in the top edge remained incompletely melted, with notable voids and dry fibers still visible.

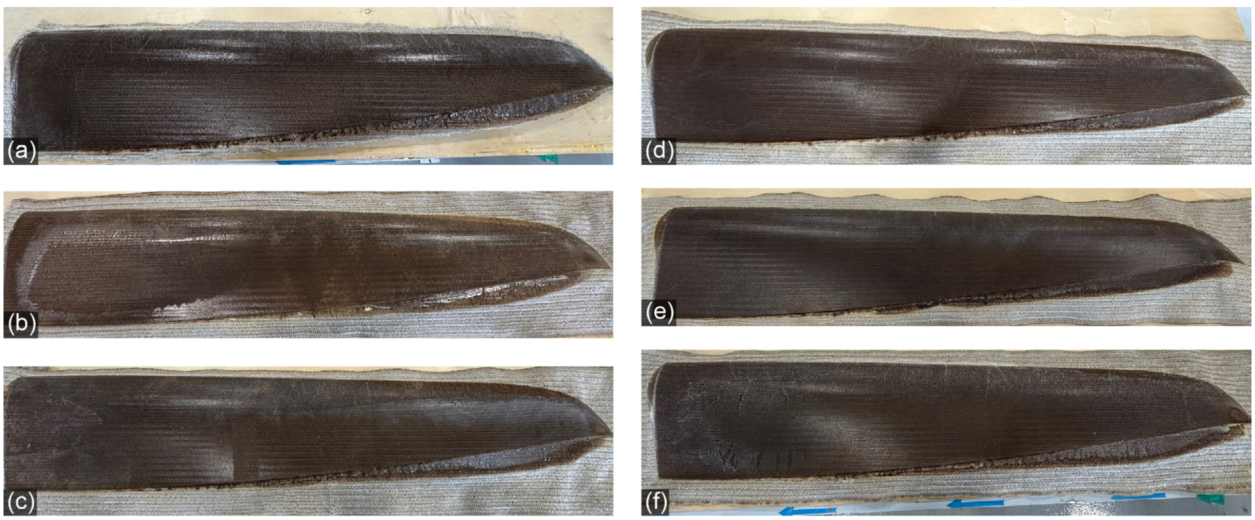


Figure 11.—Composite propeller skins produced in manufacturing campaign. (a) Trial 2. (b) Trial 4. (c) Trial 5. (d) Trial 6. (e) Trial 7. (f) Trial 8.

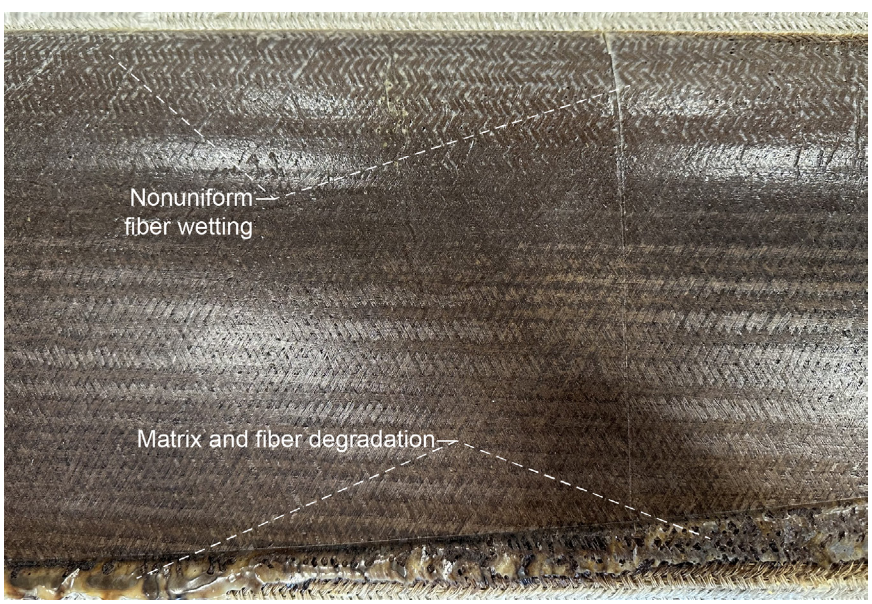


Figure 12.—Composite section displaying significant charring and matrix degradation on bottom of panel and incomplete resin infusion at top of panel due to tooling issues.

