# DESIGN AND DEVELOPMENT OF PROTOTYPE COMPOSITE DUCTS FOR AIRCRAFT COMPONENTS

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## Introduction

Unmanned aerial vehicles (UAVs) are quickly replacing manned systems in both military and civilian applications. The rapid development of such aircraft has fueled a need for faster, lower-cost alternatives to conventional prototyping. This includes looking at alternative tooling materials and different prototyping technologies.

A quad-rotor vertical take-off and landing (VTOL) UAV prototype was designed for close surveillance applications. The engines are housed in ducts in order to protect the rotor blades and other internal components from impact with objects such as buildings. The ducts need to be lightweight and stiff. The initial prototypes consisted of only the inner surface of the nacelle; since the initial test flight will be tethered and indoors, the fuel lines and wiring could be exposed.

The inner duct was modeled in SolidWorks. Two material options were chosen: a woven carbon fiber cloth/epoxy composite and a unidirectional carbon prepreg/epoxy composite. Material characterization experiments were performed to determine the mechanical properties of each material; these values were then used to perform finite element analysis on the duct to determine the optimum fiber orientations. Four ducts were then fabricated from each material. The design and labor time and costs of each method were examined.

## Experimental

*Specimen Preparation*
A panel of plain weave carbon fiber cloth/epoxy and a panel of unidirectional carbon prepreg/epoxy, each consisting of eight layers, were laid up with the fibers oriented in the same direction for each layer. The woven carbon fiber panel was cured at ambient temperature under vacuum. The prepreg panel was non-autoclave cured at 121 °C under vacuum. Once cured, the panels were fitted with glass fiber reinforced polymer end tabs and cut into 10 inch by 1 inch strips as recommended by ASTM Standard D 3039. Six specimens of each material were created; three specimens of each material were outfitted with Vishay CEA-06-24OUZ-120 strain gages, used to verify the data obtained from clip-on extensometers [1].

*Testing Methods*
Tensile tests were performed in accordance with ASTM Standard D 3039. An MTS Series 319 Axial/Torsion Material Test System fitted with a 100 kN load cell was used to perform the tests; TestStar and TestWare SX software was used to run the tests and collect the data. All of the specimens were equipped with Satec E-Series clip-on axial and transverse extensometers to record the strain. The specimens were tested to failure and the data were recorded.

*Results*
The maximum tensile strength, elastic modulus and Poisson's ratio for the major axis were determined from the data. The average values for each specimen are shown in Table 1. The prepreg is stiffer and exhibits better strength properties than the woven material.

**Table 1: Material properties obtained from experiment**

| | Woven CF | Prepreg CF |
|---|---|---|
| **Tensile Strength (MPa)** | 513 ± 33 | 1633 ± 175 |
| **Elastic Modulus (GPa)** | 45 ± 8 | 130 ± 6 |
| **Poisson's ratio** | 0.07 ± 0.01 | 0.33 ± 0.02 |

## Fabrication

Using the properties obtained from the characterization tests, the duct was modeled in Altair HyperMesh v7.0 and finite element analysis was conducted using the solver OptiStruct. Simulations were run under the same loading condition; the fiber orientations were modified for each simulation to determine the most effective orientation. The FEA model is shown in Figure 1. Since weight was a concern, designs were limited to six layers for the prepreg duct and four layers (two layers of 0/90 twill (w) cloth and two layers of unidirectional (u) fibers) for the cloth (properties for the unidirectional cloth used in the analysis were determined in a study by Nelson et al. [2]). From the analysis, a [90/0/+45/-45/0/90] orientation for the prepreg and a [$0_w$/+$45_u$/-$45_u$/$0_w$] orientation for the cloth were chosen, where 0 degrees is imposed along the length of the duct (x-axis). The geometry of the inner duct required the use of a male mold for fabrication. For tooling material, Coastal Enterprises' PBHT-30 high-temperature foam was used, which is stable up to 300°F. The mold was separated into seven pieces for easy removal after the part cured (Figure 2).