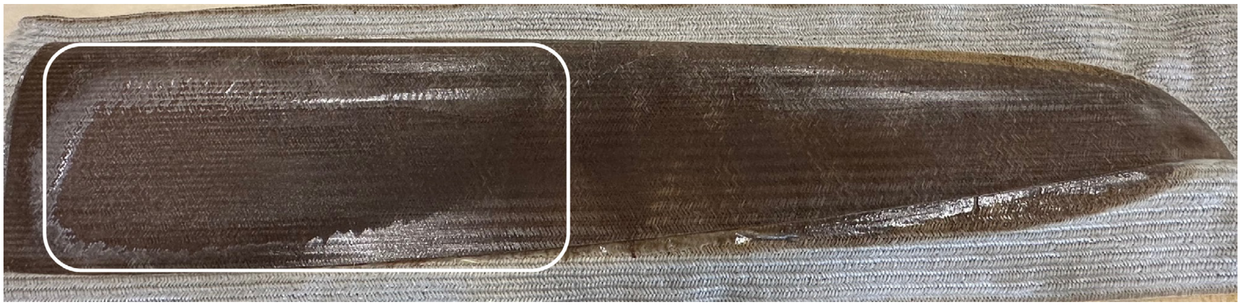

Figure 13.—Propeller made in Trial 4 with large surface defect due to air bubble caused by rubber insert gap filler.

This gradient in both pressure and heating inherent to the mold design was unable to be remedied by any change in layup or processing procedure. The dryness and uneven wetting in the top corner of the propeller was present in all trials. The addition of PA-11 sheets did not mitigate the effects of the tooling problems, nor did the addition of the rubber insert. In fact, the addition of the rubber insert created an air bubble in the composite layup that resulted in a large defect on the surface of the Trial 4 composite, as highlighted in Figure 13.

Environmental factors might also have played a role in the differing results observed. The press was not contained in a closed environment, so variations such as humidity, temperature, or air flow might have further exacerbated the inhomogeneous tooling conditions. Changes in the time required to preheat or cool the press varied slightly from trial to trial, which may have contributed to slight deviations in the actual time each propeller was held under pressure at elevated temperatures.

The time and resource limitations of this manufacturing campaign were also a contributing factor to the variations between the composite trials. For example, the coated release liners were reused multiple times due to the limited access to polyimide film. This resulted in the surface defects seen in Trials 5 and 8. The extent to which optimal processing time and temperature could be explored was also limited. Deviations in time, pressure, and temperature most likely contributed to darkening in fibers and inconsistent resin wetting at the edges of the panels. In general, had more time been available, further process development to determine an optimal manufacturing procedure could have produced propellers of more consistent quality.

Despite these variations and limitations, however, this manufacturing campaign served as a successful proof-of-concept demonstration of the ability to manufacture NFC materials at scale. Using an industrial tooling mold and a modified preformer line, the demonstration successfully produced multiple NFC propeller skins in a commercial manufacturing environment. This represents a promising step toward incorporating a bio-based FRP composite material into commercial eVTOL applications.

## C-Channel Subcomponent

This section describes the manufacturing process for the C-channel subcomponents and presents results and discussion.

### Manufacturing Process

A McGill AirPressure (Columbus, OH) autoclave was used to manufacture the C-channel subcomponents. Three trials were performed, all with 12- by 12-in. plies of commingled flax/PA-11 sheets that were pre-dried in an oven at 121 °C for 2 h before processing. The preforms were draped over an 18- by 4-in. aluminum C-channel bar mold with a mold-release-coated polyimide film release liner and approximately 3 in. of bleeder fabric on both ends to absorb any excess resin, as shown in Figure 14. A nonporous PTFE sheet was placed on top of the plies, and the setup was vacuum bagged with polyimide film before being moved into the autoclave. For all trials, vacuum was held at 91 kPa for the duration of the run to aid in conforming the plies to the shape of the mold.

The first two manufacturing trials used six plies of commingled flax/PA-11 fiber and a maximum pressure of 110 psi. Dry spots were visible on the first sample, so additional sheets of PA-11 resin were added to top of the layup for the second and third trials. The pressure was increased to 120 psi for the third trial, and the number of plies was reduced to four. The third trial produced the most well-consolidated composites and is considered the optimized processing profile, as summarized in Figure 15.

## Results and Discussion

The C-channel subcomponents produced from the three trials are shown in Figure 16. In Trial 1, the top, sides, and inside of the C-channel all had large areas of dry fiber, indicating minimal resin infusion. Including additional PA-11 sheets in the layup in trial 2 resulted in improved resin infiltration, though dry spots persisted. The most significant improvement in quality was observed in the C-channel produced in Trial 3, where the pressure was increased and part thickness was reduced.

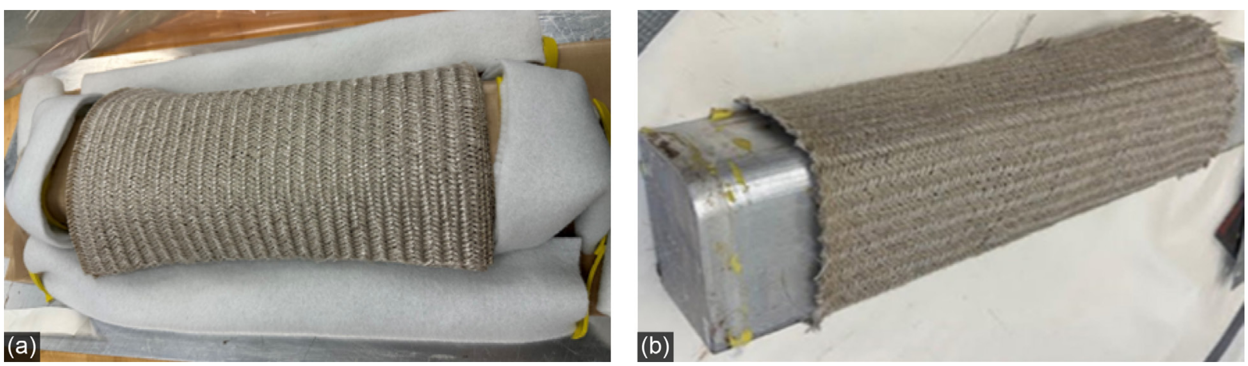


Figure 14.—Layup of flax/PA-11 preforms on C-channel subcomponent tooling. (a) Top view. (b) Side view.

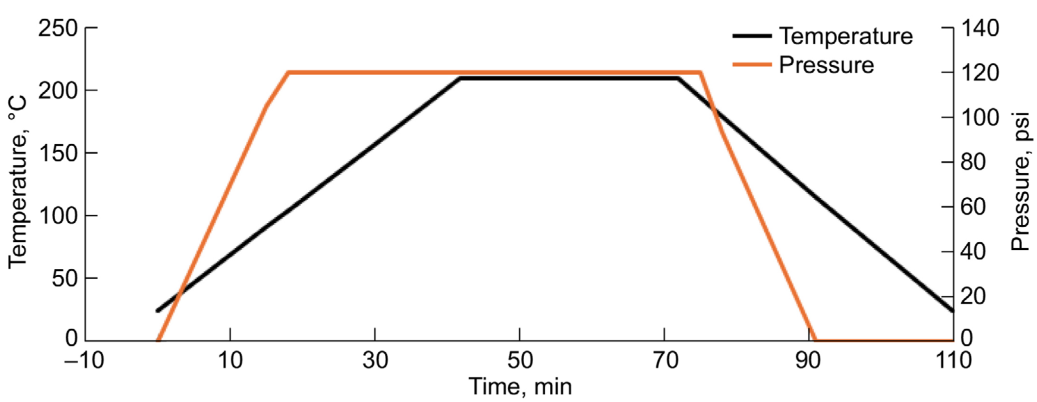


Figure 15.—Optimized autoclave processing profile from Trial 3.