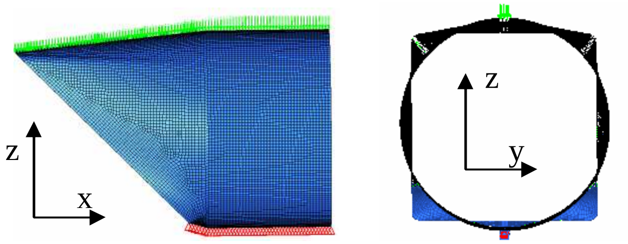


**Figure 1: FEA model of duct showing loading scenario**

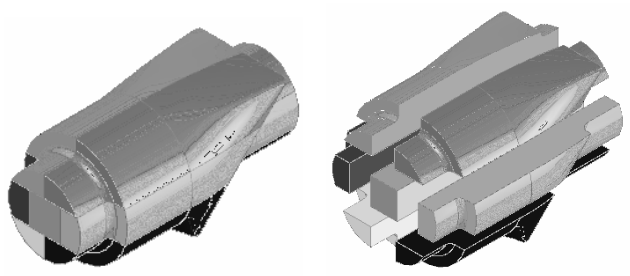

**Figure 2: CAD model of duct mold**

After CNC machining, the mold pieces were prepped with a mold release and the material was laid up in the aforementioned orientations determined by FEA. The wet lay-up ducts were laid up using 3K 5.7oz 0/90 twill weave and 12K unidirectional tape coated in a 3 to 1 epoxy resin (www.uscomposites.com). The part was subsequently wrapped in order in Teflon peel-ply, breather cloth, and vacuum bag. A vacuum was pulled to remove the excess resin and compress the layers while the part cured at room temperature. The prepreg ducts were laid up using NCT 301 34-700 carbon prepreg tape (www.newportad.com). The part was wrapped in the same manner as the wet lay-up part and a vacuum was pulled prior to placing it in an oven to cure at 127 °C (260 °F) for approximately 3 hours.

**Figure 3: Wet lay-up of duct and vacuum assembly**

Once the part was cured, the mold was removed by tapping out the center piece and then collapsing the other pieces and pulling them out as shown in Figure 4. The wet lay-up nacelle required trimming of the excess material prior to removal. The finished nacelles are shown in Figure 5.

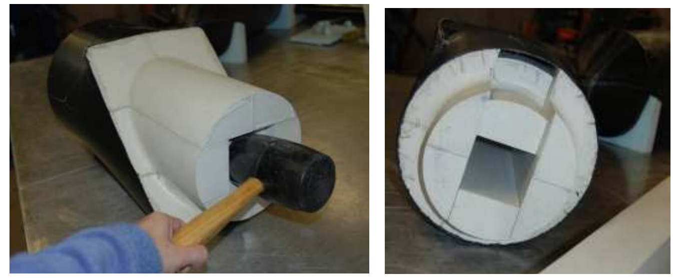

**Figure 4: Removal of mold from part after cure**

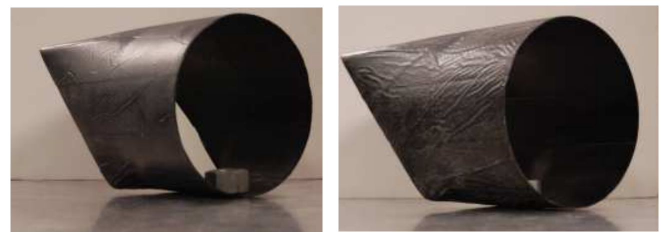

**Figure 5: Finished ducts: prepreg (left) and wet lay-up**

## Conclusions

The prepreg nacelles are lighter than the wet lay-up nacelles, but the latter are stiffer and less costly to produce. Further testing provided a load to weight ratio of 181.7 for the prepreg duct and 461.1 for the wet lay-up duct when loaded from the top. The time for fabrication and the associated costs for each method are shown in Table 2. The material cost for the wet lay-up method was calculated assuming medium density fiberboard could be used in place of the high-temperature foam for the mold. These costs are for fabrication of a full set of four ducts. Damage to the mold occurred during removal of the prepreg parts, necessitating mold reconstruction along the edges, thus increasing the fabrication time.

**Table 2: Comparison of cost and time for fabrication**

| | Prepreg | Wet Lay-Up |
|---|---|---|
| Material Cost | $825 | $455 |
| Labor Cost | $3,680 | $3,040 |
| Time for Fabrication | 13 days | 9 days |
| Total Cost | $4,505 | $3,495 |

## References

1. Huang, Gu, "Tensile and bending behaviours of laminates with various fabric orientations," Materials & Design, Volume 27, Issue 10, 2006, pp 1086-1089.

2. Nelson, S. M., Thota, J., "Characteristics of a unidirectional carbon fiber/epoxy composite for prototype design," *SAMPE 2008 Conference*, Long Beach, CA.