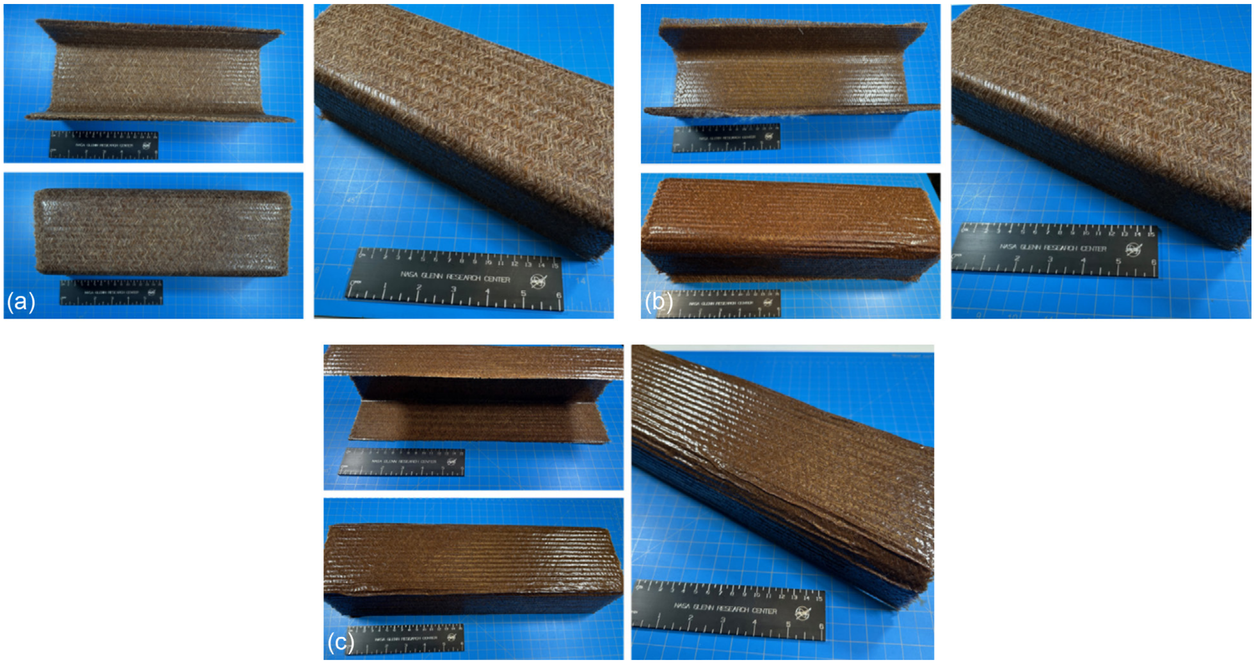


Figure 16.—C-channel subcomponents manufactured in trials. (a) Trial 1. (b) Trial 2. (c) Trial 3.

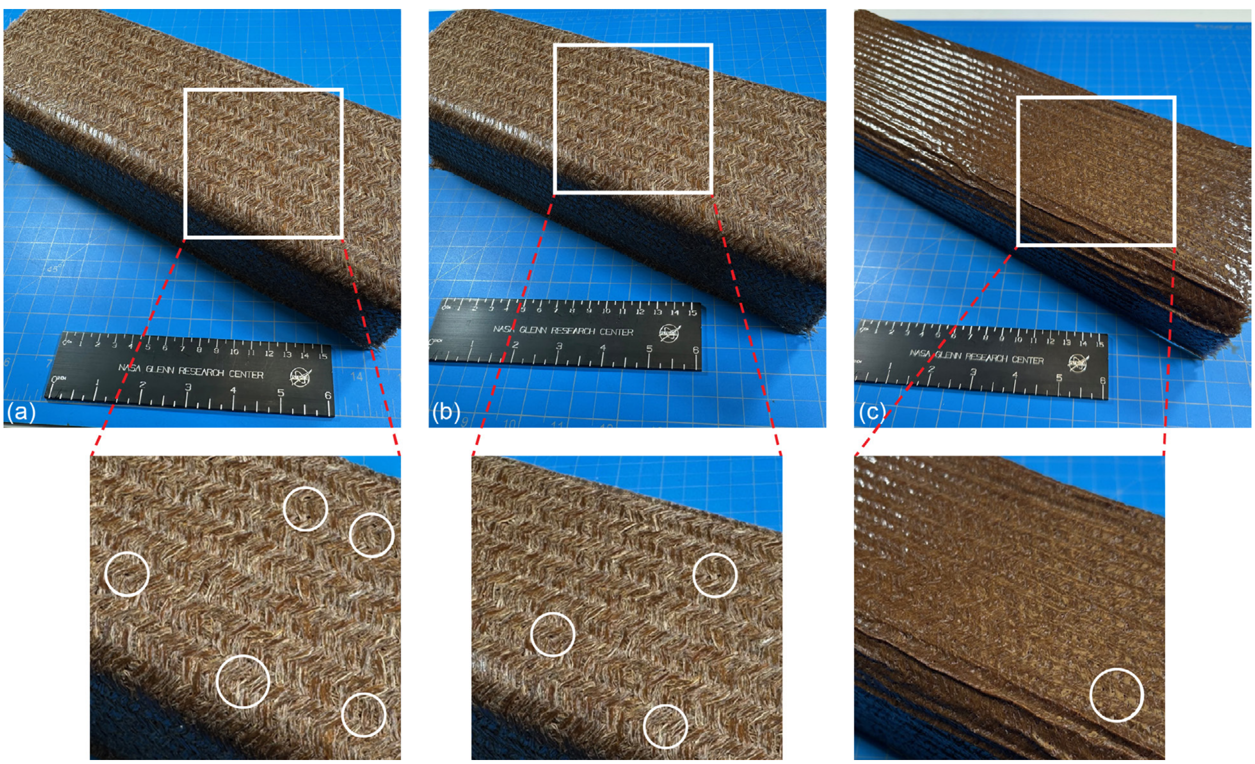


Figure 17.—Trial 1 to 3 C-channel subcomponents with closeups of dry fiber areas and voids on surface (circled in white). (a) Trial 1. (b) Trial 2. (c) Trial 3.

Figure 17 highlights this variation in fiber wetting and the voids on the surfaces of the various samples. The number of dry spots decreased from Trial 1 to Trial 2, and dry spots were almost eliminated in the Trial 3 sample. The surface of the C-channel made in Trial 3 clearly shows an improvement in composite consolidation when compared to the previous two samples. Although a few dry areas were observed on the edges of the subcomponent, further changes in the processing profile are not likely to produce significant improvements considering that the procedure reached the upper limit of pressure that can be applied by the autoclave. One approach to improve surface quality may be the addition of a top mold to apply additional, homogeneous pressure on the surface of the subcomponent. This might also aid in reducing the ridges in the composite where the resin conformed to the braided fiber structure and produce a subcomponent with a flat surface.

As in the propeller manufacturing demonstration, progress was limited by resources and time. Implementing a subtle change by including a rigid surface on the top of the layup in combination with the optimized processing profile achieved in this demonstration would likely produce optimized parts. Even with these time constraints, the demonstration was able to successfully produce a satisfactory processing profile and multiple C-channel demonstration pieces.

## Concluding Remarks

The manufacturing demonstrations reported in this work successfully scaled up the manufacturing of natural fiber composite (NFC) to large-scale commercial parts. Six propeller skins and three C-channel subcomponents were successfully fabricated in this manufacturing demonstration. The braided flax/PA-11 preform proved to be compatible with both autoclave and compression molding processes that are regularly used in commercial aerospace production. Further characterization, development, and testing will be required to fully incorporate these new materials into advanced air mobility (AAM) applications, as well as to identify specific use cases for which these materials will be best suited. Nevertheless, this initial study demonstrated the feasibility of scaling up the production of NFCs and is a crucial step in introducing these sustainable composite alternatives into real-world applications.

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